SUSTAINABILITY IN DEBATE

SUSTENTABILIDADE EM DEBATE



EDITORIAL

In war, one thing is certain: the environment always loses

ARTICLES *VARIA*

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FIFA Standard and environmental sustainability: thinking ahead

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Table of Contents / *Sumário*

EDITORIAL / *EDITORIAL*

In war, one thing is certain: the environment always loses/ *Nas guerras uma coisa é certa: o meio ambiente sempre é perdedor*
By/Por: Carlos Hiroo Saito, Marcel Bursztyn, Patrícia Mesquita, Cristiana Dobre

doi: 10.18472/SustDeb.v17n1.2026.61992 06

ARTICLES VARIA / *ARTIGOS VARIA*

Reconfiguring dependency: Latin America in the geopolitics of the energy transition and critical minerals / *Reconfigurando a dependência: América Latina na geopolítica da transição energética e dos minerais críticos*
By/Por: Axel Bastián Poque González

doi: 10.18472/SustDeb.v17n1.2026.60207 12

In-depth assessment of energy transition policies: a comparative study between PROINFA (Ceará, Brazil) and Law 8/2009 (Galicia, Spain) / *Avaliação em profundidade de políticas de transição energética: um estudo comparado entre o PROINFA (Ceará, Brasil) e a Lei 8/2009 (Galícia, Espanha)*
By/Por: Nicole Stephanie Florentino de Sousa Carvalho, Rosa Maria Regueiro-Ferreira, Gil Célio de Castro Cardoso

doi: 10.18472/SustDeb.v17n1.2026.60521 28

Assessing municipal Climate Action Plans through a health lens: the case of the City of Rio de Janeiro / *Avaliando Planos de Ação Climática municipais por uma lente de saúde: caso da cidade do Rio de Janeiro*
By/Por: Marcelo Guimarães Araújo, Vinicius Santos Soares, Lilian Bechara Elabras-Veiga

doi: 10.18472/SustDeb.v17n1.2026.60296 58

Climate change projections and impacts on raw water quality in the Paraíba do Sul River basin, Southeast Brazil / *Projeções de mudanças climáticas e seus impactos na qualidade da água bruta na bacia do Rio Paraíba do Sul Paulista*
By/Por: Diovana de Moura Rahmani, Luiz Fernando Satolo, Erica Acioli Canamary, Javier Tomasella

doi: 10.18472/SustDeb.v17n1.2026.58433 74

Analysis of grape growers' and wine producers' perceptions in Brazil regarding climate change / *Análise da percepção dos produtores de uva e vinho no Brasil em relação às mudanças climáticas*
By/Por: Daniel Trento do Nascimento, Carolina Pretto Panceri

doi: 10.18472/SustDeb.v17n1.2026.58068 122

Deforestation in the Amazon and macroeconomic variables: evidence from time-series analysis (2000–2023) / *O desmatamento na Amazônia e variáveis macroeconômicas: evidências de análises de séries de tempo entre 2000 e 2023*
By/Por: Leandro Vinicios Carvalho, Jonathan Gonçalves da Silva, Roselaine Bonfim de Almeida

doi: 10.18472/SustDeb.v17n1.2026.60904 153

Determinants of innovation in aquaculture organisations of the Peruvian Amazon / *Determinantes de innovación en organizaciones acuícolas de la Amazonía Peruana*
By/Por: Cristian Zoilo Sánchez Pariona, Marta Lucia Tostes Vieira

doi: 10.18472/SustDeb.v17n1.2026.59781 172

Application of participatory research techniques in the socio-environmental study conducted in the Jacaré-Curituba settlement in Brazil / *Aplicação de técnicas de pesquisa participativa no estudo socioambiental realizado no assentamento Jacaré-Curituba do Brasil*
By/Por: Nelson Bernal Dávalos, Caroline Barcelos, Guadalupe Sátiro, Paula Castanho, Roseli Santos, Elton Souza Oliveira, Wesly Jean, Julia Lopes Ferreira, Daniela Nogueira

doi: 10.18472/SustDeb.v17n1.2026.57119 200

Reviving the traditional use of plant dyes for sisal (Agave sisalana) fibres in a Brazilian artisan community / *Revitalizando o uso tradicional de plantas corantes de fibras de sisal (Agave sisalana) em uma comunidade artesã brasileira*
By/Por: Maria Cristina Teixeira Braga Messias, Maria Auxiliadora Drumond

doi: 10.18472/SustDeb.v17n1.2026.58328 238

Citizen science and engaged visual anthropology for climate justice: a study of the Emergent Ecologies platform / *Ciência cidadã e antropologia visual engajada para justiça climática: um estudo da plataforma Emergent Ecologies*
By/Por: Bruno Tarin, Laila Thomaz Sandroni, Erika Robb Larkins

doi: 10.18472/SustDeb.v17n1.2026.59578 254

FIFA Standard and environmental sustainability: thinking ahead / *Padrão FIFA e sustentabilidade ambiental: pensando no futuro*
By/Por: Gabrielly de Queiroz Pereira, Douglas Paulo Bertrand Renaux, Luiz Alberto Pilatti

doi: 10.18472/SustDeb.v17n1.2026.60131 291

Editorial

In war, one thing is certain: the environment always loses

Carlos Hiroo Saito, Marcel Bursztyn, Patrícia Mesquita and Cristiana Dobre

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The Spanish painter Francisco de Goya (1746–1828) left, among his rich artistic legacy, a series of engravings entitled *Los Desastres de la Guerra* (*The Disasters of War*), in which he portrays, with striking rawness, scenes of human violence during the Napoleonic conflicts. A hidden figure in these images, though no less significant than the human tragedy, is nature itself, which emerges as a casualty in every war. As Michel Serres observes in *Le Contrat Naturel* (*The Natural Contract*) (1990), the environment is an often-overlooked victim of human conflict.

Wars have always existed, and human losses have invariably been immense. However, since the First World War (1914–1918), advances in military technology have increasingly revealed a dual trend: the growing asymmetry in casualties between opposing sides, and the expanding scale of destruction inflicted upon both natural and built environments. From the earliest chemical weapons to the use of missiles and drones, including atomic and fragmentation bombs, the environmental footprint of warfare has intensified alongside its destructive capacity. At the same time, conflicts continue to proliferate, driven by intertwined religious, political, and economic interests.

The current war involving Israel and the United States of America against Iran has drawn attention to several issues already evident during the US military intervention in Venezuelan territory in 2025. Although Israel maintains longstanding political and military rivalries with Iran, the involvement of the United States highlights interests tied to energy resources — more specifically, oil and gas reserves.

Beyond the motivations surrounding access to fuel supplies, the sudden escalation of the conflict and the resulting concerns over restrictions on global oil and gas trade have exposed humanity's persistent dependence on fossil-fuel-intensive energy systems.

This dependence of nations on non-renewable fossil fuels, alongside the vulnerabilities it creates, continues to produce immediate geopolitical and economic repercussions. Beyond financial speculation, the mere prospect of supply disruption has driven prices upward almost instantaneously.

Such dynamics raise a pressing question: why does this vulnerability persist despite decades of recognition regarding the urgency of energy transition? Technological advances have already made the large-scale expansion of renewable energy sources, including solar, wind, biomass, and hydropower, viable. Scientific evidence and international protocols have reinforced the urgency of accelerating this transition. Nevertheless, geopolitical and economic interests prevail, prolonging global dependence on hydrocarbons.

An analysis conducted by Clean Creatives, examined approximately two thousand corporate communication materials (YouTube videos, digital and social media ads, executive speeches, press releases, interviews and television commercials), published between 2020 and 2024 by major oil companies, such as BP, Chevron, ExxonMobil and Shell. The study found that these firms retreated from prior commitments with transition plans and returned to prioritisng fossil fuel production and shareholder returns, while framing mitigation strategies such as carbon capture and storage as justification for continued expansion of extraction activities.

According to the study, this shift was accompanied by a gradual transformation in corporate narrative. They gradually abandoned the discourse adopted in 2021, when they claimed they would assume responsibility and leadership in the energy transition in response to the climate emergency. This shift evolved arguments focused on energy security (2022), followed by claims regarding the need for a diversified energy mix to legitimise continued fossil fuel expansion. To preserve some residual reference to climate concerns, companies mobilised references to emissions reduction and carbon sequestration (2023), before a more explicit reaffirmation of fossil fuel dependence and the necessity of maintaining extraction for economic stability and energy security re-emerged (2O24)[1]. Thus, corporate discourse has been progressively transformed, and environmental concern has receded from both the rhetoric and the practices of oil extraction companies. National governments have similarly reinforced policies aligned with economic priorities and the worldview that underpins them.

Brazil's current efforts to expand oil exploration along the Equatorial Margin of the Amazon confirm this broader context. On its official website, Petrobras justifies the initiative in the following terms:

"We work continuously to meet energy demand, develop production, and expand our horizons. Located in the country's northern region, the Equatorial Margin has significant oil potential and offers numerous opportunities to improve the lives of thousands of Brazilians. It has the potential to generate jobs, increase tax revenues, and contribute to regional and national development."[2]

The immediate economic and social appeal of this argument is evident.

This leads to a further warning: the environmental implications of this renewed trajectory. The Paris Agreement is being quietly undermined, and the environment may pay a severe price. In Brazil, there is a risk of direct damage to coastal and marine ecosystems, including mangrove areas. Continued fossil fuel combustion will intensify greenhouse gas emissions, further exacerbating climate change. In this context, investments in science, technology, and public debate concerning energy transition risk being eclipsed by the imperatives of political and financial rationality.

War merely served as the starting point for this reflection, whose conclusion highlights a planetary crisis that underscores the urgent need to free us from dependence on oil and gas and from the conflicts this dependence engenders. Advancing the transition to renewable energy is therefore not only an environmental imperative but also a strategic necessity for peace and global stability. Regardless of who prevails in any given war, the environment always loses. As a scholarly forum committed to advancing socio-environmental sustainability, *Sustainability in Debate* reaffirms its commitment to promoting critical reflection and evidence-based advocacy in support of the global transition towards renewable energy systems.

In this edition, *Sustainability in Debate* brings together contributions that directly address the structural challenges and contradictions surrounding sustainability transitions, socio-environmental governance, and climate adaptation, issues that the current geopolitical conjuncture makes impossible to ignore.

In this edition, *Sustainability in Debate* brings together contributions that directly address the structural challenges and contradictions surrounding sustainability transitions, socio-environmental governance, and climate adaptation, which are the very forces that wars over energy make impossible to ignore.

Several articles engage directly with the political, territorial, and geopolitical dimensions of the energy transition.

González examines Latin America's strategic yet constrained position in the geopolitics of critical minerals, arguing that the global shift towards renewable energy may be reconfiguring, rather than overcoming, historical centre-periphery dependency relations, thereby limiting the region's prospects for greater autonomy in the emerging geopolitical order. Complementing this macro-structural perspective, Carvalho *et al.* provide a comparative assessment of wind energy policies in Ceará, Brazil, and Galicia, Spain, demonstrating that the expansion of renewable energy infrastructure, while

essential to decarbonisation, may reproduce distributive injustices and territorial conflicts when not accompanied by robust mechanisms of procedural and distributive justice.

A second group of contributions addresses the growing complexity of climate adaptation and socio-environmental vulnerability across diverse territorial contexts. Araújo *et al.* assess the Climate Action Plan of the City of Rio de Janeiro through a public health lens, finding that while the plan addresses several determinants of the Urbanism Favourable to Health framework, significant opportunities remain to strengthen local-level vulnerability assessments. Rahmani *et al.* assess recent trends in water quality indicators in the Paraíba do Sul River basin, demonstrating that climate variability affects water quality and availability is projected to decline, particularly under high-emission scenarios, underscoring the urgency of mitigation and adaptation measures to ensure regional water security. Nascimento and Panceri investigate perceptions of climate change among grape and wine producers across Brazil, showing that although approximately 80% of producers already perceive climatic impacts on productivity and quality, adaptive responses remain limited in both scope and effectiveness.

The issue also explores the socio-economic and institutional drivers of environmental degradation and resource governance. Carvalho *et al.* examine the relationship between macroeconomic variables and deforestation in the Amazon between 2000 and 2023, showing that exchange rates and agricultural profitability are key economic drivers of land-use expansion, and that conservation policies and monitoring mechanisms remain essential counterweights to these pressures. Pariona and Vieira analyse determinants of innovation in aquaculture organisations in the San Martín region of Peru, underscoring the role of technological cooperation and fiscal incentives in fostering a more competitive and resilient sector.

Methodological and epistemological innovations in sustainability research also feature prominently in this edition. Dávalos *et al.* reflect on the application of qualitative research techniques, including participant observation and semi-structured interviews, in socio-environmental studies. The authors use the case of the Jacaré-Curituba settlement in Sergipe to demonstrate how qualitative approaches can capture subjective dimensions that quantitative methods often fail to measure. Messias and Drumond present an ethnobotanical study documenting plant species historically used to dye sisal fibres in a Brazilian artisan community, showing how the reintroduction of natural dyes through participatory workshops can revive traditional knowledge while supporting more sustainable artisanal production. Tarin *et al.* examine the Emergent Ecologies platform, focusing on its Women in Artisanal Fishing section, to argue that platforms integrating social science research, digital media and socio-environmental activism create spaces for the co-production of knowledge and can contribute to climate justice and transformative sustainability action.

Finally, Pereira *et al.* broaden the debate on sustainability governance by analysing FIFA's environmental standards for stadium infrastructure and identifying opportunities to strengthen environmental criteria in global sports governance by incorporating internationally recognised sustainability benchmarks, such as B Corp, GRI, Carbon Trust, and ISO 14001.

Taken together, the contributions in this issue reaffirm that sustainability transitions are neither linear nor inherently just. Whether in the geopolitics of critical minerals, the territorialisation of renewable energy, urban climate adaptation planning, environmental governance, or knowledge co-production, the pathways towards sustainability remain contested, uneven, and deeply political.

We hope you enjoy reading this issue.

The Editors

NOTES

1 | https://climainfo.org.br/2026/03/25/petroliferas-abandonam-discurso-verde-e-reforcam-dependencia-de-petroleo-e-gas/

2| https://petrobras.com.br/quem-somos/novas-fronteiras

Editorial

Nas guerras uma coisa é certa: o meio ambiente sempre é perdedor

Carlos Hiroo Saito, Marcel Bursztyn, Patrícia Mesquita e Cristiana Dobre

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O pintor espanhol Francisco de Goya (1746-1828) nos deixou, entre seu rico legado artístico, uma série de gravuras intitulada *Los Desastres de la Guerra* onde mostra, de forma crua e impressionante, cenas da violência humana durante os conflitos napoleônicos. Uma personagem oculta nas imagens, mas não menos importante do que a tragédia humana, é a natureza, que é uma perdedora em todas as guerras. Esse ponto já havia sido assinalado pelo filósofo e matemático francês Michel Serres, em seu livro *O Contrato Natural*, de 1990.

Guerras sempre existiram, e as perdas humanas sempre foram enormes. Mas desde a Primeira Guerra Mundial (1914-1918), o avanço da tecnologia bélica tem mostrado, crescentemente, uma dupla tendência: a desproporção entre as baixas de cada lado e a dimensão dos efeitos sobre os ambientes natural e construído. Das primeiras armas químicas ao uso de mísseis e drones, passando pelas bombas atômicas e de fragmentação, a devastação é cada vez maior. E, para completar o desastre, as guerras têm sido frequentes e intensas, sejam por motivos religiosos, sejam econômicos e/ou políticos.

A presente guerra entre Israel e Estados Unidos da América contra o Irã chamou atenção para algumas questões sobre as quais já havia evidências quando da ação norte-americana em território venezuelano em 2025. Ainda que Israel tenha fortes rivalidades políticas e militares com o Irã, o envolvimento norte-americano evidencia o interesse na questão energética, mais explicitamente, nas fontes de petróleo e gás.

Além da motivação em torno do acesso a fonte de combustíveis, a súbita escalada da guerra e a possibilidade de restrição no comércio internacional do petróleo e gás trouxeram à tona a ainda grande dependência da humanidade ao uso intensivo de energia fóssil.

Essa dependência (e correspondente vulnerabilidade) dos países em relação aos combustíveis fósseis não renováveis fez com que essa guerra no Oriente Médio trouxesse impactos geopolíticos imediatos e também instabilidade na economia global. Para além da especulação financeira, o temor da escassez fez preços se elevarem imediatamente.

O que se pergunta é por que ainda há toda essa vulnerabilidade, se há algum tempo estamos cientes do imperativo da transição energética rumo à produção a partir de fontes renováveis. O avanço tecnológico já torna viável a intensificação do uso da energia solar, eólica, da biomassa, hidráulica, entre outras fontes. Alertas científicos e protocolos internacionais reforçam a urgência dessa transição. Mas interesses geopolíticos e econômicos prevalecem, dando mais longa vida ao ciclo da nossa dependência perante os hidrocarbonetos.

A organização Clean Creatives analisou cerca de dois mil materiais de campanha publicitária (como vídeos na plataforma YouTube, publicações e anúncios digitais em plataformas de redes sociais, além de discursos de executivos, comunicados à imprensa, entrevistas e comerciais de TV) de algumas grandes companhias do setor (como BP, Chevron, ExxonMobil e Shell) entre 2020 e 2024. A conclusão do estudo foi que elas, no conjunto, abandonaram os planos de transição e voltaram a focar a produção de combustíveis fósseis e a remuneração aos acionistas, inclusive buscando justificar a expansão da exploração de combustíveis fósseis por meio de paliativos como captura e armazenamento de carbono.

Este estudo denuncia que a estratégia narrativa das petrolíferas foi mudando gradativamente, deixando de lado o discurso que faziam em 2021 quando diziam que elas também assumiriam a responsabilidade e liderança na transição energética em sintonia com a consciência das emergências climáticas. A mudança passou pelo uso de uma nova retórica sobre a importância da segurança energética (2022) e, na sequência, passou a descrever a importância da coexistência de uma diversidade de fontes para justificar a expansão dos combustíveis fósseis. Para guardar algum resquício de referência à preocupação com o clima, enfatizou-se a redução de emissões ou o sequestro de carbono (2023), até voltar a falar na dependência dos combustíveis fósseis e a importância de assegurar a continuidade de sua exploração, novamente enfatizando a segurança energética e a estabilidade das economias (2024)[1]. Assim, o discurso vem sendo paulatinamente transformado, e a preocupação ambiental deixa de se fazer presente no discurso e na prática das empresas de exploração de petróleo, e também no discurso de governos nacionais ao fortaleceram políticas alinhadas com esse interesse econômico e visão de mundo.

O esforço empreendido no Brasil para exploração do petróleo na Amazônia equatorial confirma esse contexto. A página da empresa Petrobras, por exemplo, assim justifica a iniciativa: "Trabalhamos sempre para atender à demanda de energia, desenvolver a produção e expandir nossos horizontes. Localizada no Norte do país, a Margem Equatorial apresenta um importante potencial petrolífero e conta com uma série de oportunidades para melhorar a vida de milhares de brasileiros. Existe a possibilidade de gerar empregos, aumentar a arrecadação e participar de um desenvolvimento regional e nacional."[2] O apelo imediatista sobre efeitos positivos na economia e na sociedade fica evidente.

Isso nos leva a outro alerta: os impactos ambientais decorrentes dessa guinada. O Acordo de Paris é silenciosamente sabotado, e o meio ambiente pode pagar um preço alto. No Brasil, há risco de danos diretos a ecossistemas costeiros e marinhos, entre eles os manguezais. A atmosfera vai continuar recebendo emissões de carbono pela queima desses combustíveis fósseis, retroalimentando o processo de mudanças climáticas. O investimento em ciência e tecnologia, e o debate sobre a transição energética são eclipsados pela força da razão política e financeira.

A guerra foi apenas o ponto de partida dessa reflexão, cuja conclusão reitera a existência de uma crise planetária que mostra a urgência de sairmos da dependência do petróleo e gás, e dos conflitos que gera. Pelo bem da paz e do meio ambiente e do clima, precisamos valorizar a transição energética. Independente de quem vence cada guerra, o meio ambiente sempre é perdedor. A revista *Sustainability in Debate* tem o dever de defender a luta pela transição energética para energias renováveis como parte do esforço pela sustentabilidade socioambiental de nosso planeta.

Nesta edição, a revista *Sustainability in Debate* reúne contribuições que abordam diretamente os desafios estruturais e as contradições que permeiam as transições para a sustentabilidade, a governança socioambiental e a adaptação climática, temas que a conjuntura geopolítica atual torna impossíveis de ignorar.

Vários artigos se debruçam sobre as dimensões políticas, territoriais e geopolíticas da transição energética. González examina a posição estratégica, porém limitada, da América Latina na geopolítica dos minerais críticos, argumentando que a transição global rumo às energias renováveis pode estar reconfigurando, em vez de superar, as históricas relações de dependência centro-periferia, restringindo assim as perspectivas da região por maior autonomia na nova ordem geopolítica emergente. Complementando essa perspectiva macroestrutural, Carvalho *et al.* oferecem uma avaliação comparativa das políticas de energia eólica no Ceará, Brasil, e na Galícia, Espanha, demonstrando que a expansão da infraestrutura de energias renováveis, ainda que essencial à descarbonização, pode reproduzir injustiças distributivas e conflitos territoriais quando não acompanhada de mecanismos robustos de justiça procedimental e distributiva.

Um segundo conjunto de contribuições aborda a crescente complexidade da adaptação climática e da vulnerabilidade socioambiental em contextos territoriais diversos. Araújo *et al.* avaliam o Plano de Ação Climática da Cidade do Rio de Janeiro por meio de uma perspectiva de saúde pública, constatando que, embora o plano contemple diversos determinantes da abordagem Urbanismo Favorável à Saúde, ainda

há oportunidades para o fortalecimento das avaliações de vulnerabilidade em nível local. Rahmani *et al.* avaliam tendências recentes nos indicadores de qualidade da água na Bacia do Rio Paraíba do Sul, demonstrando que a variabilidade climática afeta a qualidade da água e que a disponibilidade hídrica está prevista para declinar, sobretudo em cenários de maiores emissões, reforçando a urgência de medidas de mitigação e adaptação para garantir a segurança hídrica regional. Nascimento e Panceri investigam as percepções dos produtores de uva e vinho em diferentes regiões do Brasil sobre os efeitos das mudanças climáticas, revelando que, embora aproximadamente 80% dos produtores já percebam impactos climáticos na produtividade e na qualidade, as respostas adaptativas permanecem limitadas tanto em escopo quanto em efetividade.

A edição também explora os condicionantes socioeconômicos e institucionais da degradação ambiental e da governança de recursos. Carvalho *et al.* examinam a relação entre variáveis macroeconômicas e o desmatamento na Amazônia entre 2000 e 2023, mostrando que a taxa de câmbio e a rentabilidade agrícola são os principais motores econômicos da expansão do uso da terra e que políticas de conservação e mecanismos de monitoramento constituem contrapontos indispensáveis a essas pressões. Pariona e Vieira analisam os determinantes da inovação em organizações aquícolas na região de San Martín, no Peru, destacando o papel da cooperação tecnológica e dos incentivos fiscais no fomento a um setor mais competitivo e resiliente.

Inovações metodológicas e epistemológicas na pesquisa em sustentabilidade também se destacam nesta edição. Dávalos *et al.* refletem sobre a aplicação de técnicas de pesquisa qualitativa, como a observação participante e as entrevistas semiestruturadas, em estudos socioambientais. Os autores usam o caso do Assentamento Jacaré-Curituba, em Sergipe, para demonstrar como abordagens qualitativas são capazes de capturar dimensões subjetivas que os métodos quantitativos frequentemente não conseguem mensurar. Messias e Drumond apresentam um estudo etnobotânico que documenta espécies vegetais historicamente utilizadas no tingimento de fibras de sisal em uma comunidade artesã brasileira, mostrando como a reintrodução de corantes naturais por meio de oficinas participativas pode revitalizar conhecimentos tradicionais e promover uma produção artesanal mais sustentável. Tarin *et al.* examinam a plataforma *Emergent Ecologies*, com foco na seção Mulheres na Pesca Artesanal, para argumentar que plataformas que integram pesquisa em ciências sociais, mídias digitais e ativismo socioambiental criam espaços para a coprodução de conhecimento e podem contribuir para a justiça climática e para a ação transformadora em prol da sustentabilidade.

Por fim, Pereira *et al.* ampliam o debate sobre governança da sustentabilidade ao analisar os padrões de sustentabilidade ambiental da FIFA para a infraestrutura de estádios, identificando oportunidades para incorporar referenciais internacionalmente reconhecidos, como B Corp, GRI, Carbon Trust e ISO 14001, em futuras revisões do padrão FIFA.

Em conjunto, as contribuições desta edição reafirmam que as transições para a sustentabilidade não são lineares nem intrinsecamente justas. Seja na geopolítica dos minerais críticos, na territorialização das energias renováveis, no planejamento da adaptação climática urbana, na governança ambiental ou na coprodução do conhecimento, os caminhos rumo à sustentabilidade permanecem contestados, desiguais e profundamente políticos.

Boa leitura.

Os Editores

NOTAS

1 | https://climainfo.org.br/2026/03/25/petroliferas-abandonam-discurso-verde-e-reforcam-dependencia-de-petroleo-e-gas/

2| https://petrobras.com.br/quem-somos/novas-fronteiras

Reconfiguring dependency: Latin America in the geopolitics of the energy transition and critical minerals

Reconfigurando a dependência: América Latina na geopolítica da transição energética e dos minerais críticos

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ABSTRACT

The energy transition is central to addressing the climate crisis, yet it also fosters new geopolitical and territorial tensions. As a major supplier of critical minerals for renewable technologies, Latin America occupies a strategic yet constrained position within the world economy. This study analyses the region through the lens of dependency theory, focusing on the interplay among three global poles: the United States and China — dominant manufacturers of *cleantech* — and Latin America, particularly Brazil, Chile, and Peru, as leading mineral exporters. Methodologically, the paper adopts an analytical and interpretive approach grounded in critical political economy, based on theoretical reflection and documentary analysis of academic and institutional sources. The study examines the economic and ecological implications of the transition, showing how structural inequalities persist despite decarbonisation. The findings indicate that the energy transition constitutes a reconfiguration — rather than a rupture — of historical dependency relations, thereby limiting Latin America's prospects for greater autonomy in the emerging geopolitical order.

Keywords: Energy transition. Latin America. Critical minerals. Dependency theory. World economy. Centre-periphery relations.

RESUMO

A transição energética é fundamental para enfrentar a crise climática, mas também fomenta novas tensões geopolíticas e territoriais. Como um dos principais fornecedores de minerais críticos para tecnologias renováveis, a América Latina ocupa uma posição estratégica, porém, limitada na economia mundial. Este estudo analisa a região sob a ótica da teoria da dependência, com foco na interação entre três polos globais: os Estados Unidos e a China — principais fabricantes de tecnologias limpas — e a América Latina, particularmente o Brasil, o Chile e o Peru, como grandes exportadores de minerais. Metodologicamente, o artigo adota uma abordagem analítica e interpretativa fundamentada na economia política crítica, baseada na reflexão teórica e na análise documental de fontes acadêmicas e institucionais. O estudo examina as implicações econômicas e ecológicas da transição, mostrando como as desigualdades estruturais persistem apesar da descarbonização. Os resultados indicam que

a transição energética constitui uma reconfiguração — e não uma ruptura — das relações históricas de dependência, limitando, assim, as perspectivas da América Latina para uma maior autonomia na ordem geopolítica emergente.

Palavras-chave: *Transição energética. América Latina. Minerais críticos. Teoria da Dependência. Economia mundial. Relações centro-periferia.*

1 INTRODUCTION

The global *energy transition* (ET) is often seen as a move toward sustainability (IPCC, 2022, 2023), yet it may reinforce existing geopolitical hierarchies and dependencies (Poque González, 2025). More than technical change, it signifies a reconfiguration of power over the resources and territories embedded in global clean technologies (cleantech) value chains. While portrayed as decarbonisation through renewables and electrification, the ET is intertwined with socio-technical, cultural, and political shifts (Avelino, 2017; Geels *et al.*, 2017; Kuzemko *et al.*, 2024). Indeed, global energy systems are shifting from fossil-fuel dependence to a complex, contested landscape in which access to technology, infrastructure, and policy decisions reshapes production, consumption, transportation, and energy use (Paltsev, 2016).

According to the International Energy Agency (IEA), national economies occupy at least three strategic positions within the unfolding ET and the linked cleantech value chains: the extraction and processing of critical minerals, the manufacturing of key technologies, and the deployment of these technologies in domestic energy systems. This seemingly functional division may mask power asymmetries. Generally, the extraction of critical minerals[1] is concentrated in peripheral and semi-peripheral regions of the world economy, while technological and industrial capacities remain rooted in the core (IEA, 2022; Poque González, 2025). Tracing the production chains of emerging cleantech thus reveals a reconfiguration of power relations, the rise of new geopolitical alignments, and the geography of conflicts shaping the current era (Hughes; Quitzow, 2018).

Thus, recent scholarship has revitalised interest in dependency theory as a valuable lens for analysing the geopolitical dimensions of the sustainable ET (Overland, 2021; Poque González, 2025). Far from being a relic of the past, dependency thinking offers renewed explanatory potential in understanding how structural asymmetries persist within the ET and within global sustainability agendas. As Reis and De Oliveira (2023) argue, revisiting these perspectives allows us to (re)connect the ET debate with the broader tradition of Latin American critical thought. In this sense, Dos Santos' (1985) classic definition of dependency — "as a condition in which the development of some nations remains subordinated to the expansion of others" — retains striking relevance for interpreting today's unequal geography of *sustainability*.

This essay argues that Latin America's role in the ET reflects a reconfiguration rather than a rupture of dependency relations, in which extractivist logics persist under a green guise. Meanwhile, core economies, driven by intensifying geopolitical rivalries, have become the principal demand centres for critical minerals essential to cleantech and advanced technologies. The analysis focuses on three key global poles: the United States (US) and the People's Republic of China (hereafter China), as dominant manufacturers and technological powerhouses, and Latin America (LA), with particular attention to Brazil, Chile, and Peru — as major exporters of critical minerals that underpin the transition. The remainder of this essay is structured as follows: a contextualisation section, a brief overview of the methodology, an analytical section that develops the core argument, and concluding remarks.

2 CONTEXTUALISATION

To situate this study within its broader intellectual landscape, two central dimensions are examined: the geopolitics shaping the global ET and the critical insights of Latin American dependency theory.

2.1 RESHAPING GEOPOLITICS IN THE ENERGY TRANSITION FRAME

Although geopolitics lacks a single definition, it often centres on the interplay among territory, resources, and power (Palacio, 2013; Tuathail; Toal, 1994). Blondeel *et al.* (2021) and Dodds (2014), for instance, examine how geography shapes global politics at the national and international levels, while Palle (2021) notes that power in geopolitics is a socio-political and economic construct shaped by historical and institutional forces.

During the 20th century, oil played a pivotal role in shaping analyses of global power dynamics. Thus, the geopolitics of energy has predominantly centred on oil and gas (Yergin, 2008). Concurrently, Bradshaw (2009) defines the geopolitics of global energy security as the impact of geographical factors, such as supply and demand distribution, on the influence strategies of state and non-state actors to secure reliable, affordable energy.

Today, driven by climate mitigation imperatives, the increasing prominence of renewables — along with electrification, and demand-side and storage devices — and their associated production chains has significantly disrupted the traditional energy geopolitics paradigm (Blondeel *et al.*, 2021, 2024; O'Sullivan; Overland; Sandalow, 2017). Blondeel *et al.* (2024) and Yang, Xia, and Qian (2023) underscore pivotal domains for energy geopolitics, encompassing renewable energy adoption, electrification, critical minerals, low-carbon technology and fuel trade, carbon dioxide removal, digitalisation, cybersecurity, security implications and conflict dynamics associated with the ET, shifts in geopolitical roles, and transformations in international relations.

The year 2024, the warmest in instrumental records, highlights the growing frequency and intensity of extreme climate events, which increasingly threaten ecosystems and human societies (Rohde, 2025). This underscores, alongside the urgency of decarbonisation, the interconnectedness of local and global challenges, with local impacts intricately tied to broader systemic issues (Pörtner *et al.*, 2023).

2.2 WORLD-SYSTEMS AND DEPENDENCY THEORIES—ADDRESSING CONTEMPORARY CHALLENGES

Dependency theory, which emerged during the 1960s and 1970s, constituted a foundational framework for critically analysing global economic inequalities (Franco; Graña; Rikap, 2024; Stein, 1979). Immanuel Wallerstein expanded on this with his world-systems theory, which argues that all nations participate in a capitalist world economy characterised by structural wealth disparities (Wallerstein, 1985). The theory classifies nations into core, semi-periphery, and periphery based on their economic roles (Petras, 1981; Prebisch, 2022). Ruvalcaba and Valencia (2016) found that no Latin American countries occupy core positions, and few occupy semi-peripheral positions, highlighting LA's position in the world economy.

In a world facing climate and socio-ecological crises, research shows that a nation's place in the global economy correlates with its energy use, CO_2 emissions, and economic output. Core nations have higher energy consumption, emissions, and gross domestic product (GDP) per capita than semi-peripheral and peripheral countries. This pattern persists as (mainly) core and semi-peripheral nations see rising per capita CO_2 emissions linked to economic growth. While semi-peripheral and peripheral countries have made economic progress, environmental issues remain (Greiner, 2019; Greiner; McGee, 2018; Lawrence, 2009).

2.2.1 THREE PHASES OF DEPENDENCY

Dos Santos (1970, 1985) identified three dependency phases: (1) colonial, (2) financial-industrial (by the late 19th century, capital dominated centres and expanded via investments in raw materials and agriculture), and (3) technological-industrial (early 20th century). He highlighted the role of foreign capital in shaping class structures and capital accumulation, thereby maintaining the subordinate status of dependent economies in the world economy.

According to Treacy (2022), core countries exercise significant control over markets, absorbing a portion of the surplus generated by peripheral countries as profits or interest payments. These dynamics effectively deprive peripheral countries of the autonomy to manage their resources. Dependency theory further elucidates the patterns of capital reproduction in peripheral nations, the interrelationship between capitalist development in core countries, and the underdevelopment experienced in peripheral contexts.

2.2.2 TECHNOLOGICAL DEPENDENCY

Franco *et al.* (2024) revisit dependency theory to analyse underdevelopment, focusing on foreign and domestic capital and technological dependency. They highlight the need to update the theory beyond the traditional centre–periphery model, noting that digital platforms have created a new structure in the digital economy, with the US and China as central hubs and other regions marginalised.

A contemporary view of dependency must account for neoliberal changes such as financialisation[2], debt crises, and the subordination of peripheral economies to the core. This underscores the interconnected roles of global trade, transnational corporations, and financial volatility in sustaining structural imbalances. Capital flow instability, driven by economic policies and risk assessments, often causes crises and exchange rate depreciations, as seen during the Covid-19 pandemic (Reis; De Oliveira, 2023; Treacy, 2022).

Core economies monopolise high-value production that needs advanced expertise and technological capabilities, leaving peripheral regions with labour-intensive or resource-extractive activities. This reveals ongoing structural disparities. Though dependency now includes technological, industrial, and financial aspects, the core–periphery imbalance persists. The global division of labour continues to deepen inequalities, with core countries producing high-tech products for re-export to peripheral countries (Treacy, 2022).

2.2.3 GREEN DEPENDENCY

As a continuation of technological dependency, the current ET context fosters a *green dependency*. Following the reflections of Middelanis, Fritz, and De Paula (2026), a green dependency denotes a structural situation in which peripheral nations engage in the global ET primarily as providers of renewable energy and critical minerals, while technological capabilities, value-added manufacturing, financial control, and standard-setting remain concentrated in core economies. As demand for advanced goods increases faster than for commodities, the prices of raw materials generally decline relative to those of manufactured products, thereby worsening the terms of trade and exacerbating development disparities. This dynamic perpetuates centre–periphery asymmetries in the pursuit of a worldwide decarbonised future.

3 METHODOLOGICAL PATH

This study adopts a critical, essay-based interpretive approach rather than a conventional empirical framework. It aims to examine how dependency relations are reconfigured in LA within the global ET. The analysis draws on documentary sources — including academic literature, policy reports, and institutional data — and integrates geopolitical, historical, and socio-environmental lenses.

The argument is developed around three interconnected axes (see Figure 1). First, it explores how shifting global and regional power dynamics reshape territorial relations through new material, infrastructural, and technological flows (Guerrero, 2021). Second, it analyses socio-environmental struggles in LA[3] territories, where conflicts over mining, sustainability and justice become most visible (Temper; Bene; Martinez-Alier, 2015). Third, drawing on Franco, Graña, and Rikap (2024), it considers redefining global hegemony by analysing the US–China rivalry and its implications for Latin America's autonomy.

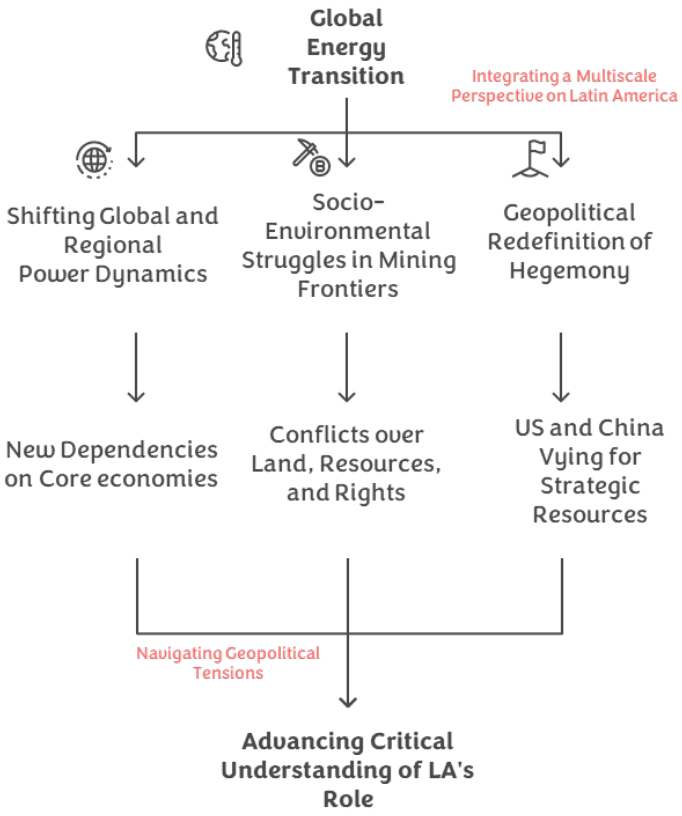


Figure 1 – Methodological path

Source: Author elaboration.

Given their central role in supplying critical minerals, Brazil, Chile, and Peru serve as illustrative cases for tracing historical dependencies, social disputes, and geopolitical entanglements. These examples serve analytical — not statistical — purposes, and are not intended to represent all of LA.

This tripartite structure adopts a multiscalar perspective, linking local socio-territorial processes with broader geopolitical shifts. Inspired by Müller's (2008) view that power operates through both space and discourse, the analysis considers how actors, nations, and corporations construct territorial imaginaries in energy and sustainability debates.

Finally, as an essay-based and interpretive study, this research does not use fieldwork or quantitative modelling. Its contribution lies not in empirical generalisation but in theoretical synthesis and a critical political economy reading of how the global ET reproduces and reshapes structural dependencies in LA.

4 RESULTS — DISCUSSING DEPENDENCY WITHIN THE ENERGY TRANSITION CONTEXT

Guided by the three axes established in the methodological path — shifting geopolitical and economic power, socio-environmental struggles, and the interplay between US and Chinese influence — this analysis examines both global trends and their local manifestations. By tracing the flows of critical minerals, technological capacities, and low-carbon energy infrastructures, the section illustrates how historical patterns of dependence persist or are transformed, revealing the complex interactions between core and peripheral economies in the emerging low-carbon era.

4.1 TRANSFORMATIONS IN LATIN AMERICA

Recent transformations in fossil extraction and liquefied natural gas (LNG) markets have reshaped global energy flows. However, despite these shifts, LA's structural position has remained centred on resource extraction rather than improvements in technological sovereignty. Climate change mitigation plans involve electrification and boosting renewables, shifting geopolitical power toward cleantech development and deployment. Under current IEA projections, the share of fossil fuels in the global energy mix could decline from around 80% to approximately 70% by 2030 (IEA, 2024a). As governments promote the ET, fossil fuel companies are diversifying into renewables, energy services, and electric devices (Guerrero, 2021).

Among Brazil, Chile, and Peru, only Brazil has supplied fossil fuels over the last few decades due to its reserves and production capacity, establishing itself as a key global energy player and developing partial energy sovereignty. Chile and Peru have focused on other resources, contributing minimally to the fossil fuel supply (Castillo *et al.*, 2023). The energy shifts of the ET have tended to homogenise these trajectories by repositioning all three primarily as suppliers of critical minerals within global value chains (Poque González, 2022).

Brazil, Chile, and Peru collectively hold significant global reserves of several essential critical minerals. This prominence is reminiscent of the region's historical importance during the fossil fuel era, when countries such as Venezuela, Mexico, and Brazil possessed considerable oil and gas reserves. Nevertheless, the paramount challenge persists: Latin America's strategic relevance rises during global tech shifts, but its integration remains concentrated in upstream extractive stages, while technological upgrading, processing, and high-value manufacturing remain external to the region.

Table 1 – Resources

Resource	*Brazil*	*Chile*	*Peru*
Oil reserves (Mbbl)	14,856	12	224
Gas reserves (Gm3)	407	8	262
Coal reserves (Mt)	6,596		7
Copper reserves (kt)		190,000	120,000
Lithium reserves (kt)	390	9,300	
Nickel reserves* (kt)	16,000		
Graphite reserves (kt)	74,000		
Rare earth elements reserves (kt)	21,000		

*Source: Data on fossil fuel reserves are drawn from Castillo et al. (2023), while information on critical mineral reserves is based on the Energy Institute (2024). * based on Wilson Center (2024).*

In fact, according to the IEA (2024b), a 2023 review of clean-technology manufacturing facilities worldwide found low levels of LA participation in global low-carbon device manufacturing. Brazil stands out in South America with its technological hubs. Quantitatively speaking, however, the efforts of these hubs remain smaller than those of the core global economies. At least wind turbines, electric vehicles, and storage components are produced in Brazil. Furthermore, Brazil has been globally recognised for its advancements in biofuel development and related technologies (Gimenez *et al.*, 2018).

According to existing policy frameworks, China's cleantech exports are projected to exceed $340 billion by 2035. This amount is approximately equivalent to the aggregate oil export revenues of Saudi Arabia and the United Arab Emirates in 2024. Furthermore, China is currently the most cost-effective location globally for cleantech manufacturing. On average, production costs associated with solar panels, wind turbines, and battery technologies are estimated to be 40% higher in the US, 45% higher in the European Union, and 25% higher in India (IEA, 2024b). Despite industrial hubs emerging in LA, such as in Brazil, their scale is insufficient to alter the global division of labour. This concentration of manufacturing reinforces LA's subordinate role in green value chains, limiting local industrial transformation.

Regarding renewables deployment, the cases of Brazil and Chile exemplify the broad implementation of solar and wind energy in the region (Table 2). Although not entirely absent, socio-environmental conflicts and emissions associated with solar and wind deployment are less significant than those associated with fossil fuels and conventional large hydroelectric projects (Poque González *et al.*, 2023). Conversely, Peru, a key producer of critical minerals, faces a paradox: it lags in renewables deployment (Poque González, 2022).

Table 2 – Renewables deployment

Resource	*Brazil*	*Chile*	*Peru*
Electrification (end-use energy shares)	19%	25%	22%
Renewable power capacity (shares)	84.65%	61.78%	41.38%
Solar power capacity (shares)	11.85%	23.97%	1.82%
Wind power capacity (shares)	11.51%	12.98%	3.42%

Source: Castillo et al. (2023).

Brazil, Chile, and Peru show uneven progress in the ET. Brazil and Chile have expanded renewables, but manufacturing and tech remain externally concentrated. Peru's limited deployment of renewable energy, despite its rich mineral resources, exemplifies the asymmetry between resource access and technological control. While increasing the supply of critical minerals boosts geopolitical visibility, it does not automatically translate into technological sovereignty, value-added industrialisation, or structural upgrading within global value chains. Taken together, these transformations suggest that the energy transition modifies the material basis of dependency — from fossil fuels to critical minerals — without fundamentally transforming the region's structural position within centre–periphery hierarchies. This asymmetry between mineral endowment and technological capability encapsulates the structural logic of green dependency.

4.2 POLITICAL AND SOCIO-ENVIRONMENTAL STRUGGLES

The mining sector frequently faces conflict due to its impacts on communities, economies, and the environment. These conflicts arise from asymmetrical power relations among states, corporations, and communities. Thus, extractive activities can worsen vulnerabilities and inequalities across gender, race, and class, especially in the periphery, while developing a 'green path' in core countries (Brown; Zhou; Sadan, 2024; Vansintjan; Kolinjivadi, 2024). These dynamics suggest that the ET redistributes

environmental and social costs geographically, concentrating extractive pressures in peripheral territories while enabling decarbonisation narratives in core economies.

Brazil, Chile, and Peru have taken different paths recently. From 2019 to 2022, Brazil's far-right government weakened environmental policies and deregulated the economy (Galbiati *et al.*, 2022; Scantimburgo, 2018)a partir do governo de Jair Bolsonaro. Visando identificar tendências e rupturas, o presente trabalho explora quatro eixos da atual governança ambiental brasileira, tomando quatro Objetivos do Desenvolvimento Sustentável (ODS. The 2019 Chilean uprising, the largest since 1990, arose from grievances against neoliberal policies and Pinochet's dictatorship's Constitution. Rooted in over a decade of collective action, it demanded social and ecological reforms, leading to a constitutional referendum (Suárez Delucchi; Rivera Ugarte, 2024). Peru's democracy faces a severe crisis marked by political instability, power fragmentation, and declining trust (Barrenechea; Vergara, 2023). Weak or contested institutional frameworks may amplify socio-environmental tensions by limiting state capacity to mediate between global mineral demand and local territorial rights.

Regarding socio-environmental conflicts associated with mining activities, the three nations display significant contested relationships, some of which can be traced to dynamics originating in the colonial era, as Acuña (2015) explored in the context of Peru. According to the Global Atlas of Environmental Justice (EjAtlas)[4] (Temper; Bene; Martinez-Alier, 2015), the ET redistributes socio-environmental conflicts and alters territorial disputes, depending on the actors, interests, and power structures involved. As demand for critical minerals rises and fossil fuels decline, the ET reshapes conflicts. In this sense, the transition does not eliminate extractivist tensions but reorganises them around new strategic resources.

Brazil (mainly in the Atlantic Forest and the Amazon) and Peru (mainly in the Peruvian Amazon), as fossil fuel producers, have faced conflicts over the extraction and transport of crude oil and natural gas. Chile's conflicts are mainly linked to the coal industry (Temper; Bene; Martinez-Alier, 2015). However, disputes over critical minerals like copper, lithium, nickel, graphite, and rare earths are rising. Copper is especially contested in the Chilean desert and Andean LA countries. In northern Chile, water conflicts are crucial to socio-environmental issues related to copper and lithium, often pitting locals against companies and governments (Poque González, 2022). These disputes reflect the territorial concentration of ecological risk in mineral-rich regions, where local communities confront environmental degradation in exchange for limited participation in the value-added segments of the cleantech industry.

Lithium largely drives socio-environmental conflicts in the 'lithium triangle' — northern Chile, Argentina, and southern Bolivia — where private multinational interests often clash with local, including Indigenous, communities. Moreover, the lithium triangle has become a geopolitical hotspot for China and the US (Fornillo; Lampis, 2023). This competition over lithium further embeds local territories in global power struggles, intensifying the drive for extraction without necessarily enhancing domestic industrial capacity. Rare-earth element and nickel mining are causing conflicts in Brazil, especially in the Amazon and the Southeast (Agusdinata; Liu, 2023).

From a dependency perspective, these socio-environmental conflicts reveal a redistribution of ecological burdens without a redistribution of structural power. While technological rents and manufacturing gains remain concentrated in core economies, peripheral territories absorb environmental degradation, water stress, and social disruption. The ET thus territorialises green dependency: decarbonisation in the centre relies on intensified extractivism in the periphery. Rather than overcoming centre–periphery hierarchies, the transition rearticulates them through new mineral frontiers.

4.3 THE US HEGEMON AND THE CHINESE EMERGENCE

Historically, the US has taken a paternalistic approach toward LA and its resources. It is now trying to counter China's influence. In 2022-2023, General Laura J. Richardson, the former leader of US Southern Command, called LA the United States' backyard[5]. This term, used in US foreign policy, signals a sphere of influence. Her remarks highlight LA's strategic importance for critical minerals, renewable energy, and security (Atlantic Council, 2023; Concordia, 2022; Oipol; Oijust Official Channel, 2022). However, these paternalistic views have faced criticism in LA, reflecting a history of interventionism and power imbalances, which are now intensified by Chinese expansion and Russian presence (Paz, 2012).

Recent political shifts in the US signal an increasingly uncertain and competitive foreign policy posture toward LA[6]. Meanwhile, the US faces challenges from China's rise as a global economic and technological leader, complicating America's post-WWII dominance (Petry, 2024; Wallerstein, 2003). Drawing on Wallerstein's world-systems theory, Xing and Bernal-Meza (2022) have identified how rising hegemonic powers dominate in three areas: production, trade, and finance. China has emerged as the largest manufacturer and trader globally, and as a major international creditor, with its financial influence growing. Although the dollar remains dominant in global finance, the Chinese yuan (RMB) is expected to become the third-most-held reserve currency within 10 years.

Thus, the intensification of US–China competition does not transform LA into an autonomous actor; rather, it reinforces the region's role as a strategic terrain within broader hegemonic struggles. Control over critical minerals and cleantech supply chains becomes a central dimension of contemporary world-system restructuring.

China's influence in LA expands beyond trade, spanning the virtual and physical realms. The Belt and Road Initiative (BRI) aims to link Eurasia, Africa, and LA through trade, infrastructure, and digital networks, challenging the dominance of the US, EU, and Japan. As global rivalry intensifies over markets and green tech, countries with key raw materials, such as Brazil, Chile, and Peru, become hotspots, attracting global competition, including from the US (Kalantzakos, 2020).

The US's historical influence on LA has often materialised through political and military disruptions (McPherson, 2019). Conversely, emergent Chinese dependence is characterised by infrastructure deployment, technology, and investment (Kalantzakos, 2020)featuring artificial intelligence (AI. Despite China's rising influence, it has not yet become a hegemonic power, as relations with the US and EU remain significant (Jenkins, 2012).

US military and diplomatic initiatives in the region reflect efforts to secure strategic influence over mineral-rich territories amid intensifying rivalry with China (Embajada de los Estados Unidos en Argentina, 2024).

Chinese interests in LA are mainly expressed through economic ties, such as the BRI, launched in 2013 by Xi Jinping and seen as a soft power strategy (Nedopil, 2022; Voon; Xu, 2020)I study why and how China uses green overseas finance in its Belt and Road Initiative (BRI. Important South and Central American and Caribbean countries have joined or engaged with the BRI (Nedopil, 2023). However, Dussel Peters (2019) notes that LA-China relations are driven by a core-periphery dynamic rather than South-South or win-win strategies. Thus, while China challenges US dominance in production, trade, and finance, its engagement with LA largely reproduces core–periphery trade patterns, with raw material exports exchanged for manufactured goods. The emerging relationship thus reflects a reconfiguration of dependency rather than its transcendence.

The trade between LA and the core is unequal: the vast majority of LA exports to China consist of raw materials, while China exports manufactured goods at varying technological levels. The trade mainly revolves around certain key products: 70% of Latin America's exports to China are soybeans,

crude oil, and copper, mostly from Brazil, Chile, Peru, Mexico, and Ecuador. This reflects the pattern in South American countries of mainly exporting minerals and primary commodities (Quiliconi; Vergara, 2025). Thus, from a dependency perspective, the US–China rivalry over strategic minerals reshapes LA's structural position but does not transform it. The ET is embedded in hegemonic contestation, with peripheral territories supplying the material base of core industrial expansion. Far from enabling emancipation, this dynamic risks reinforcing reprimarisation and subordinate integration into the global division of labour.

5 FINAL WORDS

LA has experienced successive waves of development strategies; most recently, the progressive governments of the 2000s sought to challenge structural dependency. Yet these projects relied heavily on commodity exports and often overlooked socio-environmental and territorial conflicts, reinforcing neo-extractivist dynamics. Earlier industrialisation efforts in the mid-20th century similarly failed to secure autonomy, constrained by authoritarian turns and the subsequent consolidation of neoliberal reforms that deepened structural dependence (Hedstrom, 2019; Otero, 2021; Svampa, 2019; Treacy, 2022).

The projected 55% increase in critical mineral revenues by 2030 (IEA, 2024a) offers a new opportunity. The central question is whether this moment can enable structural upgrading or merely reproduce extractivist integration within global value chains. China's rise in low-carbon technologies challenges US dominance but does not dissolve centre–periphery hierarchies; rather, LA risks becoming an intensified arena of geopolitical contention.

Contrary to Wallerstein's earlier expectation, a neofascist resurgence was in fact possible7. In 2025, the US government returned to nationalist, xenophobic, populist, and anti-intellectual rhetoric, glorifying violence and militarism. These themes echo in LA, where territorial disputes over strategic zones, minerals, or fossil fuels may occur. Despite the need to reduce fossil fuel use for climate reasons, some governments are ignoring the crisis and pursuing more fossil fuel exploitation.

While this document was being revised, the US executed a direct military operation against Venezuela, encompassing strikes on Caracas and the detention of President Nicolás Maduro. This incident was publicly characterised as a law enforcement action; however, it had explicit strategic implications for regional energy geopolitics. Positioned at the confluence of fossil fuel supply, great-power rivalry, and hemispheric influence, this event clearly exemplifies the ongoing deployment of US hard power in LA amidst escalating competition with external actors (Poque González, 2026).

The ET reconfigures LA's geopolitical landscape and territorial disputes, connecting local conflicts to international hegemonic contestation. Dependency theory must therefore integrate ecological and socio-territorial aspects, acknowledging that material and energy flows persistently mirror core–periphery disparities. Progressing beyond extractivism necessitates not only decarbonisation but also a structural transformation rooted in value-added production, innovation, equity, and environmental and energy justice.

NOTES

1 | Victor, Roche, and Saraiva (2024) list six critical minerals: copper, lithium, graphite, nickel, cobalt, and rare-earth elements. The key difference between fossil-fuel and mineral-based economies is vulnerability. Fossil fuel systems require a constant supply, while renewables can operate after initial setup, even if critical mineral supplies are disrupted. Such disruptions mainly slow the ET rather than affecting energy security (Irena, 2023).

2 | Financialisation refers to the increasing dominance of financial markets, instruments, and institutions in profit generation, with the focus shifting from traditional production and trade to the mobilisation, trading, and speculative activities of loanable capital. The influence of this process also extends to reshaping non-financial sectors and social dynamics (Reis; De Oliveira, 2023; Varoufakis, 2016).

3 | Latin America plays a pivotal role in global critical minerals production, accounting, for example, for 47% of the world's silver output and 44% of copper production. Mineral reserves position the region as a prospective global actor — for instance, 61% of global lithium reserves are in Latin America (Siroit, 2024). On the other hand, global manufacturing capacity for low-carbon energy technologies — encompassing solar PV, wind, batteries, electrolysers, and heat pumps — is highly concentrated in four countries and the European Union (EU), accounting for 80%-90% of production, with China at the vanguard (IEA, 2023).

4 | The EjAtlas is an open online platform that provides comprehensive information on socio-environmental conflicts worldwide, specifically in relation to various commodity activities (Temper; Bene; Martinez-Alier, 2015).

5 | The concept was rooted in the Monroe Doctrine and the Roosevelt Corollary (Muno; Brand, 2014).

6 | Following President Trump's inauguration on 20 January 2025, the White House announced that the US Ambassador to the United Nations must promptly submit a formal written notification of the United States' withdrawal from the Paris Agreement, as well as from the UN Framework Convention on Climate Change (The White House, 2025). Within its first week in office, the Trump administration demonstrated several hostilities toward Latin American countries, including Panama, through matters related to the Panama Canal, and Brazil and Colombia concerning the repatriation of migrants (Maihold, 2025).

7 | In his work, *After Liberalism*, Wallerstein argues that the resurgence of neofascism is unlikely in the 21st century (Wallerstein, 2003).

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used Grammarly and ChatGPT exclusively for linguistic editing and stylistic enhancement. All scientific content, analysis, and intellectual contributions were developed and verified by the authors, who assume full responsibility for the manuscript's accuracy and integrity.

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In-depth assessment of energy transition policies: a comparative study between Proinfa (Ceará, Brazil) and Law 8/2009 (Galicia, Spain)

Avaliação em profundidade de políticas de transição energética: um estudo comparado entre o Proinfa (Ceará, Brasil) e a Lei 8/2009 (Galícia, Espanha)

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ARTICLE- *VARIA*

ABSTRACT

This article aims to conduct an in-depth comparative assessment of Incentive Programme for Alternative Sources of Electricity (Proinfa/Brazil) (with a focus on the implementation of the policy in Ceará) and the Galician Wind Energy Law (Law 8/2009), examining the extent to which these policy instruments have succeeded in reconciling sectoral expansion, territorial governance, and procedural and distributive justice. The analysis is grounded in the framework of in-depth public policy evaluation proposed by Rodrigues (2008) and adopts a qualitative and documentary approach to investigate the institutional trajectories and distributive impacts. The results indicate that, although both instruments have been effective in expanding installed capacity, significant distributive paradoxes remain. In Ceará, fragmented governance has intensified land conflicts in coastal areas, whereas in Galicia, centralised planning has resulted in high levels of litigation. The study concludes that the maturity of wind energy

policy depends on moving beyond investment security to consolidate effective mechanisms for procedural justice and the democratisation of benefits.

Keywords: Wind Energy. Public Policy Evaluation. Energy Justice. Ceará/Brazil. Galicia/Spain.

RESUMO

Este artigo tem por objetivo realizar uma avaliação comparativa em profundidade do Proinfa (com foco nos desdobramentos da política no Ceará) e da Lei Eólica galega (Lei 8/2009), examinando em que medida esses instrumentos lograram conciliar expansão setorial, governança territorial e justiça procedimental e distributiva. A metodologia ancora-se na perspectiva da avaliação em profundidade de políticas públicas proposta por Rodrigues (2008), adotando uma abordagem qualitativa e documental para analisar a trajetória institucional e os impactos distributivos. Os resultados evidenciam que, embora ambos tenham logrado êxito na expansão da capacidade instalada, persistem paradoxos distributivos significativos. No Ceará, a governança fragmentada catalisou conflitos fundiários em zonas costeiras; na Galícia, o planejamento centralizado resultou em elevada litigiosidade. Conclui-se que a maturidade da política eólica exige transcender a segurança do investimento para consolidar mecanismos efetivos de justiça procedimental e democratização dos benefícios.

Palavras-chave: *Energia Eólica. Avaliação de Políticas Públicas. Justiça Energética. Ceará/Brasil. Galícia/Espanha.*

1 INTRODUCTION

The rapid expansion of wind energy in recent decades has established this source as a strategic driver of global decarbonisation, playing a prominent role in the electricity mix of major economies such as China, the United States, the European Union, and Brazil. However, the large-scale deployment of this infrastructure has sparked intense debates on spatial planning and distributive justice, highlighting that the energy transition is not merely a technological process, but also a political and territorially situated phenomenon (Paulino et al., 2023).

As systematised by Frantál, Frolova, and Liñán-Chacón (2023), this process of territorialisation gives rise to a complex array of disputes, ranging from distributive injustice and nature conservation to changes in the values and functions of the landscape, thereby requiring governance arrangements capable of mediating conflicting interests. Without a fair social contract, decarbonisation risks reproducing inequalities and generating new forms of exclusion in the territories where it is implemented (Heffron; De Fontenelle, 2024).

In Brazil, the Incentive Programme for Alternative Sources of Electricity (Proinfa), established by Law No. 10.438/2002, represented a turning point in the national electricity matrix. Conceived as a strategic response to the 2001 electricity rationing crisis and to the vulnerability of hydroelectric dependence, the programme established long-term contracts and local content requirements to facilitate the integration of wind energy into the National Interconnected System (SIN). Although it fulfilled its role as a 'kick-start' policy, the absence of a coordinated national spatial planning framework resulted in fragmented governance, catalysing socio-environmental conflicts in coastal areas, with the state of Ceará serving as a particularly illustrative case. In this context, as Torres Junior (2021) warns in his analysis of Ceará, the developmentalist discourse of the state, centred on capital accumulation and technological advancement, often obscures the perception of locally borne negative impacts, resulting in a scenario of environmental injustice in which the promised benefits, such as employment and income generation, remain diffuse or unattainable for vulnerable populations.

In contrast, in Galicia, a region in north-western Spain, Law 8/2009 established a distinct model, one oriented less towards fostering a nascent sector and more towards the reorganisation of a field that

was already mature and pioneering within the Spanish context. The legislation established the Galician Wind Energy Sector Plan (PSEGA) as a binding instrument of spatial planning and environmental regulation and created fiscal mechanisms – namely the wind energy levy and the Environmental Compensation Fund – designed to balance the impacts and benefits associated with power generation. However, the sophistication of this regulatory framework did not eliminate the tensions between stated environmental objectives and regulatory practice, nor did it prevent the persistence of socio-environmental conflicts (Regueiro-Ferreira; Doldán-García, 2010). As argued by Paz Aldrey and Cortés Vázquez (2024), these conflicts and the recent high levels of litigation should not be interpreted merely as expressions of technological resistance, but rather as symptoms of a profound 'rural crisis', in which the energy transition overlaps with dynamics of depopulation, generating specific frictions concerning land use and the future of Galician rural communities.

In light of these contexts, comparing two regions marked by such distinct idiosyncrasies: on the one hand, Ceará, located in an emerging country and characterised by historical socio-environmental vulnerabilities; on the other, Galicia, subject to European Union regulation and endowed with a consolidated administrative framework. This contextual asymmetry is what makes a comparative assessment interesting, as it allows us to examine whether, despite institutional patterns, the global logic of the energy transition tends (or does not) to reproduce analogous patterns of territorial appropriation and concentration of power, thereby challenging the effectiveness of local regulatory instruments.

Concerning ecological sustainability, the expansion of wind power places specific pressures on highly sensitive ecosystems that cannot be overlooked. In Ceará, the installation of wind farms on shifting dune fields, interdune lagoons, and salt marshes has led to habitat fragmentation and heightened erosion risks, making the strict demarcation of exclusion zones and dynamic buffer areas essential (Loureiro et al., 2015; Preuss, 2020). Criticism centres on the inadequacy of gradual environmental assessments that ignore cumulative effects on biodiversity and ecosystem services in vulnerable coastal zones. In Galicia, however, the challenge lies in reconciling the exploitation of wind energy with the protection of natural and landscape values, particularly in repowering contexts that require reverse logistics to prevent the creation of new environmental liabilities (Regueiro-Ferreira; Cadaval-Sampedro, 2023).

The analytical challenge, in this sense, goes beyond the description of legal frameworks; it involves investigating the capacity of these institutional designs to reconcile environmental sustainability, social legitimacy, and distributive equity. Therefore, the perspective of 'in-depth evaluation' of public policies proposed by Rodrigues (2008) is adopted, as an approach that emphasises the need for dense, extensive and contextualised evaluations, integrating content, institutional trajectory, and the temporal and territorial scope of the instruments evaluated.

In this sense, the article aims to conduct a comparative evaluation between Proinfa (focusing on the policy developments in Ceará) and the Galician Wind Energy Law (Law 8/2009), investigating the extent to which their institutional designs articulate economic efficiency, environmental sustainability, and territorial equity. The analysis is guided by the following question: how do these regulatory frameworks, developed in disparate institutional contexts, structure – and limit – this articulation in the expansion of wind energy? By juxtaposing the debate on energy transition with the evaluation of public policies, the aim is to highlight convergences, asymmetries, and the distributional paradoxes that remain unresolved, even in contexts of apparent success in terms of installed capacity.

2 METHODOLOGY

This study adopts a qualitative, documentary, and comparative approach, grounded in the framework of in-depth public policy evaluation (Rodrigues, 2008). From this perspective, the evaluation goes beyond the measurement of specific indicators of effectiveness or efficiency and is organised around

four interdependent analytical dimensions: (a) policy content, including formulation, stated objectives, and internal coherence; (b) institutional trajectory and governance arrangements; (c) the context of formulation and implementation, with attention to the broader sectoral regulatory framework; and (d) the temporal and territorial scope covered, including its effects on the territories and social groups affected.

The methodological framework is based on a comparative case study of two instruments: Proinfa, established by Law No. 10.438/2002, focusing on its implementation in the state of Ceará, and Law 8/2009 on wind energy development in Galicia, including its main spatial planning instrument, the Galician Wind Energy Sectoral Plan (PSEGA), as well as the fiscal mechanisms of the wind energy levy and the Environmental Compensation Fund. The selection of these cases stems from their empirical relevance – both are structural milestones in wind energy expansion within their respective contexts – and their analytical comparability, since they face similar problems (diversification of the energy mix, territorial conflicts, social participation) through distinct institutional arrangements.

In terms of data sources, the research draws on:

1. Sectoral legislation and regulations: Law No. 10,438/2002 and sub-legal regulations associated with Proinfa (decrees, ministerial orders, Aneel regulations, and official documents from Eletrobras/ENBPar), as well as national and state environmental resolutions relevant to the licensing of wind farms in Ceará;

2. Galician regulatory frameworks: Law 8/2009, documents from the Xunta de Galicia on the PSEGA, regulatory acts relating to the wind energy levy and the Environmental Compensation Fund, as well as court rulings and official reports concerning litigation in the wind energy sector in Galicia;

3. Academic and technical literature: studies on the origins and development of the wind energy sector in both contexts, critical assessments of sectoral policies, and analyses of socio-environmental conflicts arising from the expansion of wind energy in north-eastern Brazil and Galicia.

Based on this documentary corpus, an analytical matrix was developed, organised into four axes of in-depth evaluation, which engage with the proposal by Rodrigues (2008):

1. Objectives and historical-institutional context: examination of the contexts of origin of each instrument (the crisis of rationing and hydroelectric vulnerability in the Brazilian case; the consolidation of a pioneering sector and alignment with European directives in the Galician case), as well as the primary and secondary objectives and stated targets.

2. Regulatory practices and governance instruments: analysis of procurement mechanisms, cost and compensation structures, land-use planning arrangements, and mechanisms for regulatory stability and coordination between levels of government.

3. Social participation and procedural justice: identification of the envisaged participation mechanisms (public hearings, consultations, public information), of criticisms regarding their effectiveness, and of the gap between formal participation and the actual influence of local

communities, both in Brazilian licensing and in the application of the Galician environmental and territorial framework.

4. Territorial and distributional impacts: analysis of the concrete effects of the policy on territories, including sectoral development, public revenue, distribution of benefits and burdens, as well as socio-environmental conflicts and patterns of litigation, with particular attention to coastal municipalities in Ceará and Galician districts with a strong wind energy presence.

The interpretation of the data followed an inductive analytical-interpretative approach, linking the empirical findings with the theoretical framework on energy transition, territorial governance, and environmental justice. Rather than testing strict causal hypotheses, the aim was to provide a critical analysis of the convergences and divergences between the two instruments, highlighting the paradoxes and tensions that arise from attempts to reconcile the rapid expansion of wind energy infrastructure with social legitimacy and territorial equity.

Regarding the ethical aspects of the research, it should be noted that this study is based on the analysis of public documentary sources, such as legislation, institutional reports, and previously published academic literature, and does not involve the collection of primary data from human participants. Consequently, there was no need for submission to a research ethics committee, in accordance with current guidelines for documentary research.

3 RESULTS AND DISCUSSION

Considering the institutional and regulatory frameworks that shaped Proinfa (Law No. 10.438/2002) in Brazil, with particular reference to the State of Ceará, and the Galician Wind Energy Law (Law 8/2009) in Spain, it is pertinent to conduct a comprehensive comparative assessment. This analysis aims to understand how the stated objectives, regulatory instruments, mechanisms for public participation, and concrete territorial effects have materialised in distinct socio-economic and political contexts. While Proinfa represented an initial effort to diversify the Brazilian electricity mix, standing out for its focus on security of supply, nationalisation of the production chain, and the controlled integration of new sources, the Galician Wind Energy Law consolidated a model of territorial governance that combines spatial planning, environmental compensation, and the distribution of local benefits.

In this regard, the study seeks to identify convergences and asymmetries between the two experiences, examining both the institutional design and the coherence of their instruments, as well as the forms of public participation, procedural justice, and the distribution of benefits and burdens of the energy transition in the affected territories. The aim is to demonstrate the extent to which each policy was able to articulate environmental sustainability, social legitimacy, and regulatory and economic effectiveness, and how its practices shaped, positively or negatively, the energy transition process at a regional scale.

Thus, this analysis goes beyond a normative and institutional description by examining the structural and socio-territorial implications of each instrument, enabling an understanding of how the regulatory, participatory, and distributive dimensions converge or diverge in the configuration of public renewable energy policies with varying degrees of equity and territorial integration.

Proinfa and the Galician Wind Energy Law (Law 8/2009) were established in very different economic and energy contexts. While Brazil was responding to a supply crisis and a heavy reliance on hydroelectric power, Galicia aimed to consolidate and regulate a wind energy sector that was already mature and pioneering in the region, within the context of state reforms and European directives. In this regard, Table 1 below summarises the historical and institutional context in which each instrument emerged, its primary and secondary objectives, and the original targets that guided its implementation.

Table 1 – Objectives and historical context

Dimension	*Proinfa (Law No. 10.438/2002)*	*Galician Wind Energy Law (Law 8/2009)*
Context of Origin	Response to the 2001 rationing crisis and the vulnerability of the hydroelectric grid, with a need for diversification and security of supply (Brazil, 2002a; Kelman, 2001; Tolmasquim, 2012). Preceded by reforms that failed to expand capacity in line with demand (Brazil, 1995, 1996).	Consolidation of an already pioneering and mature wind power sector in Galicia, which was linked to the special state remuneration scheme and European directives (European Union, 2001; Inega, 2007; Spain, 2007). Galicia already had a consolidated installed renewable energy base prior to 2009 (REE, 2009).
Primary Objective	To increase the share of wind, small hydro, and biomass in the National Interconnected System (SIN) (Brazil, 2002a). Proinfa functioned as a start-up policy (Brazil, 2003; IEA, 2024).	To plan wind energy development through the Galician Wind Energy Sector Plan (PSEGA) and regulate the administrative authorisation regime (Galicia, 2009, art. 1). Its focus is on binding spatial planning (Xunta de Galicia, 1997).
Secondary Objectives	Strengthening security of supply and stimulating the national production chain through local content requirements (60% in Phase I) (Brazil, 2003).	To establish mechanisms for territorial balance and the sustainability of natural resources, such as the wind energy levy and the Environmental Compensation Fund (Galicia, 2009, Art. 1, Art. 7). This aims to reduce the number of turbines and protect the environment (Galicia, 2009, Art. 7).
Original Targets	Phase I: 3,300 MW (1,100 MW per source); Phase II: 10% of annual electricity consumption (Brazil, 2002a). Phase II was not implemented, giving way to the auction model (ACR) (Brazil, 2004b; IEA, 2024).	To organise wind energy development in Galicia, ensuring the rational distribution of installed capacity (Xunta de Galicia, 2010).

Source: The authors (2026)

Proinfa was conceived in 2002 as a strategic response to the 2001 rationing crisis, aiming to reduce the vulnerability of the hydroelectric matrix and stimulate industrial development (Brazil, 2002a; Tolmasquim, 2012). The programme established expansion targets (3,300 MW in Phase I) and utilised local content requirements (60% in Phase I) to foster domestic industry (Brazil, 2003). However, the more ambitious Phase II was not implemented, as expansion shifted to the auction model (Brazil, 2004b; IEA, 2024). In contrast, Law 8/2009 in Galicia was introduced to regulate and provide compensation to a sector that was already mature and consolidated (REE, 2009). Its main tool was the PSEGA, which established binding territorial planning (Galicia, 2009; Xunta de Galicia, 1997) and created fiscal instruments such as the wind energy levy to ensure sustainability and territorial balance (Galicia, 2009, art. 7).

The main similarities observed in the two contexts lie in the role of both instruments as drivers of modernisation and diversification of the energy mix, seeking security of supply and the growth of the wind energy sector on a large scale. However, the greatest divergence lies in the temporal motivation and focus of the policies. Proinfa was an emergency and induction policy, focused on creating a market where it was in its infancy – that is, a start-up programme – using subsidies and industrial policy as its structural foundations. The Galician Wind Energy Law, on the other hand, was instituted as a policy for planning and conflict management within an already established sector – in which centralised territorial planning was the priority, and compensation was provided through fiscal mechanisms rather than tariff subsidies.

In this sense, moving from an analysis of objectives and historical contexts to that of regulatory practices, it can be observed that the differences in origin result in contrasting institutional arrangements. Whilst Proinfa consolidates a model of centralised coordination through contractual and tariff-based mechanisms, the Galician Wind Energy Law establishes a centralised territorial coordination framework, based on binding spatial planning and fiscal redistribution instruments. These distinctions are summarised and detailed in Table 2 below, which highlights the regulatory mechanisms adopted in

each context and their implications for the balance between economic efficiency, territorial governance, and distributive equity.

Table 2 – Regulatory practices

Dimension	*Proinfa (Law No. 10.438/2002)*	*Galician Wind Energy Law (Law 8/2009)*
Procurement Mechanism	Long-term contracts (20 years), centralised by Eletrobras, with prices set at 'economic value' (with specific tariff floors per source in Phase I) (Brazil, 2003; Brazil, 2004a). Selection prioritised the stage of environmental licensing (LI > LP) (Brazil, 2002a).	Authorisation procedure based on free competition, transparency, and administrative streamlining (Galicia, 2009, Art. 1). Authorisation is linked to competitive public calls for tenders (Xunta de Galicia, 2010), within the limits of the Galician Wind Energy Sector Plan (PSEGA) (Galicia, 2009).
Cost Structure / Compensation	Tariff socialisation of costs via the Proinfa Account, apportioned across all consumption categories (excluding low-income households) (Brazil, 2002a; Brazil, 2004a). The average approved cost in 2025 was R$ 543.56/MWh (Aneel, 2024).	Fiscal-territorial instruments: the wind energy levy (tax on installation/operation) and the Environmental Compensation Fund (FCA), designed to ensure territorial balance and environmental compensation (Atriga, 2025; Galicia, 2009). The FCA generates around 22–22.4 million euros annually (Europa Press, 2025; La Voz de Galicia, 2024).
Land Use Planning	It did not contain explicit federal territorial guidelines for sensitive areas, relying on Conama Resolutions (e.g. Conama, 2014) and state Coema Resolutions (e.g. Ceará, 2018a). It used state-level limits to prevent geographical concentration (Brazil, 2003).	The PSEGA has sectoral planning authority and takes precedence over municipal urban plans (Galicia, 2009; Xunta de Galicia, 1997). This has created tensions between regional planning and local urban planning (Romero, 2012).

Source: The authors (2026)

Proinfa was a market-guarantee instrument that used 20-year contracts and stable prices (above the initial competitive market rate) to mitigate the risk of investment in nascent energy sources (Brazil, 2003; Chaves; Azevedo; Fernandes, 2023). This predictability was financed by the Proinfa Account, a cross-subsidy apportioned across the tariff (Aneel, 2004). Brazilian spatial planning for wind power was, however, fragmented, dependent on environmental licensing in each state and on prioritisation rules under the Installation Licence (LI) (Brazil, 2004a). In turn, Law 8/2009 ensured stability through centralised spatial planning (PSEGA), which bindingly defines the zones for development (Galicia, 2009). The compensation mechanism is fiscal in nature, as the *wind energy levy* is a direct tax on projects that feeds into the Environmental Compensation Fund (FCA), intended to channel part of the proceeds towards nature conservation and territorial rebalancing (Europa Press, 2025; Galicia, 2009).

The main regulatory similarity observed is the commitment to stability and predictability for investors, which is essential for long-term infrastructure projects. Both models sought to prevent excessive geographic concentration, whether through per-state capacity limits in Proinfa or through sectoral planning in PSEGA. The main divergence lies in financing and land use planning. Proinfa used consumer tariffs to subsidise (tariff socialisation), whereas Galicia used a tax on generation (*wind energy levy*) as compensation (fiscal mechanism). Furthermore, the Galician model imposed centralised and binding territorial planning on municipal authorities, something absent in the Brazilian Proinfa, which relied on local environmental regulations.

Thus, moving from the regulatory sphere to the consideration of social participation, a critical and fragile dimension becomes evident in both cases. As shown in Table 3 below, participation emerges as the most sensitive aspect of energy transition governance, characterised by the prevalence of formal and technocratic procedures that reduce the effective influence of local communities on route planning, licensing, and the distribution of benefits generated by wind energy projects, and this is evident in both the Ceará and Galicia cases:

Table 3 – Levels of Social Participation

Dimension	*Proinfa (Law No. 10.438/2002)*	*Galician Wind Energy Law (Law 8/2009)*
Mechanisms and Practices	Participation focused on the requirements of environmental licensing (public hearings, formal consultations) (Gorayeb; Brannstrom, 2020). There is criticism of the use of the Simplified Environmental Report (SER) in complex areas (Pereira, 2022; Sobrinho; Santos, 2022), which reduces deliberative windows (Leite, 2022).	Participation anchored in Law 21/2013 on Environmental Assessment (public information and consultations) and the Aarhus Convention (Spain, 2006; Spain, 2013). Law 8/2009 provides for administrative streamlining (Galicia, 2009).
Criticisms of Effectiveness	It presents a "social gap" (the distance between formal participation and actual impact) (Gorayeb; Brannstrom, 2020; Sobrinho; Santos, 2022). Participation tends to be informative and ex post, with no real power to alter plans or redistribute gains (Lima, 2024). Conflicts arise from information asymmetry (Silva; Rojas-Pinilla, 2023).	The regulatory framework has been criticised for its technocratic rationality and for lacking effective mechanisms for social participation and equitable distribution (Chacón; Frolova, 2024; Regueiro-Ferreira; Doldán-García, 2010). Participation is often viewed as a formal requirement (Romero; Farinós, 2011).
Social Vulnerabilities	The projects affect sensitive areas, such as shifting dunes and sandbanks, and traditional communities (fishing and quilombola communities), leading to territorial conflicts and inequalities in the distribution of benefits (Gorayeb; Brannstrom, 2020; Lima, 2024).	The Law suffers from practical gaps in social compensation. Although a levy exists, its effectiveness depends on binding programme targets, which have not translated proportionally into benefits for local communities (Heffron; De Fontenelle, 2024; Regueiro-Ferreira, 2023).

Source: The authors (2026)

The lack of participation in Proinfa is evident in Ceará through the use of the Simplified Environmental Report (RAS) in highly sensitive ecosystems, such as dunes and sandbanks, which limits the scope of the assessment and the quality of public deliberation (Pereira, 2022; Sobrinho; Santos, 2022). This creates a "social gap" in which community involvement is a formalised, standardised process, but one that in practice lacks effectiveness or *ex post* power, with no real ability to alter projects or ensure distributive justice (Gorayeb; Brannstrom, 2020; Lima, 2024). In Law 8/2009, the problem lies in the technocratic rationality imposed by the PSEGA (Regueiro-Ferreira; Doldán-García, 2010). Although the environmental framework is formally sound (Espanha, 2013), the pursuit of administrative efficiency has led to procedural flaws (such as the shortening of consultation periods), resulting in judicial annulments that confirm the fragility of effective participation (De La Justicia, 2024; Mora Ruiz, 2025).

The main convergence lies in the diagnosis of participation as a formal ritual. In both cases, the logic of energy efficiency and the imperative to attract private capital have overridden the need for democratic legitimacy and procedural justice. The result is an asymmetry of power and information between companies and communities. What distinguishes this situation across different territories is merely the origin of the procedural flaws. In Brazil, the problem is structural, linked to the weakness of environmental impact assessments (EIA) in vulnerable territories. In Galicia, the problem is systemic and legal, centred on the tension between centralised regional planning and the application of legal consultation standards (Aarhus Convention), with judicialisation being the main battleground against regulatory technocracy.

From this point, it follows that we must move from procedural criticism to the concrete effects of the policies in the territories. In both contexts, the expansion of installed capacity was unequivocal; however, its consequences reveal a distributive paradox: the concentration of corporate power coexists with the persistence of localised conflicts, especially where land use puts pressure on sensitive ecosystems

and traditional ways of life. Thus, we turn to the analysis in Table 4, which comparatively examines the observed impacts (from sectoral development to public revenues and litigation), enabling us to identify the extent to which regulatory and participatory arrangements have (or have not) translated into tangible and equitable benefits for host communities.

Table 4 – Observed Impacts in the Territories

Dimension	*Proinfa (Ceará, Brazil)*	*Galician Wind Energy Law (Galicia, Spain)*
Sectoral Development	This was the starting point of the learning curve and the formation of the National Wind Energy Sector (Araújo; Willcox, 2018; Diniz, 2018), reducing technological and market risks (Chaves; Azevedo; Fernandes, 2023). A subsequent expansion shifted towards competitive auctions (Brazil, 2004b).	It consolidated wind power as a pillar of the energy mix (38.4% of production in 2024), working synergistically with hydropower (REE, 2025). It strengthened the regional governance of the sector (Galicia, 2009).
Distribution of Benefits	There has been growth in municipal revenues (ISSQN and share of ICMS), GDP per capita and sectoral value added in host municipalities (Sampaio; Costa; Irffi, 2025; Velôso et al., 2025). However, there is evidence of land reconcentration and inequality in the appropriation of gains (Gorayeb; Brannstrom, 2020; Lima, 2024).	Fiscal instruments generate significant revenue (around €22 million/year) (Europa Press, 2025), but a high concentration of ownership among large groups persists (Regueiro-Ferreira; Doldán-García, 2020). Revenue gains do not translate into proportionate socio-economic benefits for local communities (Regueiro-Ferreira, 2023; Valle et al., 2024).
Conflicts and Litigation	Recurring conflicts in sensitive coastal areas, such as the Cumbe and Icaraizinho complexes (Lima, 2024; Sousa; Moura; Souza, 2023). Legal disputes persist regarding land ownership, environmental damage, and the adequacy of studies (Mendes; Collaço, 2024).	Law 8/2009 faced intense judicialisation. In August 2025, 92 parks were subjected to litigation, and 86 were provisionally suspended (Galician Regional Government, 2025a). Tensions are exacerbated by the prevalence of regional over municipal urban planning (Romero, 2012).

Source: The authors (2026)

The impact of Proinfa in Ceará highlights the dichotomy between economic success and social failure. There has been an increase in municipal tax revenues and sectoral development (Diniz, 2018; Sampaio; Costa; Irffi, 2025); however, this growth came at the cost of intensified conflicts, such as in Cumbe and Icaraizinho, resulting in land concentration and the exclusion of traditional communities from participating in the benefits (Gorayeb; Brannstrom, 2020; Lima, 2024). Meanwhile, Law 8/2009 consolidated Galicia as a wind power hub (REE, 2025) and secured a stream of fiscal compensation (the *royalty*) that raises millions annually (Europa Press, 2025). However, this wealth is accompanied by a persistent concentration of ownership in large groups (Regueiro-Ferreira; Doldán-García, 2020). The failure to deliver proportional benefits and the inadequacy of cumulative environmental studies have resulted in widespread litigation, with dozens of wind farms provisionally suspended until 2025 (Xunta de Galicia, 2025a).

The main similarity between the contexts lies in the distributional paradox inherent in both large-scale models. In both territories, wind energy expansion has generated wealth (fiscal or tax revenue) that has not benefited the communities bearing the environmental and territorial costs equitably, thereby reinforcing the concentration of corporate power. The main difference observed lies in the way conflicts manifest and are managed. In Brazil (specifically in Ceará), the impacts are strongly linked to socio-environmental vulnerability and conflicts over land tenure (encroachment on dunes, impacts on small-scale fishing). In Galicia, the most evident impact is legal instability and high levels of litigation, where communities and environmental groups use the judicial system to challenge the legality of regional planning and the validity of environmental procedures.

Thus, by bringing together the four axes analysed – objectives and historical contexts, regulatory practices, social participation and territorial impacts – it is evident that both Proinfa and the Galician Wind Energy Law stand out as effective instruments from the perspective of sectoral expansion, yet are limited in terms of territorial and distributive justice. Both have succeeded in establishing wind energy as a driver of modernisation and energy transition, yet without ensuring, to an equivalent degree, the democratisation of benefits and social inclusion in the affected territories, corroborating the arguments of Heffron and De Fontenelle (2024) regarding the persistence of energy justice deficits even in contexts of institutional progress.

In the Brazilian context, the absence of a national spatial planning framework and the reliance on fragmented environmental regulations have produced reactive governance, marked by localised conflicts and predominantly formal social participation, showed incapability of correcting asymmetries in economic and informational power, thereby standing in line with the 'social gap' identified by Gorayeb and Brannstrom (2020) and with the empirical evidence presented by Lima (2024) and Silva and Rojas-Pinilla (2023). In Galicia, however, although the binding territorial model and fiscal instruments bring to the front greater institutional sophistication, the technocratic emphasis and the prevalence of regional planning over municipal autonomy have ultimately shifted the conflict to the judicial arena, increasing litigation and contesting the legitimacy of decision-making processes, as analysed by Chacón and Frolova (2024), and Regueiro-Ferreira and Doldán-García (2010).

Thus, both contexts reflect a key issue regarding the contemporary energy transition, namely the reconciliation of economic efficiency, environmental sustainability, and social equity. Success in terms of installed capacity and revenue generation has not translated into proportional redistributive benefits, nor into lasting institutional stability, which aligns with the typology of territorial conflicts proposed by Frantál, Frolova and Liñán-Chacón (2023). Therefore, the comparison shows that the true maturity of a wind energy policy is not measured solely by the number of megawatts installed, but by the ability to integrate energy development with territorial development, promoting procedural justice, effective participation, and the equitable distribution of the benefits of the transition.

4 FINAL CONSIDERATIONS

The in-depth comparative assessment between Proinfa, in Ceará, and the Galician Wind Energy Law brings to light a troubling diagnosis regarding the contemporary energy transition: technological and market success does not, in itself, guarantee territorial justice. The analysis demonstrates that both instruments, although conceived in disparate institutional contexts and with distinct levels of regulatory sophistication, ultimately converged in producing an exclusionary modernisation. The success in expanding installed capacity, undeniable in both cases, operated under a logic that prioritised investor security at the expense of distributive equity, creating a paradox where energy is renewable, but power practices reproduce old asymmetries.

In the Brazilian case, it can be concluded that Proinfa fulfilled its role as an industrial 'kick-start', but failed in its territorial integration. Fragmented governance and dependence on asymmetrical environmental licensing transformed the territory of Ceará into a battleground, where the speed of expansion infringed on the rights of traditional communities. In Galicia, however, the problem was not a lack of regulation, but an excess of technocracy. Law 8/2009, with its binding planning and fiscal instruments (the *canon*), created an appearance of order that did not stand up to the test of social legitimacy, resulting in a massive wave of legal challenges that exposes the rift between centralised planning and local will.

Thus, this study has shown that the maturity of a wind energy policy can no longer be gauged solely by the volume of *megawatts* or the robustness of its financial contracts. True maturity lies in the ability of the state to reconcile decarbonisation with democracy. Comparative evidence from Ceará and Galicia

shows that command-and-control instruments (such as the PSEGA) or purely economic incentives (such as the Proinfa) are insufficient to mitigate conflicts if they are not grounded in substantive procedural justice.

In light of these dynamics, the article argues that the energy transition risks becoming a new driver of inequality, unless there is a change of course. The differences between the cases – land tenure vulnerability in Ceará versus legal-institutional tension in Galicia – are merely local manifestations of the same global phenomenon: the deterritorialisation of energy decisions.

Furthermore, the article proposes the need for a 'second generation' of wind energy policies, guided by a paradigm of just and territorially integrated transition. This implies shifting the focus from rapid expansion and corporate profitability to the effective incorporation of social and territorial dimensions, requiring that planning, financing, and compensation instruments be designed in alliance with the territories, and not only for the use of the territories. Without this ethical and political shift, wind energy, whilst carbon-clean, will remain 'dirty' in social terms, replicating power structures that the very idea of sustainability was meant to overcome.

In this context, although the study offers relevant contributions to the comparative understanding of wind energy governance, certain limitations must be acknowledged. The analysis is based predominantly on primary sources, which limits direct insight into the perceptions and strategies of local actors, whilst the territorial scope – centred on Ceará and Galicia – does not allow for automatic generalisations to other contexts. Nevertheless, these limitations do not undermine the findings but indicate the need for further empirical investigation through field research that incorporates local dynamics and the experience of affected communities. In this regard, the results also point to relevant implications for public policy formulation, highlighting the importance of integrating effective mechanisms for social participation, territorial redistribution of benefits, and planning sensitive to socio-environmental specificities. Thus, a research agenda is opened up focused on the analysis of different institutional arrangements and their repercussions on energy justice, contributing to the development of more equitable and territorially integrated energy transition models.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (OpenAI, version 5.1) for language editing and stylistic polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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Avaliação em profundidade de políticas de transição energética: um estudo comparado entre o Proinfa (Ceará, Brasil) e a Lei 8/2009 (Galícia, Espanha)

In-depth assessment of energy transition policies: a comparative study between Proinfa (Ceará, Brazil) and Law 8/2009 (Galicia, Spain)

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ARTICLE- VARIA

RESUMO

Este artigo tem por objetivo realizar uma avaliação comparativa em profundidade do Proinfa (com foco nos desdobramentos da política no Ceará) e da Lei Eólica galega (Lei 8/2009), examinando em que medida esses instrumentos lograram conciliar expansão setorial, governança territorial e justiça procedimental e distributiva. A metodologia ancora-se na perspectiva da avaliação em profundidade de políticas públicas proposta por Rodrigues (2008), adotando uma abordagem qualitativa e documental para analisar a trajetória institucional e os impactos distributivos. Os resultados evidenciam que, embora ambos tenham logrado êxito na expansão da capacidade instalada, persistem paradoxos distributivos significativos. No Ceará, a governança fragmentada catalisou conflitos fundiários em zonas costeiras; na Galícia, o planejamento centralizado resultou em elevada litigiosidade. Conclui-se que a maturidade

da política eólica exige transcender a segurança do investimento para consolidar mecanismos efetivos de justiça procedimental e democratização dos benefícios.

Palavras-chave: Energia Eólica. Avaliação de Políticas Públicas. Justiça Energética. Ceará/Brasil. Galícia/Espanha.

ABSTRACT

This article aims to conduct an in-depth comparative assessment of Incentive Programme for Alternative Sources of Electricity (Proinfa/Brazil) (with a focus on the implementation of the policy in Ceará) and the Galician Wind Energy Law (Law 8/2009), examining the extent to which these policy instruments have succeeded in reconciling sectoral expansion, territorial governance, and procedural and distributive justice. The analysis is grounded in the framework of in-depth public policy evaluation proposed by Rodrigues (2008) and adopts a qualitative and documentary approach to investigate the institutional trajectories and distributive impacts. The results indicate that, although both instruments have been effective in expanding installed capacity, significant distributive paradoxes remain. In Ceará, fragmented governance has intensified land conflicts in coastal areas, whereas in Galicia, centralised planning has resulted in high levels of litigation. The study concludes that the maturity of wind energy policy depends on moving beyond investment security to consolidate effective mechanisms for procedural justice and the democratisation of benefits.

Keywords: *Wind Energy. Public Policy Evaluation. Energy Justice. Ceará/Brazil. Galicia/Spain.*

1 INTRODUÇÃO

A rápida expansão da energia eólica nas últimas décadas consolidou essa fonte como vetor estratégico da descarbonização global, assumindo protagonismo na matriz elétrica de potências como China, Estados Unidos, União Europeia e Brasil. Contudo, a materialização dessa infraestrutura em larga escala tem suscitado intensos debates sobre ordenamento territorial e justiça distributiva, evidenciando que a transição energética não é apenas um processo tecnológico, mas um fenômeno político e territorialmente situado (Paulino et al., 2023).

Conforme sistematizam Frantál, Frolova e Liñán-Chacón (2023), essa territorialização impõe uma tipologia complexa de disputas, que abrange desde a injustiça distributiva e a preservação da natureza até a alteração dos valores e funções da paisagem, exigindo uma governança capaz de mediar interesses antagônicos. Sem um contrato social justo, a descarbonização corre o risco de reproduzir desigualdades e gerar novas formas de exclusão nos territórios onde se instala (Heffron; De Fontenelle, 2024).

No Brasil, o Programa de Incentivo às Fontes Alternativas de Energia Elétrica (Proinfa), instituído pela Lei nº 10.438/2002, representou um ponto de inflexão na matriz elétrica nacional. Concebido como resposta estratégica à crise de racionamento de 2001 e à vulnerabilidade da dependência hidrelétrica, o programa estabeleceu contratos de longo prazo e exigências de conteúdo local para viabilizar a inserção da energia eólica no Sistema Interligado Nacional (SIN). Embora tenha cumprido seu papel de política de "arranque", a ausência de um ordenamento territorial nacional articulado resultou em uma governança fragmentada, catalisando conflitos socioambientais em zonas costeiras, com destaque emblemático para o estado do Ceará. Nesse contexto, como adverte Torres Junior (2021) ao analisar o caso cearense, o discurso desenvolvimentista estatal, focado na acumulação de capital e no avanço tecnológico, muitas vezes obscurece a percepção dos impactos negativos suportados localmente, resultando em um cenário de injustiça ambiental em que os benefícios prometidos, como emprego e renda, permanecem difusos ou inalcançáveis para as populações vulneráveis.

Em contrapartida, na Galícia, região noroeste da Espanha, a Lei 8/2009 consolidou um modelo distinto, voltado menos à indução de um setor nascente e mais ao reordenamento de um campo já maduro

e pioneiro no contexto espanhol. A norma instituiu o *Plan Sectorial Eólico de Galicia* (PSEGA) como instrumento de ordenamento territorial vinculante e criou mecanismos fiscais – o *canon eólico* e o *Fondo de Compensación Ambiental* – destinados a equilibrar os impactos e benefícios da geração. Contudo, a sofisticação normativa não eliminou as tensões entre os objetivos ambientais declarados e a prática regulatória, tampouco a persistência de conflitos socioambientais (Regueiro-Ferreira; Doldán-García, 2010). Na análise de Paz Aldrey e Cortés Vázquez (2024), essa conflitividade e a elevada litigiosidade recente não devem ser lidas apenas como resistência tecnológica, mas como sintomas de uma "crise rural" profunda, na qual a transição energética se sobrepõe a dinâmicas de despovoamento, gerando atritos específicos sobre o uso do território e o futuro das comunidades rurais galegas.

À luz desses contextos, comparar duas regiões marcadas por idiossincrasias tão distintas, de um lado, o Ceará, situado em um país emergente e caracterizado por vulnerabilidades socioambientais históricas; do outro, a Galícia, inserida na regulação da União Europeia e dotada de um arcabouço administrativo consolidado. Essa assimetria contextual é o que torna uma avaliação comparativa interessante, pois ela permite demonstrar que, a despeito das diferenças institucionais, a lógica global da transição energética tende (ou não) a reproduzir padrões análogos de apropriação territorial e concentração de poder, desafiando a eficácia de instrumentos regulatórios locais.

No que se refere à sustentabilidade ecológica, a expansão eólica impõe pressões específicas sobre ecossistemas de alta sensibilidade que não podem ser negligenciadas. No Ceará, a implantação de usinas sobre campos de dunas móveis, lagoas interdunares e planícies de aspersão tem promovido a fragmentação de habitats e agravado riscos erosivos, exigindo a delimitação rigorosa de zonas de exclusão e *buffers* dinâmicos (Loureiro et al., 2015; Preuss, 2020). A crítica recai sobre a insuficiência de avaliações ambientais parcelares que ignoram efeitos cumulativos sobre a biodiversidade e os serviços ecossistêmicos em zonas costeiras vulneráveis. Já na Galícia, o desafio se pauta em compatibilizar o aproveitamento do recurso eólico com a proteção dos valores naturais e paisagísticos, especialmente em contextos de repotenciação que demandam logística reversa para evitar a consolidação de novos passivos ambientais (Regueiro-Ferreira; Cadaval-Sampedro, 2023).

O desafio analítico, nesse sentido, transcende a descrição dos marcos legais; trata-se de investigar a capacidade desses desenhos institucionais de conciliar sustentabilidade ambiental, legitimidade social e equidade distributiva. Para tanto, adota-se a perspectiva da "avaliação em profundidade" de políticas públicas proposta por Rodrigues (2008), abordagem que enfatiza a necessidade de avaliações densas, extensas e contextualizadas, integrando conteúdo, trajetória institucional e a abrangência temporal e territorial dos instrumentos avaliados.

Nesse sentido, o artigo tem como objetivo realizar uma avaliação comparativa entre o Proinfa (com foco nos desdobramentos da política no Ceará) e a Lei Eólica galega (Lei 8/2009), investigando em que medida seus desenhos institucionais articulam eficiência econômica, sustentabilidade ambiental e equidade territorial. A análise é norteada pela seguinte questão: de que modo esses marcos regulatórios, gestados em contextos institucionais díspares, estruturam – e limitam – essa articulação na expansão da energia eólica? Ao confrontar o debate sobre transição energética com a avaliação de políticas públicas, busca-se evidenciar convergências, assimetrias e os paradoxos distributivos que permanecem em aberto, mesmo em contextos de aparente sucesso em termos de capacidade instalada.

2 METODOLOGIA

O estudo adota uma abordagem qualitativa, documental e comparativa, ancorada no referencial da avaliação em profundidade de políticas públicas (Rodrigues, 2008). Nessa perspectiva, a avaliação ultrapassa a mensuração de indicadores pontuais de eficácia ou eficiência e se organiza a partir de quatro dimensões analíticas interdependentes: (a) conteúdo da política, incluindo formulação, objetivos declarados e coerência interna; (b) trajetória institucional e arranjos de governança; (c) contexto de

formulação e de implementação, com atenção ao marco regulatório setorial mais amplo; e (d) espectro temporal e territorial abrangido, incluindo seus efeitos sobre os territórios e grupos sociais afetados.

O desenho metodológico parte de um estudo de caso comparativo entre dois instrumentos: o Proinfa, instituído pela Lei nº 10.438/2002, com foco em seus desdobramentos no estado do Ceará, e a Lei 8/2009, de aproveitamento eólico na Galícia, incluindo o seu principal instrumento de ordenamento territorial, o *Plan Sectorial Eólico de Galicia* (PSEGA), bem como os mecanismos fiscais do *canon eólico* e do *Fondo de Compensación Ambiental*. A seleção dos casos decorre de sua relevância empírica – ambos são marcos estruturantes da expansão eólica em seus respectivos contextos – e de sua comparabilidade analítica, na medida em que enfrentam problemas semelhantes (diversificação da matriz, conflitos territoriais, participação social) por meio de arranjos institucionais distintos.

Do ponto de vista das fontes de dados, a pesquisa se apoia em:

1. Legislação e normas setoriais: Lei nº 10.438/2002 e normas infralegais associadas ao Proinfa (decretos, portarias, regulamentos da Aneel e documentos oficiais da Eletrobras/ENBPar), além de resoluções ambientais nacionais e estaduais pertinentes ao licenciamento de parques eólicos no Ceará;

2. Marcos normativos galegos: Lei 8/2009, documentos da Xunta de Galicia sobre o PSEGA, atos normativos relativos ao *canon eólico* e ao *Fondo de Compensación Ambiental*, bem como decisões judiciais e relatórios oficiais relativos à litigiosidade do setor eólico na Galícia;

3. Literatura acadêmica e técnica: estudos sobre a gênese e a trajetória do setor eólico em ambos os contextos, avaliações críticas das políticas setoriais e análises sobre conflitos socioambientais decorrentes da expansão da energia eólica no Nordeste brasileiro e na Galícia.

Com base nesse corpus documental, foi elaborada uma matriz analítica organizada em quatro eixos de avaliação em profundidade, que dialogam com a proposta de Rodrigues (2008):

1. Objetivos e contexto histórico-institucional: exame dos contextos de origem de cada instrumento (crise de racionamento e vulnerabilidade hidrelétrica, no caso brasileiro; consolidação de um setor pioneiro e articulação com diretivas europeias, no caso galego), bem como dos objetivos primários e secundários e das metas declaradas.

2. Práticas regulatórias e instrumentos de governança: análise dos mecanismos de contratação, estrutura de custos e compensações, arranjos de ordenamento territorial e dispositivos de estabilidade regulatória e de coordenação entre níveis de governo.

3. Participação social e justiça procedimental: identificação dos mecanismos de participação previstos (audiências públicas, consultas, informação pública), das críticas quanto à sua efetividade e da distância entre participação formal e incidência real das comunidades locais, tanto no licenciamento brasileiro quanto na aplicação do arcabouço ambiental e territorial galego.

4. Impactos territoriais e distributivos: análise dos efeitos concretos da política nos territórios, incluindo desenvolvimento setorial, receitas públicas, distribuição de benefícios e ônus, conflitos socioambientais e padrões de litigiosidade, com especial atenção aos municípios costeiros cearenses e às comarcas galegas de forte presença eólica.

A interpretação dos dados seguiu um procedimento analítico-interpretativo, de caráter indutivo, articulando os achados empíricos com o referencial teórico sobre transição energética, governança territorial e justiça ambiental. Em vez de testar hipóteses causais estritas, buscou-se produzir uma leitura crítica das convergências e divergências entre os dois instrumentos, evidenciando paradoxos e tensões que emergem da tentativa de conciliar expansão rápida da infraestrutura eólica com legitimidade social e equidade territorial.

No que concerne aos aspectos éticos da pesquisa, destaca-se que o presente estudo se fundamenta na análise de fontes documentais públicas, tais como legislações, relatórios institucionais e literatura acadêmica previamente publicada, não envolvendo coleta de dados primários com participantes humanos. Desse modo, não houve necessidade de submissão a comitê de ética em pesquisa, em conformidade com as diretrizes vigentes para pesquisas de natureza documental.

3 RESULTADOS E DISCUSSÃO

Considerando os marcos institucionais e normativos que estruturaram o Proinfa (Lei n.º 10.438/2002) no Brasil, com enfoque específico no estado do Ceará, e a Lei Eólica galega (Lei 8/2009) na Espanha, torna-se pertinente realizar uma avaliação comparativa abrangente. Esta análise volta-se à compreensão de como os objetivos declarados, os instrumentos regulatórios, os mecanismos de participação social e os efeitos territoriais concretos se materializaram em contextos socioeconômicos e políticos distintos. Enquanto o Proinfa representou um esforço inaugural de diversificação da matriz elétrica brasileira, destacando-se na segurança de suprimento, nacionalização da cadeia produtiva e inserção controlada de novas fontes, a Lei Eólica galega consolidou um modelo de governança territorial que combina ordenamento espacial, compensações ambientais e repartição de benefícios locais.

Nesse sentido, buscou-se identificar convergências e assimetrias entre as duas experiências, examinando tanto o desenho institucional e a coerência de seus instrumentos quanto as formas de participação pública, justiça procedimental e distribuição dos benefícios e ônus da transição energética nos territórios afetados. O intuito foi apresentar em que medida cada política foi capaz de articular sustentabilidade ambiental, legitimidade social e efetividade regulatória e econômica, e como as suas práticas moldaram, positiva ou negativamente, o processo de transição energética em escala regional.

Desse modo, a presente análise transcende a descrição normativa e institucional ao perscrutar as implicações estruturais e socioterritoriais de cada instrumento, permitindo compreender como as dimensões regulatória, participativa e distributiva convergem (ou divergem) na configuração de políticas públicas de energia renovável com maior ou menor grau de equidade e integração territorial.

O Proinfa e a Lei Eólica galega (Lei 8/2009) foram instituídos em cenários econômicos e energéticos muito distintos. Enquanto o Brasil reagia a uma crise de abastecimento e a uma forte dependência hidrelétrica, a Galícia buscava consolidar e ordenar um setor eólico que já era maduro e pioneiro na região, inserido em um contexto de reformas estatais e diretivas europeias. Nesse sentido, o Quadro 1 a seguir sintetiza o momento histórico-institucional de emergência de cada instrumento, seus objetivos primários e secundários, e as metas originais que orientaram a implementação.

Quadro 1 – Objetivos e contexto histórico

Dimensão	*Proinfa (Lei nº 10.438/2002)*	*Lei Eólica galega (Lei 8/2009)*
Contexto de Origem	Resposta à crise de racionamento de 2001 e à vulnerabilidade da matriz hidrelétrica, com necessidade de diversificação e segurança de suprimento (Brasil, 2002a; Kelman, 2001; Tolmasquim, 2012). Precedido por reformas que não expandiram a capacidade no ritmo da demanda (Brasil, 1995, 1996).	Consolidação de um setor eólico já pioneiro e amadurecido na Galícia, que se articulava com o regime especial de remuneração estatal e diretivas europeias (Espanha, 2007; Inega, 2007; União Europeia, 2001). A Galícia já possuía uma base instalada renovável consolidada antes de 2009 (REE, 2009).
Objetivo Primário	Aumentar a participação da eólica, PCH e biomassa no Sistema Interligado Nacional (SIN) (Brasil, 2002a). O Proinfa funcionou como uma política de arranque (Brasil, 2003; IEA, 2024).	Planificar o aproveitamento eólico por meio do Plan Sectorial Eólico de Galicia (PSEGA) e ordenar o regime de autorização administrativa (Galicia, 2009, art. 1). Seu foco é o ordenamento territorial vinculante (Xunta de Galicia, 1997).
Objetivos Secundários	Reforçar a segurança de suprimento e estimular a cadeia produtiva nacional através da exigência de conteúdo local (60% na Fase I) (Brasil, 2003).	Instituir mecanismos de equilíbrio territorial e sustentabilidade dos valores naturais, como o canon eólico e o Fondo de Compensação Ambiental (Galicia, 2009, art. 1, art. 7). Busca reduzir o número de máquinas e proteger o meio ambiente (Galicia, 2009, art. 7).
Metas Originais	Fase I: 3.300 MW (1.100 MW por fonte); Fase II: 10% do consumo anual de eletricidade (Brasil, 2002a). A Fase II não foi implementada, perdendo espaço para o modelo de leilões (ACR) (Brasil, 2004b; IEA, 2024).	Ordenar o aproveitamento eólico no território galego, garantindo a distribuição racional da capacidade instalada (Xunta de Galicia, 2010).

Fonte: Os autores (2026)

O Proinfa foi concebido em 2002 como uma resposta estratégica à crise de racionamento de 2001, visando reduzir a fragilidade da matriz hidráulica e estimular o desenvolvimento industrial (Brasil, 2002a; Tolmasquim, 2012). O programa estabeleceu metas de expansão (3.300 MW na Fase I) e utilizou a exigência de conteúdo local (60% na Fase I) para fomentar a indústria interna (Brasil, 2003). No entanto, a Fase II, mais ambiciosa, não foi implementada, pois a expansão migrou para o modelo de leilões (Brasil, 2004b; IEA, 2024). Em contraste, a Lei 8/2009 na Galícia surgiu para disciplinar e compensar um setor já maduro e consolidado (REE, 2009). Sua principal ferramenta foi o PSEGA, que estabeleceu um planejamento territorial vinculante (Galicia, 2009; Xunta de Galicia, 1997) e criou instrumentos fiscais como o *canon eólico* para garantir a sustentabilidade e o equilíbrio territorial (Galicia, 2009, art. 7).

As principais convergências observadas nos dois contextos fincam-se no papel de ambos os instrumentos como vetores de modernização e diversificação da matriz energética, buscando a segurança de suprimento e o crescimento do setor eólico em larga escala. No entanto, a maior divergência permeia a motivação temporal e o foco da política. O Proinfa foi uma política de emergência e indução, focada em criar mercado onde ele era incipiente, ou seja, programa de arranque, utilizando o subsídio e a política industrial como bases estruturantes. Já a Lei Eólica galega constituiu-se como uma política de ordenamento e gestão de conflitos em um setor já estabelecido, no qual o planejamento territorial centralizado era a prioridade, e a compensação se dava por meio de mecanismos fiscais, e não via subsídio tarifário.

Nesse sentido, ao transitar da análise dos objetivos e contextos históricos para a das práticas regulatórias, observa-se que as diferenças de origem se desdobram em arranjos institucionais contrastantes. Enquanto o Proinfa consolida um modelo de coordenação centralizada pela via contratual e tarifária, a Lei Eólica galega estrutura uma coordenação territorial centralizada, pautada no planejamento espacial vinculante e em instrumentos fiscais de redistribuição. Essas distinções são sintetizadas e detalhadas

no Quadro 2, a seguir, que evidencia os mecanismos regulatórios adotados em cada contexto e suas implicações sobre o equilíbrio entre eficiência econômica, governança territorial e equidade distributiva.

Quadro 2 – Práticas regulatórias

Dimensão	*Proinfa (Lei nº 10.438/2002)*	*Lei Eólica galega (Lei 8/2009)*
Mecanismo de Contratação	Contratos de longo prazo (20 anos), centralizados pela Eletrobras, com preços fixados pelo "valor econômico" (com pisos tarifários específicos por fonte na Fase I) (Brasil, 2003; Brasil, 2004a). A seleção priorizava o estágio de licenciamento ambiental (LI > LP) (Brasil, 2002a).	Procedimento autorizativo baseado em livre concorrência, transparência e agilização administrativa (Galicia, 2009, art. 1). A autorização é vinculada a convocatórias públicas competitivas (Xunta de Galicia, 2010), dentro dos limites do Plan Sectorial Eólico de Galicia (PSEGA) (Galicia, 2009).
Estrutura de Custo / Compensação	Socialização tarifária dos custos por meio da Conta Proinfa, rateada entre todas as classes de consumo (excluindo baixa renda) (Brasil, 2002a; Brasil, 2004a). O custo médio homologado em 2025 era de R$ 543,56/MWh (Aneel, 2024).	Instrumentos fiscais-territoriais: o canon eólico (tributo sobre a instalação/operação) e o Fondo de Compensação Ambiental (FCA), destinados a garantir o equilíbrio territorial e a compensação ambiental (Atriga, 2025; Galicia, 2009). O FCA movimenta cerca de 22-22,4 milhões de euros anualmente (Europa Press, 2025; La Voz de Galicia, 2024).
Ordenamento Territorial	Não continha diretrizes territoriais federais explícitas para zonas sensíveis, dependendo das Resoluções Conama (ex.: Conama, 2014) e Coema estaduais (ex.: Ceará, 2018a). Utilizava limites por estado para evitar concentração geográfica (Brasil, 2003).	O PSEGA possui eficácia de ordenação setorial e prevalência sobre planos urbanísticos municipais (Galicia, 2009; Xunta de Galicia, 1997). Isso gerou tensões entre o planejamento autonômico e o urbanismo local (Romero, 2012).

Fonte: Os autores (2026)

O Proinfa foi um instrumento de garantia de mercado, utilizando contratos de 20 anos e preços estáveis (acima do mercado competitivo inicial) para mitigar o risco do investimento em fontes incipientes (Brasil, 2003; Chaves; Azevedo; Fernandes, 2023). Essa previsibilidade foi financiada pela Conta Proinfa, um subsídio cruzado rateado na tarifa (Aneel, 2004). O ordenamento territorial brasileiro para eólicas era, contudo, fragmentado, dependente do licenciamento ambiental em cada estado e das regras de priorização por Licença de Instalação (LI) (Brasil, 2004a). A Lei 8/2009, por sua vez, garantiu a estabilidade por meio do ordenamento territorial centralizado (PSEGA), que define de forma vinculante as zonas de implantação (Galicia, 2009). O mecanismo de compensação é de natureza fiscal, isso porque o *canon eólico* é um tributo direto sobre os empreendimentos que alimenta o Fundo de Compensação Ambiental (FCA), destinado a reverter parte dos ganhos para a proteção natural e o reequilíbrio territorial (Europa Press, 2025; Galicia, 2009).

A principal similaridade regulatória observada é o compromisso com a estabilidade e a previsibilidade para o investidor, o que é essencial para projetos de infraestrutura de longo prazo. Ambos os modelos tentaram atuar para evitar a concentração geográfica excessiva, seja por limites de capacidade por estado no Proinfa, seja por planejamento setorial no PSEGA. A divergência principal pauta-se no financiamento e no ordenamento do solo. O Proinfa usou a tarifa do consumidor para subsidiar (socialização tarifária), enquanto a Galícia usou o imposto sobre a geração (*canon eólico*) para compensar (mecanismo fiscal). Além disso, o modelo galego impôs um planejamento territorial centralizado e vinculante sobre as autonomias municipais, algo ausente no Proinfa brasileiro, que dependia da regulamentação ambiental local.

Desse modo, ao avançar da esfera regulatória para a apreensão da participação social, evidencia-se uma dimensão crítica e fragilizada em ambos os casos. Conforme apresentado no Quadro 3, a seguir, a participação emerge como o ponto mais sensível da governança da transição energética, marcada pela prevalência de procedimentos formais e tecnocráticos que reduzem a incidência efetiva das comunidades locais sobre a definição dos traçados, o licenciamento e a distribuição dos benefícios

gerados pelos empreendimentos eólicos, e isso se evidencia tanto no caso cearense como no caso galego:Parte superior do formulárioParte inferior do formulário

Quadro 3 – Níveis de Participação Social

Dimensão	*Proinfa (Lei nº 10.438/2002)*	*Lei Eólica galega (Lei 8/2009)*
Mecanismos e Práticas	Participação focada nas exigências do licenciamento ambiental (audiências públicas, consultas formais) (Gorayeb; Brannstrom, 2020). Há críticas ao uso do Relatório Ambiental Simplificado (RAS) em áreas complexas (Pereira, 2022; Sobrinho; Santos, 2022), reduzindo janelas deliberativas (Leite, 2022).	Participação ancorada na Lei 21/2013 de Avaliação Ambiental (informação pública e consultas) e no Convênio de Aarhus (Espanha, 2006; Espanha, 2013). A Lei 8/2009 prevê a agilização administrativa (Galicia, 2009).
Críticas à Efetividade	Apresenta um "social gap" (distância entre participação formal e incidência real) (Gorayeb; Brannstrom, 2020; Sobrinho; Santos, 2022). A participação tende a ser informativa e ex post, sem poder real para alterar traçados ou redistribuir ganhos (Lima, 2024). Conflitos decorrem de assimetria informacional (Silva; Rojas-Pinilla, 2023).	O arranjo regulatório tem sido criticado por sua racionalidade tecnocrática, carente de mecanismos efetivos de participação social e distribuição equitativa (Chacón; Frolova, 2024; Regueiro-Ferreira; Doldán-García, 2010). A participação é frequentemente vista como um requisito formal (Romero; Farinós, 2011).
Vulnerabilidades Sociais	Os projetos atingem áreas sensíveis, como dunas móveis e restingas, e comunidades tradicionais (pesqueiras, quilombolas), levando a conflitos territoriais e assimetrias na apropriação dos ganhos (Gorayeb; Brannstrom, 2020; Lima, 2024).	A Lei convive com lacunas práticas na compensação social. Embora haja o canon, a sua efetividade depende de metas programáticas vinculantes, o que não tem revertido de forma proporcional em benefícios para as comunidades locais (Heffron; De Fontenelle, 2024; Regueiro-Ferreira, 2023).

Fonte: Os autores (2026)

A insuficiência participativa no Proinfa manifesta-se no Ceará através do uso do Relatório Ambiental Simplificado (RAS) em ecossistemas de alta sensibilidade, como dunas e restingas, o que limita o escopo da avaliação e a qualidade da deliberação pública (Pereira, 2022; Sobrinho; Santos, 2022;). Isso gera um "social gap" onde o envolvimento das comunidades trata-se de uma formalização normatizava, mas que na prática não tem efetividade ou *ex post*, sem poder real para alterar os projetos ou garantir a justiça distributiva (Gorayeb; Brannstrom, 2020; Lima, 2024). Na Lei 8/2009, o problema pauta-se na racionalidade tecnocrática imposta pelo PSEGA (Regueiro-Ferreira; Doldán-García, 2010). Embora o arcabouço ambiental seja formalmente sólido (Espanha, 2013), a busca por agilidade administrativa levou a falhas no procedimento (como a redução do prazo de consulta), resultando em anulações judiciais que confirmam a fragilidade da participação efetiva (De La Justicia, 2024; Mora Ruiz, 2025).

A principal convergência é o diagnóstico da participação como um ritual formal. Em ambos os casos, a lógica da eficiência energética e o imperativo de atração de capital privado sobrepujaram a necessidade de legitimidade democrática e justiça procedimental. O resultado é a assimetria de poder e informação entre as empresas e as comunidades. O que diferencia essa situação nos territórios trata-se apenas da origem das falhas procedimentais. No Brasil, o problema é estrutural, ligado à fragilidade dos estudos ambientais (RAS) em territórios vulneráveis. Na Galícia, o problema é sistêmico e jurídico, focado na tensão entre o planejamento regional centralizado e a aplicação dos padrões legais de consulta (Convênio de Aarhus), sendo a judicialização o principal campo de batalha contra a tecnocracia regulatória.

Desse ponto, torna-se consequente transitar da crítica procedimental para os efeitos concretos da política nos territórios. Em ambos os contextos, a expansão da capacidade instalada foi inequívoca; entretanto, seus desdobramentos revelam um paradoxo distributivo: a concentração de poder empresarial convive com a persistência de conflitos localizados, especialmente onde a ocupação do solo tensiona

ecossistemas sensíveis e formas de vida tradicionais. Assim, abre-se a análise do Quadro 4, no qual se examinam comparativamente os impactos observados (do desenvolvimento setorial às receitas públicas e à litigiosidade), permitindo identificar em que medida os arranjos regulatórios e participativos se converteram (ou não) em benefícios tangíveis e equitativos para as comunidades anfitriãs.

Quadro 4 – Impactos observados nos Territórios

Dimensão	*Proinfa (Ceará, Brasil)*	*Lei Eólica galega (Galícia, Espanha)*
Desenvolvimento Setorial	Foi o ponto de partida para a curva de aprendizado e a formação da cadeia eólica nacional (Araújo; Willcox, 2018; Diniz, 2018), reduzindo riscos tecnológicos e de mercado (Chaves; Azevedo; Fernandes, 2023). A expansão posterior migrou para leilões competitivos (Brasil, 2004b).	Consolidou a eólica como pilar da matriz (38,4% da produção em 2024), atuando sinergicamente com a hidrelétrica (REE, 2025). Reforçou a governança autonômica do setor (Galicia, 2009).
Distribuição de Benefícios	Observam-se crescimento de receitas municipais (ISSQN e cota-parte do ICMS), PIB per capita e valor adicionado setorial nos municípios hospedeiros (Sampaio; Costa; Irffi, 2025; Velôso et al., 2025). Contudo, há evidências de reconcentração fundiária e desigualdade na apropriação dos ganhos (Gorayeb; Brannstrom, 2020; Lima, 2024).	Os instrumentos fiscais geram arrecadação significativa (cerca de €22 milhões/ano) (Europa Press, 2025), mas persiste uma elevada concentração proprietária em grandes grupos (Regueiro-Ferreira; Doldán-García, 2020). Os ganhos de arrecadação não se traduzem em benefícios socioeconômicos proporcionais para as comunidades locais (Regueiro-Ferreira, 2023; Valle et al., 2024).
Conflitos e Litigiosidade	Conflitos recorrentes em zonas costeiras sensíveis, como os complexos do Cumbe e Icaraizinho (Lima, 2024; Sousa; Moura; Souza, 2023). A judicialização persiste sobre posse, danos ambientais e suficiência dos estudos (Mendes; Collaço, 2024).	A Lei 8/2009 enfrentou intensa judicialização. Em agosto de 2025, 92 parques estavam submetidos a litígios e 86 suspensos cautelarmente (Xunta de Galicia, 2025a). As tensões são exacerbadas pela prevalência do planejamento autonômico sobre o urbanismo municipal (Romero, 2012).

Fonte: Os autores (2026)

O impacto do Proinfa no Ceará demonstra a dicotomia entre sucesso econômico e fracasso social. Houve aumento de receitas tributárias municipais e desenvolvimento setorial (Diniz, 2018; Sampaio; Costa; Irffi, 2025). No entanto, o desenvolvimento se deu à custa da intensificação de conflitos, como no Cumbe e Icaraizinho, resultando em reconcentração fundiária e exclusão de comunidades tradicionais da apropriação dos ganhos (Gorayeb; Brannstrom, 2020, Lima, 2024). A Lei 8/2009 consolidou a Galícia como potência eólica (REE, 2025) e garantiu um fluxo de compensação fiscal (o *canon*) que arrecada milhões anualmente (Europa Press, 2025). Contudo, essa riqueza é acompanhada por uma persistente concentração proprietária em grandes grupos (Regueiro-Ferreira; Doldán-García, 2020). A falha do modelo em reverter benefícios proporcionais e a inadequação dos estudos ambientais cumulativos resultaram em uma judicialização maciça, com dezenas de parques suspensos cautelarmente até 2025 (Xunta de Galicia, 2025a).

A principal similaridade entre os contextos pauta-se no paradoxo distributivo inerente a ambos os modelos de grande escala. Em ambos os territórios, a expansão eólica gerou riqueza (fiscal ou tributária), mas essa riqueza não beneficiou de forma equitativa as comunidades que suportam os custos ambientais e territoriais, reforçando a concentração de poder empresarial. A principal diferença observada reside na forma como os conflitos se manifestam e são gerenciados. No Brasil (Ceará), os impactos estão fortemente ligados à vulnerabilidade socioambiental e aos conflitos pela posse da terra (invasão de dunas, impactos à pesca artesanal). Na Galícia, o impacto mais evidente é a instabilidade jurídica e a alta litigiosidade, em que as comunidades e os grupos ambientais usam o sistema judicial para contestar a legalidade do planejamento regional e a validade dos procedimentos ambientais.

Dessa forma, ao reunir os quatro eixos analisados, objetivos e contextos históricos, práticas regulatórias, participação social e impactos territoriais, constata-se que tanto o Proinfa quanto a Lei Eólica galega destacam-se como instrumentos eficazes sob o ponto de vista da expansão setorial, mas limitados em termos de justiça territorial e distributiva. Ambos lograram consolidar a energia eólica como vetor de modernização e transição energética, porém, sem garantir, de modo equivalente, a democratização dos benefícios e a inclusão social nos territórios impactados, corroborando as formulações de Heffron e De Fontenelle (2024) acerca da persistência de déficits de justiça energética mesmo em contextos de avanço institucional.

No caso brasileiro, a ausência de um ordenamento territorial nacional e a dependência de normas ambientais fragmentadas produziram uma governança reativa, marcada por conflitos localizados e por uma participação social predominantemente formal, incapaz de corrigir as assimetrias de poder econômico e informacional, em consonância com o "social gap" identificado por Gorayeb e Brannstrom (2020) e com as evidências empíricas apresentadas por Lima (2024) e Silva e Rojas-Pinilla (2023). Já na Galícia, embora o modelo territorial vinculante e os instrumentos fiscais tragam à tona uma sofisticação institucional maior, a ênfase tecnocrática e a prevalência do planejamento autonômico sobre as autonomias municipais acabaram por deslocar o conflito para a arena judicial, ampliando a litigiosidade e questionando a legitimidade dos processos decisórios, conforme analisado por Chacón e Frolova (2024), e Regueiro-Ferreira e Doldán-García (2010).

Desse modo, ambos os contextos refletem uma questão importante no que tange à transição energética contemporânea, que é a conciliação entre eficiência econômica, sustentabilidade ambiental e equidade social. O êxito em termos de capacidade instalada e geração de receitas não se traduziu em benefícios redistributivos proporcionais, tampouco em estabilidade institucional duradoura, o que dialoga com a tipologia de conflitos territoriais proposta por Frantál, Frolova e Liñán-Chacón (2023). Assim, a comparação evidencia que a verdadeira maturidade de uma política eólica não se mede apenas pelo número de megawatts instalados, mas pela capacidade de integrar o desenvolvimento energético ao desenvolvimento territorial, promovendo justiça procedimental, participação efetiva e repartição equitativa dos ganhos da transição.

4 CONSIDERAÇÕES FINAIS

A avaliação comparativa em profundidade entre o Proinfa, no Ceará, e a Lei Eólica galega traz à tona um diagnóstico inquietante sobre a transição energética contemporânea: o êxito tecnológico e de mercado não garante, por si só, a justiça territorial. A análise demonstra que ambos os instrumentos, embora concebidos em contextos institucionais díspares e com níveis de sofisticação normativa distintos, acabaram por convergir na produção de uma modernização excludente. O sucesso na expansão da capacidade instalada, inegável em ambos os casos, operou sob uma lógica que priorizou a segurança do investidor em detrimento da equidade distributiva, gerando um paradoxo em que a energia é renovável, mas as práticas de poder reproduzem velhas assimetrias.

No caso brasileiro, conclui-se que o Proinfa cumpriu sua função de "arranque" industrial, mas falhou em sua inserção territorial. A governança fragmentada e a dependência de licenciamentos ambientais assimétricos transformaram o território cearense em um palco de disputas, onde a celeridade da expansão atropelou direitos de comunidades tradicionais. Já na Galícia, o problema não foi a falta de regulação, mas o excesso de tecnocracia. A Lei 8/2009, com seu planejamento vinculante e instrumentos fiscais (o *canon*), criou uma aparência de ordem que não resistiu à prova da legitimidade social, resultando em uma judicialização massiva que expõe a fratura entre o planejamento centralizado e a vontade local.

Assim, foi possível perscrutar neste estudo que a maturidade de uma política eólica não pode mais ser aferida apenas pelo volume de *megawatts* ou pela robustez de seus contratos financeiros. A verdadeira

maturidade reside na capacidade do Estado de articular a descarbonização com a democracia. As evidências comparadas do Ceará e da Galícia mostram que instrumentos de comando e controle (como o PSEGA) ou de incentivo econômico puro (como o Proinfa) são insuficientes para mitigar conflitos se não estiverem alicerçados em justiça procedimental substantiva.

À luz dessas dinâmicas, o artigo sustenta que a transição energética corre o risco de se tornar um novo vetor de desigualdade se não houver uma correção de rota. As diferenças entre os casos – a vulnerabilidade fundiária no Ceará versus a tensão jurídico-institucional na Galícia – são apenas manifestações locais de um mesmo fenômeno global, a desterritorialização das decisões energéticas.

Ademais, propõe-se a necessidade de uma "segunda geração" de políticas eólicas, orientada por um paradigma de transição justa e territorialmente integrada. Isso implica deslocar o foco da expansão rápida e da rentabilidade corporativa para a incorporação efetiva das dimensões sociais e territoriais, exigindo que os instrumentos de planejamento, financiamento e compensação sejam concebidos com os territórios, e não para os territórios. Sem esse deslocamento ético e político, a energia do vento, embora limpa em termos de carbono, continuará "suja" em termos sociais, replicando arranjos de poder que a própria ideia de sustentabilidade deveria superar.

Nesse contexto, embora o estudo ofereça contribuições relevantes para a compreensão comparativa da governança da energia eólica, algumas limitações devem ser reconhecidas. A análise fundamenta-se predominantemente em fontes primárias, o que restringe a apreensão direta das percepções e estratégias dos atores locais, ao passo que a delimitação territorial – centrada no Ceará e na Galícia – não permite generalizações automáticas para outros contextos. Ainda assim, tais limites não comprometem os achados, mas indicam a necessidade de aprofundamento empírico por meio de investigações de campo que incorporem as dinâmicas locais e a experiência das comunidades afetadas. Nessa direção, os resultados também apontam implicações relevantes para a formulação de políticas públicas, destacando a importância de integrar mecanismos efetivos de participação social, redistribuição territorial dos benefícios e ordenamento sensível às especificidades socioambientais. Assim, abre-se uma agenda de pesquisa voltada à análise de diferentes arranjos institucionais e suas repercussões sobre a justiça energética, contribuindo para o desenvolvimento de modelos de transição energética mais equitativos e territorialmente integrados.

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Assessing municipal Climate Action Plans through a health lens: the case of the City of Rio de Janeiro

Avaliando Planos de Ação Climática municipais por uma lente de saúde: caso da cidade do Rio de Janeiro

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ARTICLE - VARIA

ABSTRACT

Climate change is a complex global challenge that requires collaboration across multiple scientific disciplines. In urban areas, its effects are more intense due to several factors, such as high population density, building materials, and transportation emissions. Climate Action Plans (CAPs) are the core documents guiding climate-related strategies and initiatives in urban areas. This article analyses the Climate Action Plan of Rio de Janeiro City (CAP_RJC) to assess how it addresses human health. The methodology employs a Content Analysis guided by the approach Urbanism Favourable to Health developed by EHESP France, which is based on Urban Health Determinants. The results indicate that CAP_RJC addresses several determinants of the Urbanism Favourable to Health approach; however, there remains an opportunity to improve vulnerability assessments at the local level.

Keywords: Urban. Adaptation. Climate change. Planning. Health determinants.

RESUMO

As mudanças climáticas representam um desafio global complexo que exige a colaboração entre diversas disciplinas científicas. Nas áreas urbanas, seus efeitos são mais intensos devido a vários

fatores, como alta densidade populacional, materiais de construção e emissões do transporte. O Plano de Ação Climática (PAC) é o documento central que orienta as estratégias e iniciativas relacionadas ao clima em áreas urbanas. Este artigo analisa o Plano de Ação Climática da Cidade do Rio de Janeiro (PAC_RJC) para avaliar como ele aborda a saúde humana. A metodologia emprega uma Análise de Conteúdo guiada pela abordagem Urbanismo Favorável à Saúde, desenvolvida pela EHESP França, que se baseia nos Determinantes Urbanos da Saúde. Os resultados indicam que o PAC_RJC discorre sobre diversos determinantes da abordagem Urbanismo Favorável à Saúde; no entanto, ainda há espaço para aprimorar as avaliações de vulnerabilidade em nível local.

Palavras-chave: *Urbano. Adaptação. Mudanças climáticas. Planejamento. Determinantes de saúde.*

1 INTRODUCTION

Cities demand major attention to the topic of Climate Change (CC), not only in academic research but also in the development of mitigation and adaptation policies at the local level. However, many authors (Hoeben *et al.*, 2023; Sheehan *et al.*, 2022) argue that health is still a less visible dimension in climate change efforts. Additionally, there is limited research on the adaptive capacity of Public Health (Burton, 2015). According to Fagliano and Diex-Roux (2018), climate change is the largest global health challenge of the current century. The authors state that, even though urban areas pose challenges for addressing health consequences, they also offer many possibilities. The Pan American Health Organisation (PAHO) emphasised the development of the PAHO Regional and Global Plan in 2008, to ensure that Public Health is the central axis of the response to Climate Change (Paho, 2009).

The Climate Action Plan (CAP) serves as the central document outlining actions to mitigate and adapt to greenhouse gas (GHG) emissions across various governmental and economic sectors. The urban health components of adaptation policies can prepare municipalities for climate change, mitigate its adverse effects, and enhance the benefits of available technologies and management solutions. According to a recent World Health Organisation (WHO, 2021) report, based on a survey across multiple countries, there has been an increase in the inclusion of health issues in CAPs. However, the level of health inclusion remains inconsistent. Sanches *et al.* (2020) note that the health sector often adopts siloed approaches to address climate change. There is a clear need for an integrated approach that connects health systems with other sectors, such as water and sanitation, transportation, and housing. Turner *et al.* (2023) indicate that while all European Union countries have national adaptation policies, the implementation of health considerations is uneven and often undervalued. Reinwald *et al.* (2024) found that inadequate consideration of exposure and vulnerability hampers effective adaptation planning. Furthermore, some researchers point out a lack of research on adaptation and mitigation in low- and middle-income countries (Jabakhanji *et al.*, 2022).

In fact, cities are more vulnerable to climate events and extreme weather than rural areas. Therefore, the urban population is increasingly susceptible to health problems. In this sense, urban adaptation is critical, particularly in low and middle-income (LMI countries) where urbanisation occurs very fast without adequate planning and infrastructure. The vulnerable population will be more impacted, and inequality is a central issue in LMI countries and must be adequately considered in urban climate plans.

Although numerous mitigation and adaptation programs have been developed in various cities, a clear methodology for analysing the health impacts of these strategies in urban contexts, particularly in developing countries, is lacking. Public health researchers and practitioners typically employ a determinant-based model when promoting intersectoral collaboration to improve health in urban environments (Vlhahov *et al.*, 2007). The fundamental premise is that sectors responsible for social determinants should integrate health considerations into their research and policymaking (Kim *et al.*, 2023).

Rio de Janeiro City (RJC) has sought to create this synergy, producing reports and plans on climate change with input from various municipal management sectors, academia, and civil society. Understanding the social, urban, and economic determinants and conditions is a "sine qua non" condition for municipalities to carry out adequate climate action.

In this study, we analyse the Climate Action Plan of Rio de Janeiro City (CAP_RJC) to understand how human health is addressed. The methodology employs a Content Analysis based on human health criteria of the Urbanism Favourable à la Santé – UFS approach developed by the School of Public Health in France (EHESP), which is grounded in health determinants (Roue-Le Gall *et al.*, 2014).

2 URBAN CLIMATE ACTION PLANS

Global emissions attributed to urban areas increased by 25 GtCO2-eq, to 29 GtCO2-eq in 2020, representing about 62% of total emissions and 67% of the global share (IPCC, 2022). This rise is associated with urban population growth and higher per capita consumption, a trend that is expected to continue, with projections indicating that 70% of the world's population will live in cities by 2050 (UNDP, 2024).

Greenhouse gas (GHG) emissions vary significantly among cities in developed regions, with notable differences in per capita emissions (Kennedy *et al.*, 2009). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change defines adaptation as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities" (IPCC, 2014). Adaptation plans aim to reduce the adverse effects of climate change and enhance resilience to its impacts (Unep, 2023; WHO, 2021).

Health considerations are increasingly addressed in a structured manner in the recent IPCC report AR6 (IPCC, 2022), building on earlier analyses by Rosenweig *et al.* (2018) and other reports. According to a special report from the World Health Organisation on climate change and health (WHO, 2021), health adaptation assessments should encompass national evaluations of climate impacts, vulnerabilities, and adaptation strategies for health, along with national and city-level climate change risk assessments.

Cities are actively engaging in both climate change mitigation and adaptation efforts. However, adaptation presents numerous challenges, often affecting multiple sectors over an extended timeframe. Focusing on public health within transformational adaptation goals can help protect the health of individuals, particularly those most vulnerable to climate change effects (WHO, 2021). The Lancet Countdown on Health and Climate Change in Europe, a collaborative initiative led by The Lancet, suggests that climate plans should prioritise health, well-being, and equity, which could represent a significant public health opportunity in this century (van Daalen *et al.*, 2022).

A review of academic literature on adaptation in Low and Middle-Income Countries (LMIC) by Scheelbeck *et al.* (2021) revealed that evaluations of adaptation strategies for gradual climate change are limited, with most studies focusing solely on extreme weather events. At the national level, Paz-Soldan *et al.* (2023) assessed the Climate Action Plans (CAPs) of 12 South American countries regarding their consideration of climate change impacts on health. Their findings indicated a lack of connection to health issues and insufficient detailed information to assist policymakers in implementing effective actions. Aboagye and Sharifi (2023) drew similar conclusions when they examined 287 CAPs from cities around the world and noted a lack of inclusivity, integration, and transparency. Additionally, Farkas *et al.* (2024) conducted a content analysis of climate plans from Slovenian cities and found that interventions often neglect the most vulnerable groups affected by heat waves.

Currently, the development of knowledge regarding effective CAPs is progressing slowly and still requires more effort. Olazabal and Gopegui (2021) argue that there is significant room for improvement in

adaptation planning in major global cities, highlighting the importance of how adaptation is integrated into local planning processes and of governments' prior experience. If this complexity is overlooked in a CAP, it can lead to maladaptation. Maladaptation refers to ineffective planning that fails to adequately address vulnerability, stemming from a misunderstanding of what vulnerability entails. It often results from poorly constructed plans based on limited or incorrect assumptions. Scheelbeek *et al.* (2021) found that instances of maladaptation in low- and middle-income countries were primarily associated with increasing inequalities and unforeseen adverse effects. Identifying vulnerabilities is critical and may be one of the most challenging aspects of CAPs (Juhola *et al.*, 2016).

3 DETERMINANTS OF URBAN HEALTH

Many urban health issues arise from inadequate urban conditions, poverty, limited access to urban infrastructure and services, weak social cohesion, and inequalities (Barton; Tsourou, 2004; Vlahov *et al.*, 2007). Urban Health Determinants are life and work conditions that affect health and can be used to elaborate and evaluate policies (Friche *et al.*, 2015; Vlahov, 2014). The intricate interplay of urban factors affecting health necessitates methodological approaches that incorporate the perspectives of various stakeholders to identify ways to mitigate health problems and enhance positive health outcomes. Chapman *et al.* (2016) assert that climate change in urban areas should be viewed as an analysis of a complex system, requiring an integrated approach that aligns urban, health, and environmental objectives.

The UN-Habitat and WHO (2020) guide for integrating health into urban planning suggests utilising traditional health sector elements, including disease prevention (e.g., waterborne diseases), health promotion (e.g., physical activity and mobility), and ecological public health (e.g., local food systems and resilience strategies). This guide emphasises that health considerations should permeate all planning phases: diagnosing problems through ex-ante evidence, formulating interventions via health impact assessments, implementing interventions through engagement and inclusion, and finally, monitoring and evaluating outcomes through health outcome reports. The guide advocates an integrated approach that connects the social determinants of health with the Sustainable Development Goals (SDGs) and influences decision-makers across various urban sectors, underscoring the role of public health professionals in planning for the health and well-being of populations.

Roue-Le Gall *et al.* (2014) from the School of Public Health at Rennes - EHESP in France present a systemic approach to the social determinants of health in urban environments, aiming to promote the dissemination and standardisation of concepts related to urban health determinants. Their guide is divided into two sections: the first addresses concepts linking urbanism and health, while the second provides a practical guide to analysing the health impacts of urban projects.

This study for CAP will apply the first section, which outlines governance criteria essential for an urban health approach: health, participation, inequality, vulnerability, sensitivity, adaptive capacity, susceptibility, social inclusion, coordination, risk, and intersectoral action. The guide includes an assessment matrix with Urban Health Determinants (UHD), such as health behaviour, social cohesion and equity, local democracy, accessibility of urban services and facilities, economic development and employment, habitat, urban spaces, security, nature, Climate Change Adaptation, outdoor air pollution, soil, water, waste management, noise and electromagnetic fields.

The Guide highlights two mechanisms by which environmental exposures can contribute to social health inequities: vulnerability differential (exposures affect populations with precarious health situations more intensely) and exposure differential (underprivileged populations may have higher levels of exposure). Interventions should maximise protective factors and reduce risk factors, always prioritising the most vulnerable populations. The authors also note that these mechanisms may

overlap, underscoring the need for an integrated analysis of the various determinants that influence health in the urban environment.

Finally, the UFS guide suggests five axes of action that should summarise the planned urban intervention: reduction of pollutants and other harmful agents; promotion of healthy individual behaviours; change the social environment to foster social cohesion, the well-being of inhabitants and the mitigation of health inequities between different groups and populations, considering the antagonisms and possible synergies in the implementation of urban projects.

4 METHODOLOGY

The objective of this study is to assess the Climate Action Plans of Rio de Janeiro City (CAP_RJC) through a health lens. To carry out this assessment, a Content Analysis is applied to analyse the plans. Given the characteristics of the research object, the study chose a manifesto-type analysis method. Manifesto-type analysis is more superficial and seeks to identify what was said (Bengtsson, 2016). The structure adopted in this study has three phases, based on Bardin (1997): 1) pre-analysis, 2) exploration of the material and 3) treatment of results, inference, and interpretation.

The choice for Rio de Janeiro City was due to its complexity. Also, RJC is prone to extreme weather events and CC disasters, which mainly affect a high percentage of the vulnerable population living in informal settlements without adequate infrastructure.

4.1 PRE-ANALYSIS

In pre-analysis or de-contextualisation, researchers initially analyse the documents before extracting the most important excerpts. The study prepares a list of codes to perform the analysis. The methodological design of this study, which seeks to identify the health content of CAP, suggests that the codes are deductive. The researchers create them in advance, in line with the study's objective and the UFS criteria described in section 3.

As a federative republic, Brazil has a three-level government: National, State, and Municipal, in which the lower levels must follow the legislation and regulations of the upper levels. The municipal CAP plan must follow the national and Rio de Janeiro State CAPs. This way, to analyse municipal plans, we must also consider State and National regulations. This study will analyse the following plans:

- National Climate Action Plan – NCAP2016 (MMA, 2016)
- Adaptation Plan of Rio de Janeiro State – RJS2018 (ERJ, 2018)
- Sustainable Development and Climate Action Plan of Rio de Janeiro City – RJC2021 (PMRJ, 2021a).
- National Adaptation Plans: cities sectoral plan – NAP Cities 2026 (Brasil, 2025).

4.2 EXPLORATION OF THE MATERIAL

In the material exploration or re-contextualisation phase, the analysis produces an analytical description that may include the following items: coding and classification. In this phase, the analysis defines categories and identifies registration units, followed by frequency counting.

4.3 INTERPRETATION

In this phase, the interpretation or re-contextualisation of the excerpts defined in the previous item takes place. Researchers can make inferences and categorise data based on homogenisation criteria and other criteria. A categorisation can occur within rules or criteria: mutual exclusion, homogeneity, relevance, and objectivity. At this stage, researchers must compare inferences with the context in which the research object occurs. For this study, the researchers created keywords/codes categories based on the UFS approach (Roue-Le Gall *et al.*, 2014) to draw inferences about the inclusion of health in the plans.

5 RESULTS

In Brazil, Rio de Janeiro State has the highest level of population exposed to the adverse effects and risks of climate change, compared with the other 26 states (MMA, 2016). Its capital, Rio de Janeiro City, is the second most populous city in Brazil, with a population of 6,2 million in 2022 (IBGE, 2024) in an area slightly superior to 1.300 sq. km. According to the GHG inventory for Rio de Janeiro City, 31% of the city's emissions are attributable to transport. Solid waste accounts for 9%, and industrial energy consumption accounts for 11% (PMRJ, 2015).

The municipality of Rio de Janeiro has approximately 1,018 slums, which concentrate 23% of the city's population and still present inadequate conditions for water supply, sanitation, waste disposal, and storm drainage (PMRJ, 2022a). Bortz *et al.* (2015) created the Urban Health Inequalities index for the city of Rio de Janeiro, which indicated that over the period of 2002-2010, the ratio of inequality extremes declined. Yet, the social distinction between poor and rich areas remained.

5.1 RE-ANALYSIS

The Brazilian National Adaptation Plan – NCAP2016 (MMA, 2016) provides guidance for initiatives to manage and reduce the risks of climate change's adverse impacts in the long term. It was elaborated with the participation of several institutions, including the health sector, and has specific chapters dedicated to strategies for health, infrastructure and cities. One of the city's strategy guidelines is to improve urban planning models. NCAP2016 recognises the limitations of the water and sanitation infrastructure that lead to population vulnerability and ensures the establishment of intersectoral actions to reduce population exposure.

At the state level, the Adaptation Plan of Rio de Janeiro State – RJS2018 (ERJ, 2018) focus on impacts such as floods, landslides, and vector-borne diseases. It also presents adaptation actions for roads, seashores, and green areas. The State Environmental Agency developed the plan with the support of the academia. It states that the region is highly vulnerable to climate disasters. RJS2018 underscores the region's high hydrological stress and the need for adaptation. Regarding human health, it focuses on chronic diseases (cardio and respiratory) and infectious vector-borne diseases. It also indicates that the actual vulnerability of the poor population due to inadequate urban infrastructure and services increases the impacts of climate change.

Academia, several institutions, and urban international networks supported the elaboration of the Sustainability Development and Climate Action Plan of Rio de Janeiro City – RJC2021 (PMRJ, 2021a), with community participation. It presents interventions in five areas linked to one or more SDGs, with 138 goals and 978 actions. It includes four main axes for sustainability actions: green (forests, parks), brown (infrastructure), blue (water, rivers, oceans), and orange (social and economic issues). In addition, its scenarios include short-, medium-, and long-range estimates.

In 2026, the federal government released a comprehensive package of national climate plans comprising three parts: mitigation plans, adaptation plans, and transversal climate plans. The Climate Adaptation plans package has as its first National Adaptation Goal "to increase the resilience of the population, the cities, the territories and infrastructures in response to climate emergency" (Brasil, 2025). One of these national adaptation plans, NAP Cities 2026, is dedicated to cities. This is an extensive document that reinforces the unique characteristics of adaptation in cities, underscoring the need for an intersectoral approach to management.

5.2 EXPLORATION OF THE DOCUMENTS

In the Material Exploration phase, the analysis quantified the codes using the keywords. One of the authors first counted them, a second author later confirmed or rejected this count, and a third author judged the relevance of disagreements between the first two authors. This triangulation minimises potential interpretation errors. The results of the analysis appear according to the categories of the UFS approach (Roue-Le Gall *et al.*, 2014):

5.2.1 URBAN HEALTH GOVERNANCE - UHG

Table 1 presents categorisation counting for criteria based on governance of health in urban environments. Health is an important criterion for the NAP 2016 and RJC 2021 plans, the second-most-cited criterion. There is a similar profile between RJS 2018 and RJC 2016; in both plans, vulnerability was the most cited category.

Table 1 – Categorisation counting for UHG – Urban Health Governance

Governance	*NAP 2016*	*RJS 2018*	*RJC 2021*	*NAP Cities 2026*
Health	116	47	397	24
Participation	27	5	425	23
Inequality	-	1	4	-
Vulnerability	359	97	144	64
Sensitivity	43	3	4	3
Adaptive capacity	42	11	8	5
Susceptibility	28	30	19	-
Social inclusion	1	-	16	1
Coordination	24	3	15	7
Risks	251	110	177	75
Intersectoral	18	1	35	7

Source: The authors

NAP 2016 is the national adaptation plan for the entire country. Not surprisingly, it discusses several aspects of human health that are affected by CC. In doing so, Vulnerability and Risks appear as the most cited criteria. Indeed, these concepts are already common among the stakeholders involved in the climate change debate. And it highlights the importance that national authorities attach to the population's vulnerability to disasters and other climate events. Sensitivity was seldom used, except for NAP 2016. Except in NAP 2016, CC plans did not frequently address Adaptive Capacity, a concept linked to vulnerability.

RJS 2018 discussed the less-frequent concept of Susceptibility, focusing on several areas affected by landslides, drought, and flooding in Rio de Janeiro State. This is also the reason for a higher risk and vulnerability score in RJS 2018.

Healthy behaviour and participation were poorly considered in NAP Cities 2026, while vulnerability and risks remain on top. There is a significant opportunity to develop Health Promotion interventions, which should be vigorously pursued at the city level.

RJC 2021 is a long, detailed document with several chapters covering different SDG goals for the city. It highlights a significant concern regarding popular participation and intersectoral action, which were less emphasised in the other plans. Indeed, it emphasises public participation and the involvement of several institutions. It also proposes actions to promote social inclusion. Health, vulnerability and risks are also highly cited.

5.2.2 URBAN HEALTH DETERMINANTS - UHD

As shown in Table 2, the Climate Change Adaptation category had high scores across the three plans, as expected for climate adaptation plans. Water was also highly cited across all plans, confirming the relevance of this environmental determinant in tropical urban areas. Living environment determinants such as Habitat, Urban Spaces and Security were almost absent in the NAP 2016 and RJS 2018. Still, they were often cited in RJC 2021 and in NAP Cities 2026, reinforcing the urban profile of these plans. Also, we must mention that RJC 2021 presents some actions for Social Cohesion and Equity, a determinant that is also emphasised in NAP Cities 2026.

Table 2 – Categorisation counting for UHD – Urban Health Determinants.

Urban Health Determinants	*NAP 2016*	*RJS 2018*	*RJC 2021*	*NAP Cities 2026*
I - Lifestyles, social and economic structures				
Healthy behaviour	-	-	7	-
Social cohesion and equity	-	4	35	18
Local democracy	-	-	11	1
Urban services and equipments accessibility	3	11	6	89
Economic development employment	42	20	21	3
II - Living environment				
Habitat	16	-	80	64
Urban spaces	2	13	196	16
Security	9	10	93	17
III - Environment and resources				
Nature	155	1	21	14
Climate Change adaptation	561	182	123	192
Outdoor air pollution	10	-	4	-
Water	287	48	197	88
Waste management	15	9	48	27

Urban Health Determinants	NAP 2016	RJS 2018	RJC 2021	NAP Cities 2026
Soils	5	25	72	3
Noise and electromagnetic fields	-	-	-	-

Source: The authors

The plans do not mention some urban health determinants, such as noise and electromagnetic fields. Indeed, some mitigation and adaptation actions could reduce noise. For example, electric cars are quieter than fossil-fuel engines and might reduce human stress from noise. These are co-benefits of CC interventions that should be evaluated and monitored by the plans. Several plans did not cite air pollution, which suggests a lack of association between local air pollution and greenhouse gas impacts. Moreover, the plans presented few explicit actions on Healthy Behaviour. The absence of some of these determinants shows the need to improve debate on adaptation in cities.

5.3 INTERPRETATION OF THE CAPS

The municipal plan RJC2021 has demonstrated a more consistent integration of urban health determinants than the national and state climate plans. It emphasises determinants such as Habitat, Urban Spaces, Social Cohesion, and Equity. Although these plans seldom addressed concepts such as Susceptibility, Inequality and Adaptive Capacity, CAPs included several urban health determinants.

The RJC2021 presents several programs and actions for the next decades. The study selected one of those programs to analyse, due to its urban and social relevance. The so-called Reviver Program - Requalification Plan for the Centre of Rio de Janeiro, created through Municipal Decree No. 48348/2021 (PMRJ, 2021b), was developed to re-qualify the RJC downtown area, as its business area occupation rate decreased significantly after the Covid-19 pandemic. This program aimed to comprehensively requalify the area and bring the population back downtown. The plan also comprised several other actions for public spaces, with the final goal of downtown revitalisation and reduction of urban sprawl. As happened in many other cities worldwide, the goal is to renovate commercial buildings and to build new residential units. It is worth mentioning that this is the oldest part of the town. Some of the actual inhabitants are descendants of the Africans who were enslaved for three centuries.

According to the decree, the district's regulations align with the City of Rio de Janeiro's Sustainable Development and Climate Action Plan (RJC2021). It involved several municipal offices, such as Transport and Mobility, Historical Heritage, Waste Management, Environment, Energy, Water & Sanitation services, Drainage, Park and Forest, Social Service, Urbanism, Security, Planning, and so on.

One of the subprojects of the Reviver Program is the Low Greenhouse Gas Emission District – LGGED (item P.L.L.10), which aims to radically transform the mobility profile of the downtown area, considering the existing infrastructure of subways, trams, and other modes. It includes several actions, such as restrictions on fossil fuels, fostering walking and cycling with the expansion of routes, and so on. The program will also support Health Promotion activities. C40 cities and other institutions also support these actions. Annex I presents a summary of the Reviver Project assessment considering the UFS criteria. Other actions include an intersectoral plan for the homeless population, a program for waste pickers of recycling materials, cultural programs for creative economics, fire prevention for historical buildings, greening of parks and so on.

Table 3 – Analysis of an urban health action according UFS (Roue-Le Gall *et al.*, 2014): low emissions zone in downtown Rio de Janeiro city.

Axe 1 – control of emissions, annoyance reduction and its cumulative effects	This is the main goal of the Low Emissions Zone (LZE) of the Reviver Project. The project will discourage fossil fuel vehicles and expand cycling routes. This measure will reduce not only GHG emissions but also local atmospheric pollution and noise.
Axe 2 – promotion of healthy behaviour and physical activity of the population.	Active mobility is a priority for the project. Plans for the expansion of cycling routes. Also, actions for green areas.
Axe 3 – contribution to the improvement of the economy and social environment.	A new economic profile will emerge with services and stores for family consumption. Cultural and Green spaces will also be a gathering opportunity for social cohesion.
Axe 4 – reduction of social and environmental health inequalities.	Some actions focus on the reduction of inequalities, including affordable housing and reductions in transportation costs for poor communities, students, and retired people.
Axe 5 – management of antagonisms and fostering of synergies.	New habits, such as walking instead of driving, and the lack of car parking, will result in conflicts. The project must pursue population engagement to avoid confrontation. Health and climate literacy can make an important contribution.

Source: The authors

According to the concept of Urbanism Favourable to Health – UFS, the final analysis of urban projects should be conducted along five axes, as shown in Table 3. All five axes have applicability to the Reviver Project. The main goal of the Low Emission Zone is GHG mitigation (axis 1). Health Promotion (axe 2) is a Public Health strategy that has the potential to change harmful habits and promote healthier behaviour. The Reviver Project mentions economic development, focusing on reducing inequality (axes 3 and 4), though the sources of investment are unclear. Finally, axis 5 will demand a strong political effort and citizen participation.

6 DISCUSSION

This paper applies an urban health determinant approach to evaluate how Climate Action Plans of Rio de Janeiro City address human health. Results show that these plans have evolved to a more comprehensive and inclusive design that considers multiple aspects of health in accordance with selected criteria. The criteria suggested by the Urban Health Determinants (Roue-Le Gall *et al.*, 2014) served as the basis for the analysis, providing a robust approach to guide urban planners and other stakeholders in integrating a human health perspective into climate planning and action. Furthermore, it can support decision makers in promoting an effective transformation of the RJC downtown area. Moreover, other cities that are fostering climate adaptation in urban environments can apply this approach.

RJC2021 has several mentions of Urban Spaces, Security, Social Cohesion, and Habitat, suggesting a broader vision that includes urban determinants not directly related to human health. Reviver Project is one of the actions planned in RJC2021 that aims to requalify the old downtown area. It presents an opportunity to emphasise the importance of integrating health into CC plans. It includes a Low Emissions Zone that could have a significant impact on GHG mitigation and pollution reduction, potentially creating a better environment for individuals with allergies, cardiovascular and respiratory diseases. The project includes actions for the homeless population living in the downtown area and for the social inclusion of waste pickers, reflecting its concern for vulnerable populations. Reviver represents a paradigm shift in lifestyle: from car-based transportation to active mobility, a 15-minute city. However, the project does not specify the necessary adaptations for vulnerable populations such as children, older people, and people with disabilities.

The plans include some of the health determinants but neglect or rarely mention others. There is an opportunity to integrate health into CAPs to enhance citizens' quality of life. This way, all actions will

take into account the vulnerability and adaptive capacity of populations. Therefore, CAPs must align with Master Plans, Building Codes, and, most importantly, Municipal Health Plans.

For each urban health determinant, the plan must identify populations' vulnerabilities and focus actions on them. The plan must address specific issues so the support does not break down. To avoid this, the plan should organise intersectoral group meetings throughout the project with popular participation. The plan must also develop and analyse vulnerability indicators for every climate action. Territorial inequalities demand local analysis and reinforce the need to identify specific vulnerabilities at the local level, since informal settlements and low-income neighbourhoods are more vulnerable (Muñoz-Pizza *et al.*, 2023). Local actors should implement climate vulnerability assessment at the local level (Kim; Jung, 2023).

Given the need for integrated action to address environmental crises, the three branches of government (executive, legislative and judiciary) in Brazil signed a pact with the objectives of promoting sustainable cities, reducing the environmental impact of productive activities, and reducing greenhouse gas emissions in all sectors of the economy, among other topics (Brasil, 2023).

More recently, in June 2024, Brazil issued a new law establishing Guidelines for the Elaboration of Adaptation Plans (Brasil, 2024). The law reinforces the coordination of adaptation investments based on people's vulnerability and the need to articulate among federal, state, local, and socioeconomic sectors, while considering popular participation. It emphasises the need to harmonise methodologies for risk and vulnerability analysis, and for the identification and prioritisation of adaptation measures. Lobo *et al.* (2023) also suggested such integration to develop the knowledge of urban science and climate. Also, the guideline suggests that urban infrastructure and the right to the city should be a priority for climate change adaptation plans that pursue inequality reduction, aligned with other sector policies and urban plans.

In this sense, a strong connection must be established between CAPs and other urban plans, such as the Municipal Master plan, Transportation plan, Health plan, and others, to ensure effective coordination with the agendas of social, political, and economic stakeholders, as suggested by NAP Cities 2026. Monitoring and evaluating adaptation actions can generate valuable data and insights for society, using indicators such as those outlined in Agenda 2030. This can also help identify and reduce existing inequalities while preventing the emergence of new ones that could result from climate interventions.

The Rio de Janeiro Municipal Health Plan (PMRJ, 2022b) highlights the importance of social determinants and the need to combat health inequalities. It considers actions connected to the RJC2021 adaptation plan, such as reducing road injury fatalities. Also, it has Health Promotion actions, such as physical activity programs, in 202 health units.

Notably, institutions such as ICLEI (Local Government for Sustainability), C40 (Global Network of Mayors), and local academic institutions supported the development of the municipal plan RJC2021. These networks have been playing an important role in encouraging cities to adopt climate policies and in guiding their implementation (Rashidi; Patt, 2018).

In this application of Content Analysis, we used predefined categories based on Urbanism Favourable to Health, an approach developed at EHESP - France, which established urban health criteria following a three-year project that included several intersectoral sectors. Nonetheless, we acknowledge that our methodology has limitations. These criteria might be more or less appropriate for a developing country in a tropical region, a phenomenon denominated validation in Content Analysis (Dalla Valle; Ferreira, 2025). But the UFS approach is being applied in other countries, such as the Republic of Georgia in Eastern Europe, so we are confident that it is not restricted to France.

Reliability is also a common limitation in Content Analysis. Therefore, the reliability of a Content Analysis is high when other researchers obtain similar results using the same procedures and coding for the same material (Sampaio; Lycarião, 2018). In this article, the three authors counted the categories separately after semantic training and consensus interpretation, thereby performing triangulation.

Another limitation is that the frequency criterion does not always reflect a topic's importance. (Dalla Valle; Ferreira, 2025). Indeed, in our analysis, we do not compare the absolute frequencies of the CAPs, but rather the evolution of the criteria over time and the relevance of each criterion for each CAP.

Overall, the methodology used in this article can help stakeholders develop and elaborate municipal plans that consider urban health issues. This is an innovative approach to a city-level climate plan and should be applied and improved in other cities and contexts. One of the characteristics of AC is that it reduces the complexity of a collection of texts; systematisation by urban health criteria can refine extensive documents, allowing for shorter analysis time. Also, it should be noted that the methodology is replicable in other cities within diverse urban contexts.

7 CONCLUSION

This article applied the Urbanism Favourable to Health (UFS) approach to analyse how the Climate Action Plans of Rio de Janeiro City integrate health. EHESP – France developed the UFS approach based on the health determinants and health promotion principles of governance, health literacy, adequate environments, and popular participation. Overall, the climate plans under analysis address several issues recommended by UFS. The approach could be applied more comprehensively across all adaptation actions. This action would minimise the risk of maladaptation while protecting vulnerable populations.

In fact, Climate Action Plans should be tailored to the specific needs of local contexts. Furthermore, capacity building for the planning team should include developing a health-oriented vision. For the same tasks, health professionals need to receive training to recognise and respond to the potential health impacts of climate change. The UFS approach can serve as a valuable guide in the design and evaluation of climate action plans, helping to reduce climate impacts, promote benefits, and enhance the quality of human life in urban areas.

Based on our findings, we recommend adopting a health determinants approach in the development and evaluation of climate action plans. This can help minimise health risks and prevent maladaptation, improving population health. We also suggest further research to identify climate change vulnerability at a very local level. In this way, planned actions can reduce climate change impacts and enhance knowledge of the urban determinants of health in the context of climate change, in line with the PAHO statement that "Public Health must be the central axis of the response to climate change".

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

MGA: Conceptualisation, Methodology, Data Curation - Writing - Original draft preparation. VSS: Visualisation, Investigation, Data curation. LBEV: Data curation - Writing - Reviewing and Editing.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors declare that no generative AI or AI-assisted technologies were used in the creation, writing, or editing of this manuscript.

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Climate change projections and impacts on raw water quality in the Paraíba do Sul River basin, Southeast Brazil

Projeções de mudanças climáticas e seus impactos na qualidade da água bruta na Bacia do Rio Paraíba do Sul Paulista

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ABSTRACT

This study aims to assess recent trends in water quality indicators in the Paraíba do Sul River Basin in the state of São Paulo and to analyse the influence of climate change on these parameters. A comparative analysis between future projections and a historical reference scenario reveals that climate variability plays a significant role in water quality. Additionally, the findings indicate a decline in water availability, particularly under high-emission scenarios, underscoring the urgency of mitigation and adaptation measures to ensure water security in the region.

Keywords: Regional climate models. Future scenarios. Water resources. Water security.

RESUMO

Este estudo tem como propósito avaliar a evolução dos indicadores de qualidade da água na Bacia do Rio Paraíba do Sul paulista ao longo dos últimos anos, bem como investigar os efeitos das mudanças climáticas sobre esses parâmetros. A análise comparativa entre projeções futuras e um cenário de referência revela que as variações climáticas estão associadas a alterações nos indicadores de potabilidade da água. Ademais, os resultados indicam uma tendência de redução da disponibilidade hídrica, sobretudo em cenários de maior emissão de gases de efeito estufa, o que evidencia a necessidade de ações voltadas à mitigação e à adaptação para garantir a segurança hídrica da região.

Palavras-chave: *Modelos climáticos regionais. Cenários futuros. Recursos hídricos. Segurança hídrica.*

1 INTRODUCTION

Climate change is likely to generate profound impacts on ecosystem health, the global economy, and the daily lives of populations. It is widely recognised as one of the main contemporary environmental challenges. Among the sectors most vulnerable to these transformations is the water resources sector, which faces direct consequences for both water quality and availability (IPCC, 2021; Prado, 2024). Previous studies have shown that changes in the physicochemical properties of water, influenced by climatic and hydrological factors, can compromise not only natural systems but also the water security of human societies (Amâncio; Cataldi, 2019; Cravinho *et al.*, 2004).

Extreme climate events, such as rising temperatures and variations in precipitation patterns, directly affect the quality and availability of water resources worldwide (Prado, 2024). According to the Intergovernmental Panel on Climate Change (IPCC, 2021), the frequency of these events has increased significantly, placing additional pressure on basic sanitation systems and water supply infrastructure. Recent examples include the 2014 water crisis in Brazil, which had major impacts on water, energy, and food security (Canamary *et al.*, 2023; Nobre *et al.*, 2016).

In the case of the Paraíba do Sul River Basin, several studies have indicated that the basin is highly vulnerable. Amâncio and Cataldi (2019) warn that, from the 2070s onward, there is a clear trend toward reduced streamflows in the basin, regardless of the climate scenario analysed. Therefore, understanding variations in water quality and the challenges associated with water treatment is essential for formulating effective management strategies to ensure access to safe drinking water for the population. To this end, climate models from the National Institute for Space Research (Inpe) were used, including EtaHadGEM2-ES, EtaMIROC5, and EtaCanESM2, to project future scenarios and assess potential impacts on water quality in the basin. Moreover, projected climate changes pose not only technical challenges but also financial impacts on treatment systems.

Previous studies support these projections (Delpla *et al.*, 2009; Whitehead *et al.*, 2009), indicating that climate change tends to degrade surface water quality, thereby increasing the challenges for conventional treatment. These changes may require investments in treatment technologies, monitoring, and operational control.

Climate change increases the operational costs of water treatment systems due to the greater demand for chemical inputs and the adoption of advanced technologies, such as membrane filtration. In addition, structural investments are required in modernisation, automated monitoring, and technical capacity building (Vörösmarty *et al.*, 2010). Incorporating climate risk into financial planning for sanitation systems becomes essential, given the direct and indirect impacts on public health, the environment, and the regional economy (Organisation for Economic Co-operation and Development – OECD, 2018).

Climate change is one of the most pressing contemporary environmental problems, with profound impacts on ecological health, the global economy, and people's lives. These changes have an impact.

Among the sectors most vulnerable to them are water resources, with direct consequences for both water quality and availability (IPCC, 2021; Prado, 2024). The physicochemical properties of water, which vary with climatic and hydrological factors, could jeopardise natural systems and human societies' water security (Amâncio; Cataldi, 2019; Cravinho *et al.*, 2004).

Certain extreme climate phenomena (temperature rise, changing precipitation patterns, etc.) affect water resources globally, directly impacting quality and access (Prado, 2024). Moreover, according to the Intergovernmental Panel on Climate Change (IPCC, 2021), these episodes are becoming increasingly frequent, placing greater strain on basic sanitation facilities and water supply systems. For example, a severe case that has been highlighted recently and is similarly important is the 2014 water crisis in Brazil, with dire implications for water, energy, and food security (Canamary *et al.*, 2023; Nobre *et al.*, 2016).

The Paraíba do Sul River Basin has a high hydrologic vulnerability. Amâncio and Cataldi (2019) caution that, from the 2070s onward, streamflows in the basin have fallen sharply, regardless of the climate scenario examined. Therefore, understanding variations in water quality and the challenges associated with its treatment is essential to designing effective, sustainable management strategies to ensure potable water is within reach for the populace. To this end, climate models from the National Institute for Space Research (Inpe) were used: EtaHadGEM2-ES, EtaMIROC5, and EtaCanESM2, to predict future scenarios and determine the probable impacts on water quality in the basin.

Some of the projected changes may be challenging. In the future, technological issues and financial hardship will arise with water supply and treatment systems. The simulations in this paper suggest that elevated climate variability—especially under more extreme warming scenarios such as the Representative Concentration Pathway 8.5 (RCP 8.5)—is directly linked to declines in water quality parameters, including turbidity, ammonia (NH_3–N), pH, and colour. These projections are consistent with prior investigations (Delpla *et al.*, 2009; Whitehead *et al.*, 2009), which show that climate change more commonly leads to decreased surface water quality and more difficult treatment for conventional solutions. The changes would likely require investment in treatment technologies, monitoring, and operational controls.

The operational costs of water treatment systems are increasing due to increased demand for chemical inputs and the adoption of innovative technologies, such as membrane filtration. Cost increases of up to 20% are based on climate-stress estimates (United Nations World Water Development Report, 2022; Water Environment Federation, 2023). Moreover, structural investments will be needed in modernisation, automated monitoring, and technological capacity development (Vörösmarty *et al.*, 2010). "Integrating climate risk into a financial planning framework for sanitation systems becomes crucial because it has direct and indirect influences on public health, the environment, and the regional economy" (Organisation for Economic Co-operation and Development – OECD, 2018).

2 STUDY AREA

This study focuses on the São Paulo portion of the Paraíba do Sul River Basin, located approximately between 22°00'S and 23°30'S latitude and 44°00'W and 45°52'W longitude, encompassing the Paraíba Valley in the State of São Paulo. The Mantiqueira Mountain Range bounds this region to the north, and the Serra do Mar to the south, extending from the headwaters of the Paraíba do Sul River—formed by the confluence of the Paraibuna and Paraitinga rivers—to the border with the State of Rio de Janeiro. The Paraíba do Sul River Basin has a drainage area of approximately 55,500 km², spanning the states of São Paulo (13,900 km²), Rio de Janeiro (20,900 km²), and Minas Gerais (20,700 km²). It is bounded to the north by the Grande and Doce river basins and by the Mantiqueira, Caparaó, and Santo Eduardo mountain ranges.

To the northeast, the basin is limited by the Itabapoana River; to the south, by the Serra dos Órgãos and Serra do Mar; and to the west, by the Tietê River basin, separated by branches of the Serra do Mar and Mantiqueira ranges. The Paraíba do Sul River is formed by the confluence of the Paraibuna and Paraitinga rivers and has a total length exceeding 1,100 km (National Water Agency, 2011).

Figure 1 below presents the spatial extent of the São Paulo portion of the Paraíba do Sul River Basin.

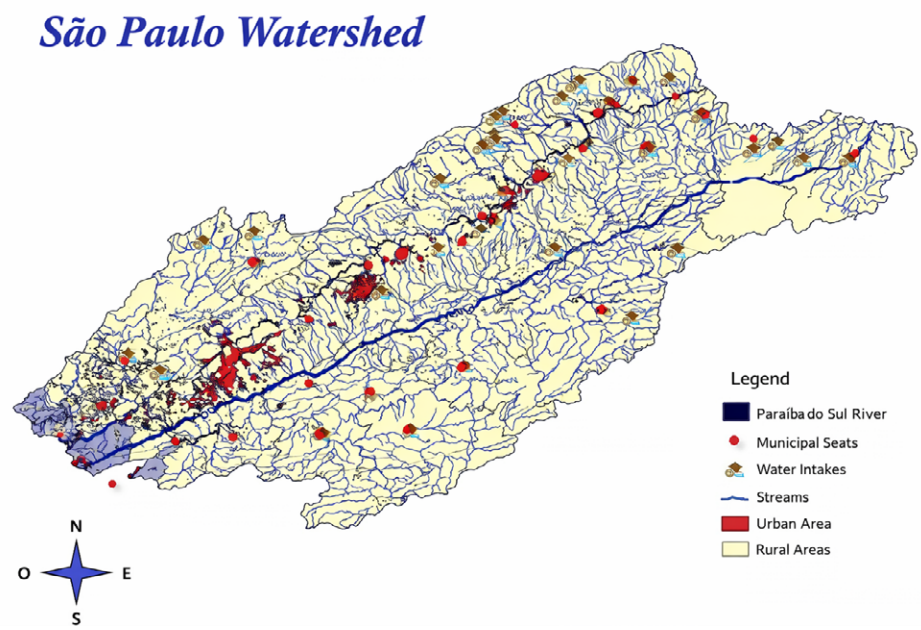


Figure 1 – São Paulo portion of the river basin considered in this study, indicating municipal centres, water intake points, the Paraíba do Sul River, and urban and rural areas.

Source: Prepared by the authors (2025).

3 METHODOLOGY

The integrated methods, combining climate models, hydrological modelling, and machine learning, used in the current work evaluated the effects of climate change on water-quality proxies in the São Paulo portion of the Paraíba do Sul River Basin.

Climate models are numerical approximations based on physical equations. They are employed to simulate, in a detailed (and computationally sound) way, the fundamental processes that regulate the Earth's climate system, including interactions among the atmosphere, oceans, land surface, and biosphere. These models integrate basic physical principles, including conservation of mass, energy, and momentum, to represent climate dynamics at different spatial and temporal scales (IPCC, 2021). From each of these simulations, it is possible to project future changes in important meteorological variables, such as temperature, precipitation, and solar radiation, which can be used to calculate expected environmental and hydrological effects of climate change.

Climate models can be divided into two types: Global Climate Models (GCMs) and Regional Climate Models (RCMs). GCMs are large-scale models of the Earth's atmosphere that simulate constant global atmospheric circulation, ocean dynamics, and interactions among different parts of the system. These models often provide only coarse spatial resolution for regional or local-scale analyses, and they still have limitations. Regional Climate Models provide valuable insights into regional variation and have been shown to address this limitation by leveraging climate downscaling to refine global projections spatially at finer spatial scales. Utilising this method allows for more representative, regionally reflective

climate projections in regions where dynamic topography and hydrology intersect, such as river basins (Almagro *et al.*, 2020).

The regional climate model Eta is widely used in Brazil to downscale global climate scenarios. The regionalised climate projections from Eta offer higher spatial resolution, enabling more nuanced insights into the impacts of climate change on hydrological and environmental systems. Herein, projections were extracted from Global Climate Models (GCMs) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and then downscaled utilising the Eta model.

The selected models—HadGEM2-ES, MIROC5, and CanESM2—are recognised for representing climate variability and greenhouse gas emissions, known for their ability to capture diverging climate variability patterns. These models simulate climate trajectories under different greenhouse gas concentration scenarios, called Representative Concentration Pathways (RCPs).

The regionalised climate projections were used as inputs to the MHD-INPE hydrological model (e.g., precipitation, infiltration, evapotranspiration, surface runoff, groundwater flow). The MHD model is based on physical and mathematical concepts that enable the simulation of hydrological dynamics in the watershed system and provide a valuable reference for water resource availability and environmental conditions (Paiva *et al.*, 2023).

To study how climatic influences affect water quality systems of the Paraíba do Sul River, climate models and hydrological models, along with computer methods based on machine learning studies, could be integrated to conduct a combined investigation, along with an analysis of the downstream potential for a climate-variable impact of climate change on regional water resources. Indeed, although climate simulation methods are commonly used in environmental modelling, they are inherently limited because they must be overly simplified to represent the complex climate system. Climate projections are subject to different sources of uncertainty, arising from:

- Structural limitations of the models, related to the representation of atmospheric and oceanic processes.
- Differences among global climate models in simulating climate variability.
- Uncertainties associated with future greenhouse gas emission scenarios (IPCC, 2021).

Another important source of uncertainty is related to the climate downscaling process, which applies regional constraints to global estimates using boundary conditions derived from global models (e.g., the Eta climate model). In this context, any errors or biases in global models may be propagated and reflected in scale. In some cases, microscale spatial resolution may fail to capture important local processes, such as intense convective events and hydrological variability.

Due to these limitations, the use of multiple climate models—such as those adopted in this study (HadGEM2-ES, MIROC5, and CanESM2)—is widely regarded in the scientific literature as a common strategy to reduce overreliance on a single model and enhance the robustness of climate projections. This approach allows evaluating the sensitivity of results to different representations of climate processes, enabling a more comprehensive analysis of current and future scenarios (Almagro *et al.*, 2020; IPCC, 2021).

3.1 CLIMATE CHANGE SCENARIOS

HadGEM2-ES, MIROC5, and CanESM2 were selected as the climate models for this study. The selection of these models was based on their established reliability and high ability to simulate a broad spectrum

of future climate scenarios (Almagro *et al.*, 2020). Among climate models, the HadGEM2-ES model from the Met Office Hadley Centre provides a particularly detailed and comprehensive representation of potential future climate changes. Conversely, MIROC5, developed by the Japan Agency for Marine-Earth Science and Technology, and CanESM2, developed by the Canadian Centre for Climate Modelling and Analysis, offer distinct approaches and perspectives for analysing climate phenomena. The integration of these three models made a comparison. It led to a better understanding of how climate change affects the water quality of the Paraíba do Sul River, as well as environmental factors and society (Rodrigues, 2022).

3.2 WATER TEMPERATURE SIMULATION

The calculation of water temperature is based on the principle of thermal equilibrium (Edinger *et al.*, 1968). This formulation has been widely used in several hydrological models, such as CE-QUAL-W2 (Cole; Wells, 2006) and MIKE SHE (Dhi, 2017), owing to its simplicity and numerical stability.

In the case of uniform temperature, where spatial gradients are equal to zero, the one-dimensional heat transport equation (Equation 1) can be expressed as:

$$\rho_w c_{pw} \frac{dTw}{dt} = \frac{q_{net}}{depth} \qquad (1)$$

Where ρ_w is the water density; c_{pw} is the specific heat of water; q_{net} is the net surface radiation; T_w is the water temperature; and $depth$ is the water depth.

Net radiation is composed of fluxes from several physical processes: net solar radiation; atmospheric longwave radiation; longwave radiation emitted by the water surface; evaporative heat flux; convective heat flux; and precipitation heat flux. Among these components, the most significant contribution corresponds to the net solar radiation term q_{atm}. Therefore, the previous equation can be simplified as:

$$\rho_w c_{pw} \frac{dTw}{dt} = \frac{q_{atm} + \varepsilon_q}{depth} \qquad (2)$$

Where ε_q is a parameter that incorporates the remaining radiation terms.

Edinger *et al.* (1968) defined the equilibrium temperature as the water temperature at which the net atmospheric heat flux () equals q_{atm}) is equal to zero. Under these conditions, the radiation balance can be expressed as:

$$q_{atm} = K(Te - Tw) \qquad (3)$$

Where T_e is the equilibrium temperature and K is the overall surface heat exchange coefficient. The total surface heat exchange coefficient, K, can be calculated using Edinger's empirical equations. K is a function of water temperature, dew point temperature T_{dew}, and wind speed , expressed as:

$$K = 4.48 + (\beta + 0.47) f_w + 0.05Tw \qquad (4)$$

Where:

$$f_w = 9.2 + 0.46w^2$$

$$\beta = 0.35 + 0.015\left(\frac{Tdew + Tw}{2}\right) + 0.0012\left(\frac{Tdew + Tw}{2}\right)^2$$

$$Te = Tdew + \frac{S}{K} + \varepsilon_t \qquad (4)$$

Where S is the incident shortwave radiation, and ε_t is an adjustment parameter. By combining the two previous equations, the following expression is obtained:

$$\rho_w c_{pw} \frac{dTw}{dt} = \frac{K(Te - Tw) + \varepsilon_q}{depth} \qquad (5)$$

By integrating over the time interval, we obtain:

$$Tw_{t+\Delta t} = Te\left(1 - e^{-\frac{Kt_{res}}{\rho_w c_{pw} depth}}\right) + Tw_{in,t} e^{-\frac{Kt_{res}}{\rho_w c_{pw} depth}} + \frac{\varepsilon_q}{K}\left(1 - e^{-\frac{Kt_{res}}{\rho_w c_{pw} depth}}\right) \qquad (6)$$

Where T_w in represents the heat input from adjacent cells. This equation is very similar to that presented by Bogan *et al.* (2004).

3.3 PYTHON SIMULATION USING THE HISTGRADIENTBOOSTINGREGRESSOR MODEL

We employed the HistGradientBoostingRegressor algorithm from the scikit-learn library to estimate physicochemical parameters of water in the Paraíba do Sul River using Python for the analysis.

Predictor variables were climatic and hydrological indicators, including air temperature, precipitation, and streamflow, whereas response variables were key water quality indicators, namely pH, turbidity, apparent colour, and ammoniacal nitrogen (NH_3–N).

The datasets used to train the models were time series; these data were recorded and saved by official institutions such as the National Institute for Space Research (Inpe), the National Water and Sanitation Agency (ANA), and the National Institute of Meteorology (Inmet). This model provided quantitative insights into the climatic and hydrological impacts on water quality parameters, generating data applicable to predict future scenarios under climate change.

Recent work validates that model building using machine learning is effective when applied in the same field. Khan *et al.* (2021) used Principal Component Regression (PCR) combined with the Gradient Boosting algorithm to predict and classify water quality, achieving 95% and 100% accuracy in estimating the Water Quality Index (WQI) based on variables such as pH, turbidity, and dissolved oxygen (DO).

Similarly, Manikandan *et al.* (2024) showed that Gradient Boosting algorithms can achieve high accuracy in estimating the WQI using 20 physicochemical characteristics of water samples. The authors highlight a direct link between water quality degradation and associated risks to water security.

In this context, Wang *et al.* (2017) proposed a Support Vector Regression (SVR) method to predict the Water Quality Index (WQI), achieving over 90% accuracy using 22 input variables.

The prediction of water quality will be based on multidimensional data and complex relationships among environmental and chemical variables (as demonstrated by the HistGradientBoostingRegressor model).

3.4 WATER QUALITY SCENARIOS

For the development of land use and land cover maps, the study by Rezende *et al.* (2018) was adopted, which outlined three future scenarios for land use and occupation changes between 2010 and 2050. This study emphasised transitions among forestry, forest, and pasture categories. These projections were later refined by Paiva *et al.* (2023), who incorporated urban expansion into the model.

Additionally, the scenarios proposed by Rezende *et al.* (2018) were further refined by incorporating assumptions about water demand behaviour for both human supply and industrial use, resulting in Optimistic, Pessimistic, and Current scenarios (Canamary *et al.*, 2023).

In the present study, water quality information was incorporated into these scenarios, considering the following parameters: water temperature (°C) and air temperature (°C) as physical variables; phosphorus (mg/L), biochemical oxygen demand – BOD_5 (mg/L O_2), pH (pH units), turbidity (NTU), and dissolved oxygen – DO (mg/L) as key physicochemical indicators. The scenarios were structured across three time horizons: Historical, Current, and Future. For the Current and future periods, three projected scenarios were considered: Optimistic, Pessimistic, and Current.

- Historical Period: 1976 to 2015.
- Current Period: 2016 to 2035.
- Future Period: 2036 to 2055.

a) Optimistic Scenario (O): A major rise in participation in the public water supply services, as well as a decrease in the per capita water use, considering a rise in public awareness in conserving water resources.

b) Pessimistic Scenario (P): Reflects enhanced access, even though per capita water demand is going up.

c) Current Scenario (A): As per the consumption and land use profiles found hitherto. The study by Martins *et al.* (2023) is extended to this model as well, with consideration of agricultural water consumption in the Paraíba do Sul River Basin in the São Paulo region. Also, both RCP 4.5 and RCP 8.5 models were developed to estimate greenhouse gas emissions, as they represent the two scenarios used to determine possible climate outcomes (Martins *et al.*, 2023).

4 RESULTS

The results of the executed modelling were presented graphically, supported by numerical tables and comparisons over the decades studied. The analysis enabled verification of the progressions, inclusions, and exclusions of each parameter in the treatment of raw water over the years analysed.

To confirm the model's accuracy, a comparative statistical analysis was performed between the data measured during raw water treatment processes (historical data, referred to as the Baseline) and the data simulated by the hydrological model.

4.1 AIR AND WATER TEMPERATURE

Projections from the CAM, MIROC, and HADGEM climate models indicate a progressive increase in air temperature across municipalities in the state of São Paulo between 2035 and 2055. The baseline

scenario (Baseline) presents the lowest medians, with values concentrated between 21 °C and 22 °C for all three models. In 2035, temperatures show a slight increase compared to historical data, with minimal differences among the scenarios (current, optimistic, and pessimistic). By 2055, a more pronounced increase is observed, with pessimistic scenarios indicating the highest median values, suggesting a clear warming trend. Below is a graph, along with an analysis that includes descriptive statistics, variance, and Tukey's test.

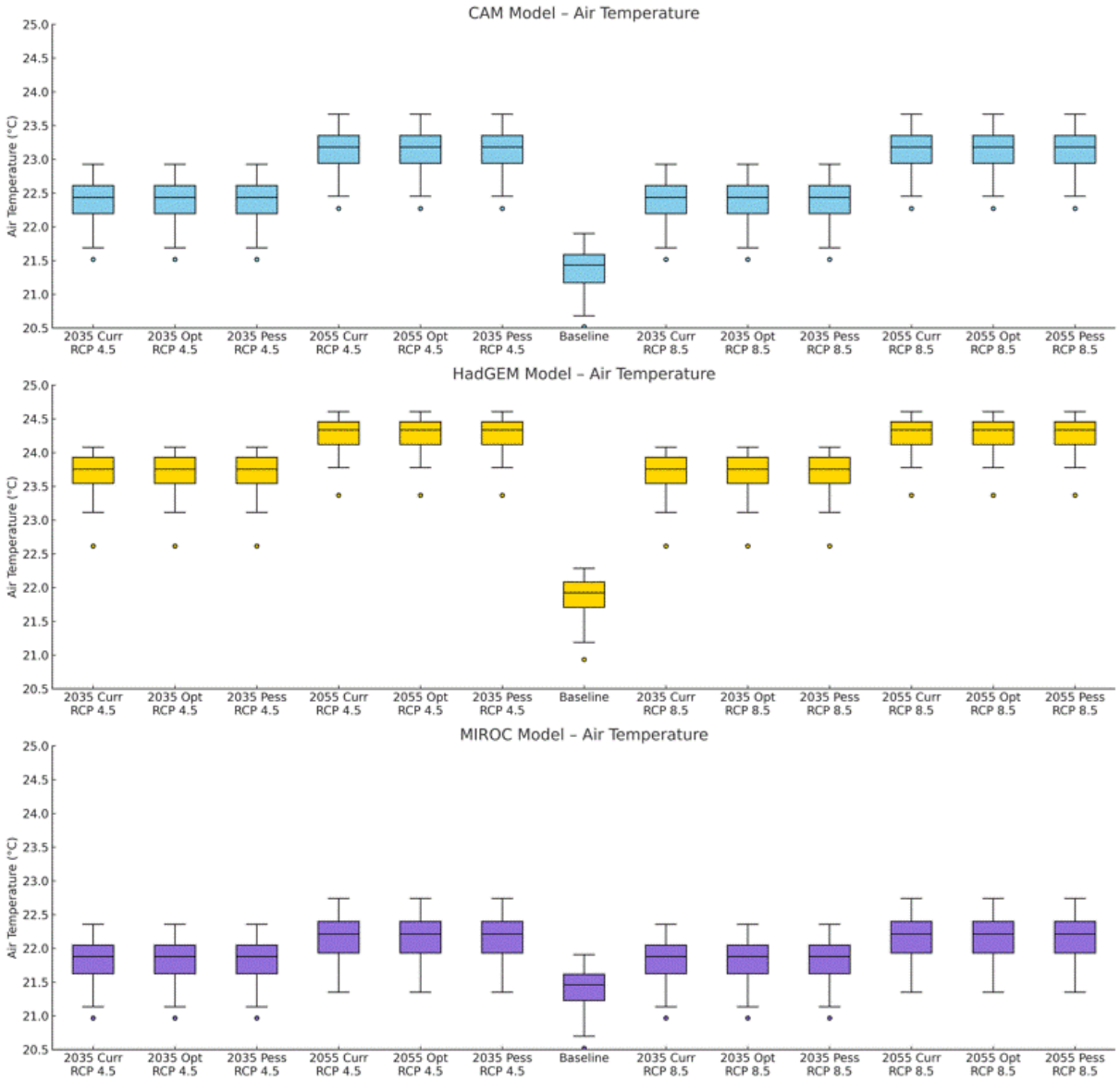


Figure 2 – Air temperature projections based on regional climate models (Eta–CMIP5).

Abbreviations: Curr= Current, Opt=Optimistic, Pess = Pessimistic

Source: Prepared by the authors (2025).

After conducting a post hoc analysis, we observed statistically significant differences across all climate models, underscoring the importance of multiple approaches to forecasting future climate scenarios. Projections for 2035 and 2055 indicate gradual increases in water temperature relative to the baseline scenario. Differences between scenarios in 2035 are small, but in 2055, there is a greater rise in temperature, most notably under the pessimistic scenario (RCP 8.5), which shows greater climate pressure and possibly other impacts on the water system.

Table 1 – Statistical analysis for the air temperature parameter

Descriptive statistics for the air temperature parameter				
Climate Model	*Mean Temperature (°C)*	*Mean Standard Deviation*	*Mean Range*	*Observations*
CAM	22,644	0,342	1,402	Moderate variability among scenarios.
HADGEM	23,809	0,3	1,352	Slightly lower variability compared to the CAM model.
MIROC	21,941	0,35	1,391	Variability comparable to the CAM model.
Air Temperature Among Scenarios Within Each Model				
Climate Model	*F-Statistic*	*p-Value*	*Statistical Significance*	*Interpretation*
CAM	83,52	< 0,0001	Yes	Statistically significant differences among the model scenarios.
HADGEM	161,21	< 0,0001	Yes	Marked statistical differences among the simulated scenarios.
MIROC	15,72	< 0,0001	Yes	All scenarios exhibited statistically significant variations.
Tukey's Test for Comparison of Mean Air Temperature Among Models				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HadGEM	+1,1649	< 0.001	Yes
CAM	MIROC	−0,7030	< 0.001	Yes
HadGEM	MIROC	−1,8679	< 0.001	Yes

Source: Prepared by the authors (2025).

The thermal behaviour of water follows, in an attenuated manner, the pattern observed for air temperature, reflecting the coupling between the atmosphere and the water surface. In future scenarios, the medians increase slightly, and the thermal amplitude expands under the pessimistic scenarios for 2055. These observations can be verified in Figure 3 below:

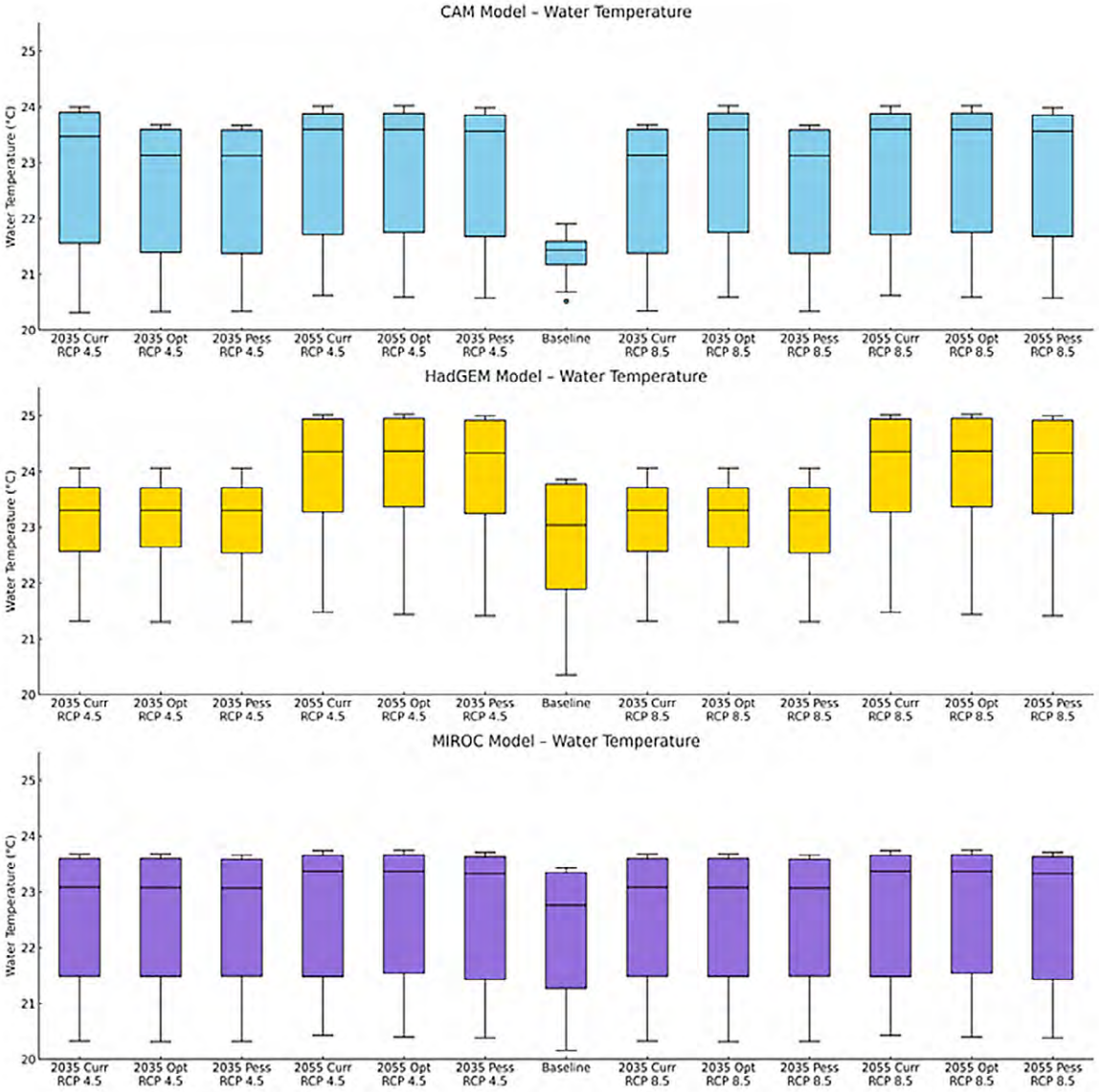


Figure 3 – Water temperature projections estimated by the MHD-INPE hydrological model.
Abbreviations: Curr= Current, Opt=Optimistic, Pess = Pessimistic
Source: Prepared by the authors (2025).

The statistical analysis of the Water Temperature parameter (Table 2) reveals distinct thermal patterns among the Eta-CamESM2, HadGEM, and MIROC climate models, reflecting structural differences in how these models represent energy exchange between the atmosphere and the water surface. The mean values ranged from 23.1 °C (MIROC) to 24.0 °C (HadGEM), with CAM presenting an intermediate value (23.5 °C). This difference of up to 0.9 °C between the extremes confirms the presence of a statistically significant inter-model thermal gradient.

Table 2 – Statistical analysis for the water temperature parameter

Descriptive statistics for the air temperature parameter				
Climate Model	*Mean Temperature (°C)*	*Mean Standard Deviation*	*Mean Range*	*Observations*
CAM	23,5	0,342	1,402	Moderate dispersion; considerable variability among scenarios.
HADGEM	24	0,3	1,352	Higher means than CAM; significant internal variability.
MIROC	23,1	0,35	1,391	Higher variability than HADGEM; homogeneous distribution.
Analysis of Variance (ANOVA) – Water Temperature Among Scenarios Within Each Model				
Climate Model	*F-Statistic*	*p-Value*	*Statistical Significance*	*Interpretation*
CAM	4,77	< 0,0001	Yes	Relevant statistical differences among model scenarios.
HADGEM	8,75	< 0,0001	Yes	big statistical differences among simulated scenarios.
MIROC	0,25	< 0,0001	No	No statistically significant differences.
Tukey's Test for Comparison of Mean Water Temperature Among Models				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HADGEM	+0,774	< 0.001	Yes
CAM	MIROC	- 0,084	>0.05	No
HADGEM	MIROC	-0,858	< 0.001	Yes

Source: Prepared by the authors (2025).

4.2 ESTIMATES OF WATER QUALITY PARAMETERS – PH, COLOR, TURBIDITY, AND NH_3

For the simulations presented, water and air temperature data were used as inputs, obtained from climate model simulations integrated with the hydrological model (MHD) and processed using Python. The graphs below present and analyse the four water quality parameters.

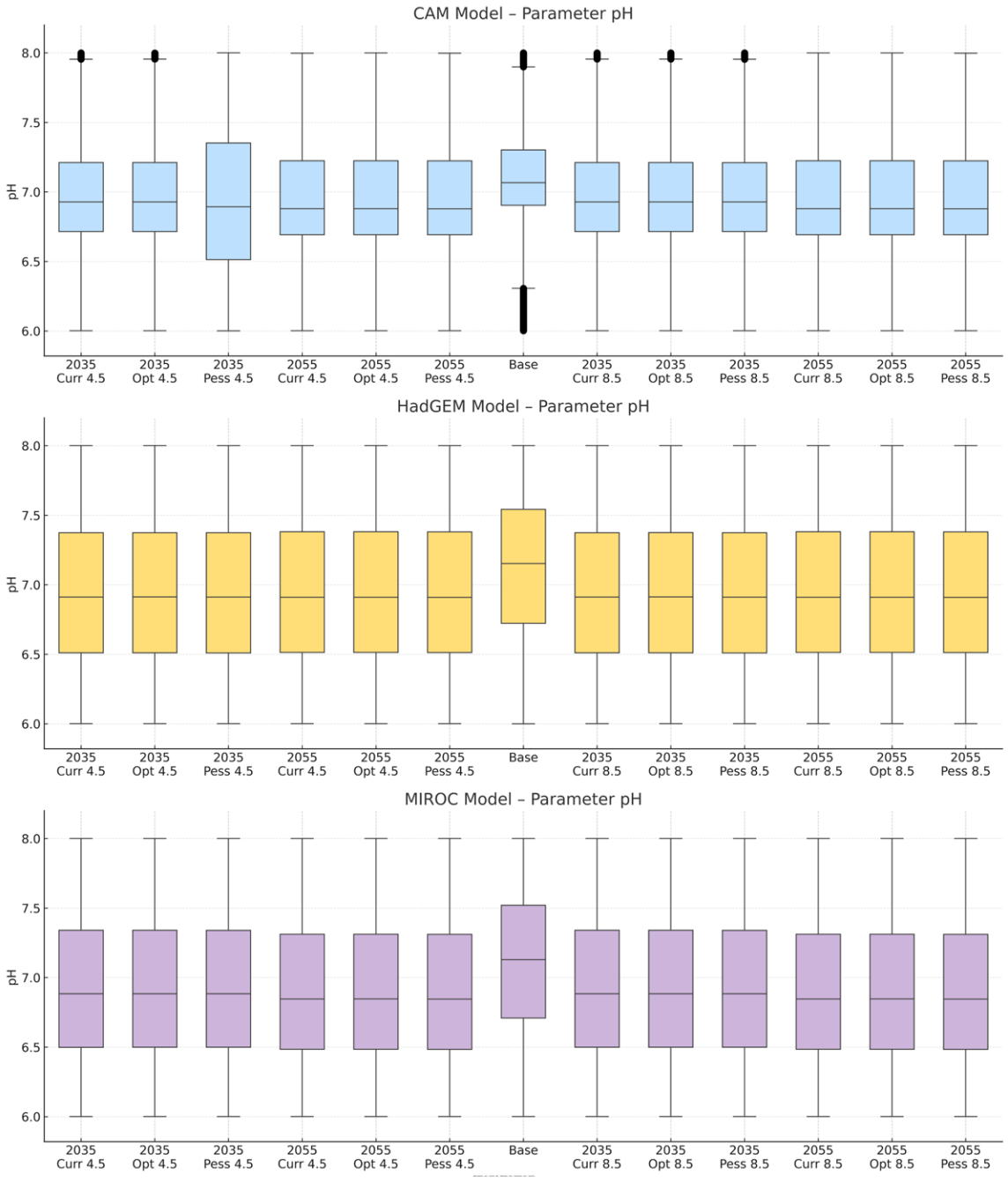


Figure 4 – Projections of water pH (Gradient Boosting) under climate variables (Eta–CMIP5) and hydrological variables (MH-D-Inpe) for 2035 and 2055.

Abbreviations: Curr= Current, Opt=Optimistic, Pess = Pessimistic

Source: Prepared by the authors (2025).

The graphics results for pH noted negligible differences. There remained near 7.0 as a means, indicating a neutral state in the absence of significant variation in any of the periods. Moderate variation was observed, as the CAM model generally had a pH between 6.7 and 7.7 across scenarios.

The pH observed in the 2055 scenarios is decreasing slightly, with a weaker trend toward outliers but no major outliers. The model indicates stable behaviour, though slightly more acidic in the future, at

least as the model anticipates. Overall, according to the analyses, HADGEM had the most stable pH projections among the climate models in these studies, with median values near 7, low variability, and no outliers (the lowest value of a significant extreme-out variable), suggesting a stable model of climate projections. Regarding trends, MIROC showed greater variability and a negative trend in pH values in the 2055 scenarios, particularly under the pessimistic scenario, indicating wider dispersion of projections. The general trend indicates a modest decrease in pH in 2055 between the MIROC and CAM cases, whereas HADGEM shows little change. No significant acidification occurred, except in the CAM model for the high-emission scenario (RCP 8.5). Statistical findings revealed differences between the models and underscored the importance of using multiple modelling strategies in environmental evaluations.

Table 3 – Statistical analysis for the water pH parameter

Descriptive statistics for the pH parameter				
Climate Model	*Mean Temperature (°C)*	*Mean Range*	*Observations*	
CAM	0,365	1,999	Low dispersion, values concentrated near neutrality.	
HADGEM	0,543	6,931	Extreme values influence greater dispersion.	
MIROC	0,536	6,858	Variability similar to HADGEM; presence of extremes.	
Analysis of Variance (ANOVA) – pH Among Scenarios Within Each Model				
Climate Model	*F-Statistic*	*p-Value*	*Statistical Significance*	*Interpretation*
CAM	1387,44	< 0,0001	Yes	Statistically significant differences; however, with a small effect size.
HADGEM	697,85	< 0,0001	Yes	Significant; very small effect magnitude.
MIROC	905,09	< 0,0001	Yes	Significant; reduced effect size.
Tukey's Test for Comparison of Mean pH among models				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HADGEM	+ 0,01451	< 0,001	Yes
CAM	MIROC	+ 0,04487	< 0,001	Yes
HADGEM	MIROC	+ 0,03035	< 0,001	Yes

Source: Prepared by the authors (2025).

Turbidity analysis revealed many significant outliers (that is, measurements far from the mean) in the turbidity parameter. As in the baseline scenario, the median turbidity is near 20; however, some samples are in the 80 range due to intense rainfall and runoff events.

In the 2035 interval (C, O, P), the median is slightly higher while the outliers remain significant. In the 2055 projections (C, O, P), the median rises slightly, indicating a higher rate of turbidity events. The extensive outliers and peaks in turbidity across all periods indicate that turbidity control remains a continuing problem, which may necessitate operational adaptations in the future (Figure 5).

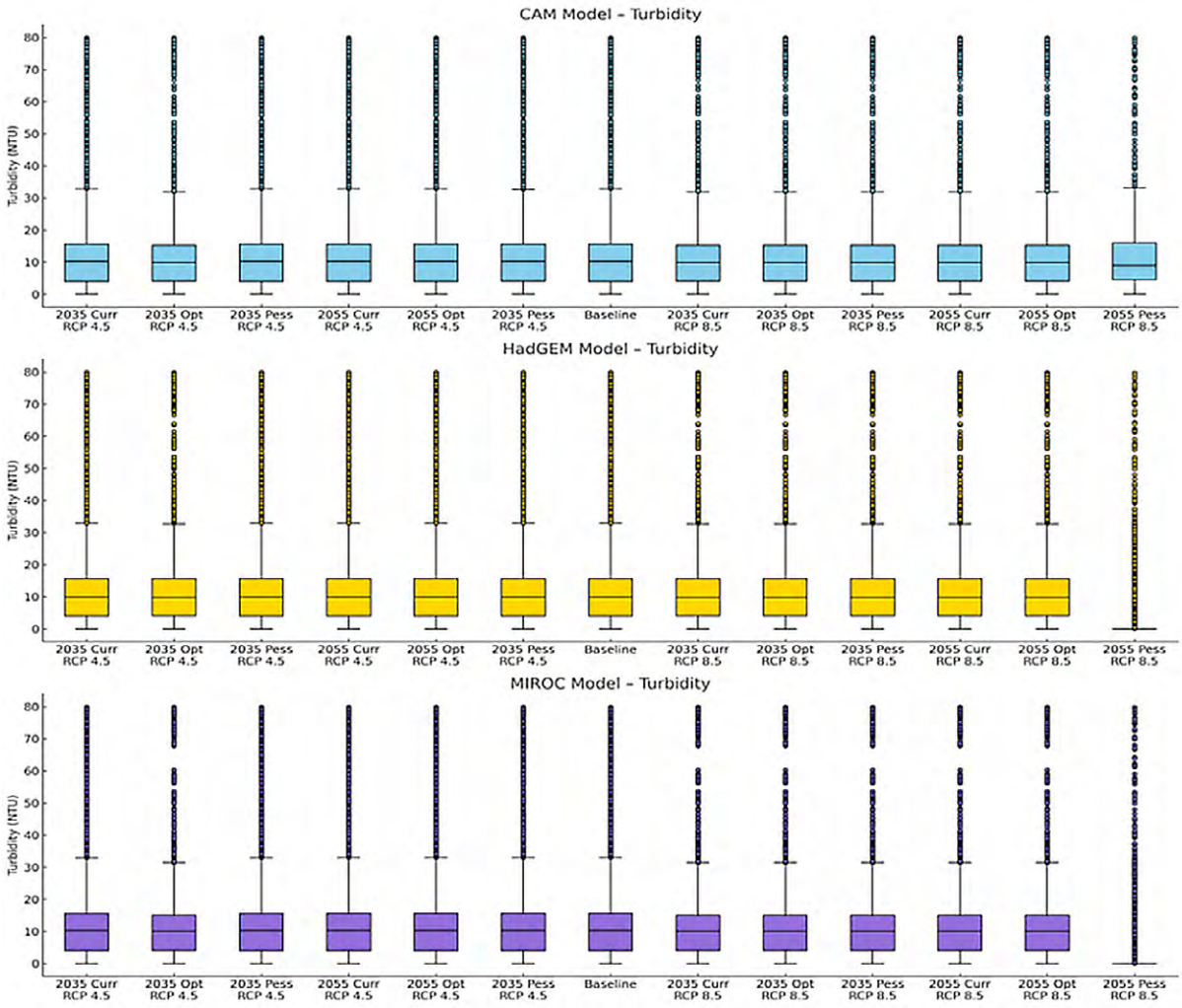


Figure 5 – Projections of water turbidity (Gradient Boosting) under climate variables (Eta–CMIP5) and hydrological variables (MHD-Inpe) for 2035 and 2055.

Abbreviations: Curr= Current, Opt=Optimistic, Pess = Pessimistic

Source: Prepared by the authors (2025).

In the descriptive statistics, heterogeneity among models is observed, with standard deviations ranging from 11.77 to 12.64 NTU and maximum ranges of approximately 80 NTU across all models, indicating the recurring presence of extreme values.

However, the overall means were very similar (≈12.5-12.8 NTU), suggesting little structural difference among the simulated average regimes.

Table 4 – Statistical analysis for the turbidity parameter

Descriptive statistics for the turbidity parameter			
Climate Model	*Mean Temperature (°C)*	*Mean Range*	*Observations*
CAM	12,188	79,999	Skewed distribution; presence of high extreme values.
HADGEM	12,636	79,997	Highest mean among the models; slightly greater dispersion.
MIROC	11,769	79,939	Lower mean; variability comparable to CAM.

Analysis of Variance (ANOVA) – Turbidity Among Scenarios Within Each Model				
Climate Model	*F-Statistic*	*p-Value*	*Statistical Significance*	*Interpretation*
CAM	0,182	0,9991	No	No differences among scenarios.
HADGEM	5,933	< 0,0001	Yes	Statistical difference with an extremely small effect size.
MIROC	0,068	0,999	No	No differences among scenarios.
Tukey's Test for Comparison of Mean Turbidity Among Models				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HADGEM	+0,1225	< 0.001	Yes
CAM	MIROC	−0,1069	< 0.001	Yes
HADGEM	MIROC	−0,2294	< 0.001	Yes

Source: Prepared by the authors (2025).

The apparent colour parameter of water (Figure 6) illustrates the trend toward greater variance and dispersion predicted for the 2035 and 2055 phases of the study based on the CAM, HADGEM, and MIROC climate models. Such enhanced variability under worst-case scenarios implies a greater potential for instability in watercolour and could pose an ongoing operational challenge, given its direct correlation with turbidity. HADGEM is the most conservative for high-regulatory-precision applications, with low variability, smaller interquartile dispersion, and lower median values. Although CAM presented moderately stable projections with consistent medians across scenarios, MIROC suggested greater susceptibility to variability — particularly in the long run.

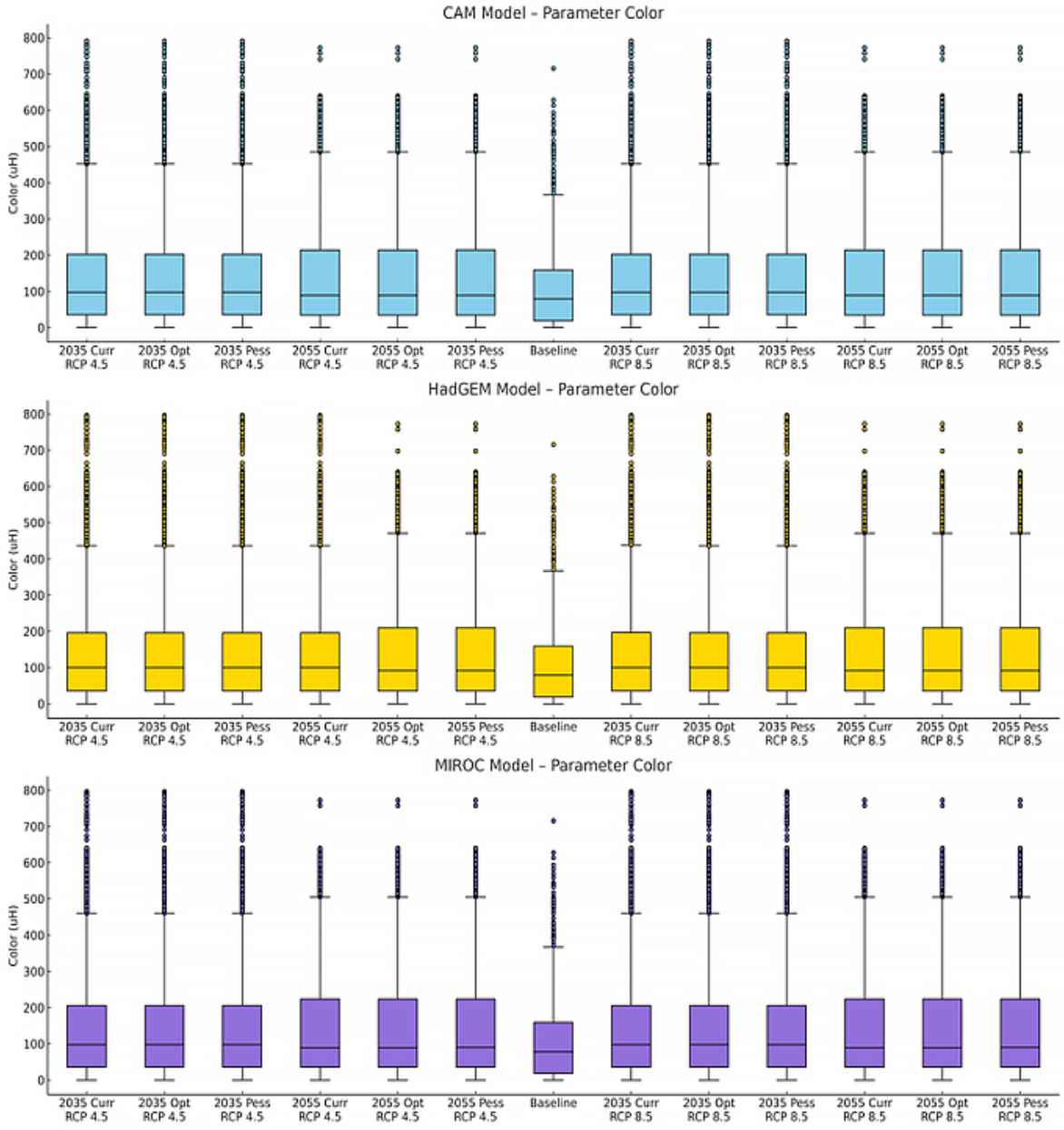


Figure 6 – Projections of apparent watercolour (Gradient Boosting) under climate variables (Eta–CMIP5) and hydrological variables (MHD-Inpe) for 2035 and 2055.

Abbreviations: Curr= Current, Opt=Optimistic, Pess = Pessimistic

Source: Prepared by the authors (2025).

The statistical analysis of the colour parameter (uH) provides quantitative support for interpreting the effects of climate on water quality. The Eta-CamESM2 model yielded a much wider interquartile range and many outliers, indicating greater internal variability. The ANOVA among scenarios within the CAM model yielded no significant differences ($F = 0.294$; $p = 0.995$), indicating no systematic shifts across alternative climate scenarios. The MIROC model, however, showed lower dispersion and median values close to the baseline, which indicates relative stability. The HadGEM model exhibited intermediate behaviour, with a median value slightly above the baseline and moderate variability.

Table 5 – Statistical analysis for the apparent colour parameter

Descriptive statistics for the turbidity parameter				
Climate Model	*Mean Temperature (°C)*	*Mean Range*	*Observations*	
CAM	32,418	199,998	Skewed distribution; recurring presence of high extreme values.	
HADGEM	33,104	199,997	Highest mean among the models; slightly greater dispersion.	
MIROC	31,884	199,995	Lower mean; variability comparable to CAM.	
Analysis of Variance (ANOVA) – Turbidity Among Scenarios Within Each Model				
Climate Model	*F-Statistic*	*p-Value*	*Statistical Significance*	*Interpretation*
CAM	0,294	0,995	No	No differences among scenarios.
HADGEM	7,814	< 0,0001	Yes	Statistical difference with an extremely small effect size.
MIROC	0,117	0,999	No	No differences among scenarios.
Tukey's Test for Comparison of Mean Turbidity Among Models				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HADGEM	+0,724	< 0,001	Yes
CAM	MIROC	-0,335	< 0,001	Yes
HADGEM	MIROC	-1,059	< 0,001	

Source: Prepared by the authors (2025).

Figure 7 shows NH_3–N parameter (ammoniacal nitrogen) behaviour under multiple climate scenarios based on the Eta-CamESM2, HADGEM, and MIROC models. In general, the projected future NH_3–N concentrations tend to increase under RCP 8.5 (pessimistic), suggesting that water quality is more susceptible to warming and hydrological variability.

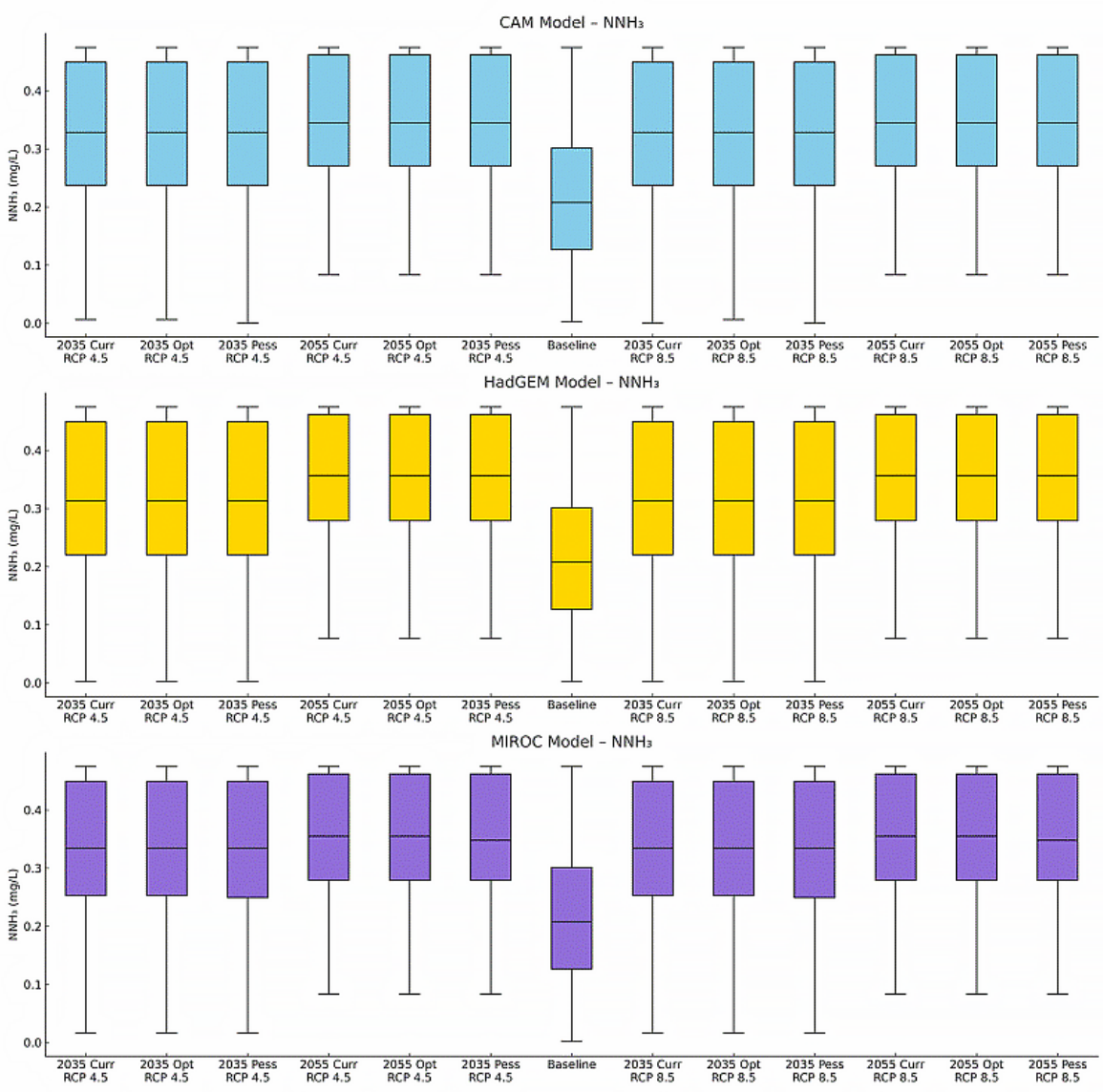


Figure 7 – Projections of NH_3–N in water (Gradient Boosting) under climate variables (Eta–CMIP5) and hydrological variables (MHD-Inpe) for 2035 and 2055.

Abbreviations: Curr= Current, Opt=Optimistic, Pess = Pessimistic

Source: Prepared by the authors (2025).

From an integrated perspective, the results indicate that Eta-CamESM2 shows greater sensitivity to internal variability, HADGEM exhibits more concentrated behaviour, and MIROC combines central stability with occasional extreme values.

However, the overall variability of NH_3–N is explained by the internal dynamics of the series and the occurrence of extreme events, rather than by robust structural differences among models or scenarios.

Table 6 – Statistical analysis for the NH_3–N parameter

Descriptive statistics for the turbidity parameter			
Climate Model	*Mean Temperature (°C)*	*Mean Range*	*Observations*
CAM	0,1086	0,477	Moderate variability; presence of occasional outliers; relatively stable distribution across scenarios.
HADGEM	0,1051	0,472	Dispersion similar to CAM; concentrated central behaviour.
MIROC	0,104	0,472	Lower relative dispersion; occasional occurrence of extremes.

Analysis of Variance (ANOVA) – Turbidity Among Scenarios Within Each Model				
Climate Model	*F-Statistic*	*p-Value*	*Statistical Significance*	*Interpretation*
CAM	2,873	< 0,0001	Yes	Detectable statistical difference; however, with a small effect size and low practical relevance.
HADGEM	4,912	< 0,0001	Yes	Detectable statistical difference; reduced effect magnitude.
MIROC	1,964	< 0,0001	Yes	Detectable statistical difference; variation explained by scenarios is small.

Tukey's Test for Comparison of Mean Turbidity Among Models				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HADGEM	+0,0037	< 0,001	Yes
CAM	MIROC	−0,0052	< 0,001	Yes
HADGEM	MIROC	−0,0089	< 0,001	Yes

Source: Prepared by the authors (2025).

The Python simulation of the NNH_3_predicted parameter shows a considerable increase over the baseline, around 0.2 mg/L. The results for the 2035 period (C, O, P) show a median of approximately 0.25 mg/L, an increase of about 25%.

In the 2055 period (C, O, P), the median remains stable, although variability persists.

The choice of climate model affects ammonia (NNH_3) projections, which in turn inform management objectives and acceptable risk levels.

5 DISCUSSION

The simulations suggest that climate change may exacerbate water-quality challenges in the Paraíba do Sul River basin. From the data review, we observed a direct correlation between air and water temperatures, and largely between the effects on pH, turbidity, colour, and ammonia (NNH_3).

It is predicted that more severe weather events, including prolonged droughts and heavy rainfall, will significantly impact the region's hydrological systems and pollutant and sediment concentrations,

requiring modifications to treatment processes. Furthermore, rising temperatures promote algal growth and toxin production, exacerbating BOD and operational difficulties. Previous studies support these findings.

Andrade *et al.* (2016) showed that urbanisation, agriculture, and deforestation affect the water cycle (hydrological cycle) in the Paraíba do Sul River, thereby directly influencing water quality. Furthermore, Gonçalves *et al.* (2015) used the water quality index (WQI) to assess contamination in the domestic sewage (and other pollution sources), emphasising the importance of extra management strategies. Thermotolerant coliforms and total phosphorus had non-compliance rates of 54% and 12%, respectively, in the lower Paraíba do Sul region, between 2012 and 2019, indicating a need for improved governance (Nunes *et al.*, 2024).

Alvarenga *et al.* (2012) showed that conservation methods and environmental restoration within the Ribeirão dos Macacos watershed improved environmental quality, focusing on hydrological sustainability in general, whilst considering temperature as the most affected parameter with respect to flow seasonality.

Canamary *et al.* (2023), focusing on food and energy security under climate change in the Paraíba do Sul River basin, adopted the same deterministic hydrological model. Considering such a context, several ways can be made to reduce such impacts based on this context, potentially:

- Prepare water-stress scenarios to predict and plan actions in time-critical situations (e.g., severe drought or flooding).
- Build contingency reservoirs to ensure you have secure supplies during extreme climate events.
- Try alternative water sources (underground abstraction, desalination, or reuse) to reduce reliance on a single source.
- Modify operational protocols with climate-based forecast models, so that systems can adapt as hydrological variability increases.
- We can promote awareness of actions that minimise damage to water bodies.
- Reforest areas of aquifer recharge and environmental protection zones within the basin.
- Restore degraded and unused areas through reforestation.
- Reduce deforestation and advance environmentally sensitive conservation policies. Control 100% of domestic and industrial wastewater.
- Cut down on using fossil fuels.
- Strengthen monitoring of physical and chemical indicators of basin water quality.

Such measures help make water treatment systems more resilient, ensuring that treated water quality meets desired levels even under climate change. However, these will, of course, make the process costlier.

6 CONCLUSIONS

The purpose of this study is to assess the effects of climate change on water quality in the Paraíba do Sul River Basin using climate models (CAM, HADGEM, and MIROC) and machine learning approaches. The results obtained support the proposed objectives by providing evidence of the potential connection between climate change and variation in water quality parameters, and by supporting mitigation and adaptation approaches. The difference between future scenarios and the Baseline (historical) scenario shows that its climate variability has a high impact on water potability and availability.

This trend of incremental changes in air and water temperatures, as well as long-term projections of pessimistic scenarios like 2055, is increasingly common. They may result in warming that alters the area's climate and hydrological conditions, raising raw water treatment costs and welfare. Rising temperatures lead to higher levels of algae and cyanobacteria, which can produce toxins harmful to human and animal health.

Warmer temperatures and more frequent extreme climate events, such as flooding and prolonged droughts, favour the spread of dangerous algae. These organisms degrade water quality by increasing biochemical oxygen demand (BOD) and decreasing dissolved oxygen (DO) levels. Previous studies have also confirmed their findings, indicating that they must be monitored and prevented from recurring. Climate change influences essential water quality parameters, including turbidity, colour, ammonia (NNH_3), and pH. Long-lasting droughts disrupt river flow, increasing pollutant concentrations, and extreme rainfall carries sediment and organic matter into water systems. The need for more sophisticated technologies is as high as 20%. As such, many mitigation measures were outlined in the previous section to address these challenges.

Taking these steps can increase the resilience of water treatment systems and ensure that, even under climate change scenarios, managed water meets applicable standards. Please note the financial implications of these steps, which will further increase treatment costs. While this study uses climate models (CAM, HADGEM, and MIROC), each with varying degrees of sensitivity and uncertainty, it is limited to these models. Further investigations should consider which treatment technologies are most suitable for extreme climate contexts and examine the influence of socio-environmental interventions on water quality.

The inclusion of high-resolution temporal and spatial data may also enhance projections.

The essence of the study is that water supply integration includes both technological ways and environmental management practices. Effective public policy for water security would benefit all concerned. It is therefore crucial to implement mitigation measures to ensure high-quality water for future generations.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (OpenAI) only for language editing and stylistic polishing. All scientific content, analysis, and intellectual input were developed and verified by the authors, who take full responsibility for the accuracy and integrity of the manuscript.

ETHICAL CONSIDERATIONS

This study was based exclusively on secondary environmental data and computational modelling, without involving human subjects or animal experimentation. Therefore, submission to or approval by a research ethics committee was not required.

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Projeções de mudanças climáticas e seus impactos na qualidade da água bruta na Bacia do Rio Paraíba do Sul paulista

Climate change projections and impacts on raw water quality in the Paraíba do Sul River basin, Southeast Brazil

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ARTICLE- VARIA

RESUMO

Este estudo tem como propósito avaliar a evolução dos indicadores de qualidade da água na Bacia do Rio Paraíba do Sul paulista ao longo dos últimos anos, bem como investigar os efeitos das mudanças climáticas sobre esses parâmetros. A análise comparativa entre projeções futuras e um cenário de referência revela que as variações climáticas estão associadas a alterações nos indicadores de potabilidade da água. Ademais, os resultados indicam uma tendência de redução da disponibilidade hídrica, sobretudo em cenários de maior emissão de gases de efeito estufa, o que evidencia a necessidade de ações voltadas à mitigação e à adaptação para garantir a segurança hídrica da região.

Palavras-chave: Modelos climáticos regionais. Cenários futuros. Recursos hídricos. Segurança hídrica.

ABSTRACT

This study aims to assess recent trends in water quality indicators in the Paraíba do Sul River Basin in the state of São Paulo and to analyse the influence of climate change on these parameters. A comparative analysis between future projections and a historical reference scenario reveals that climate variability plays a significant role in water quality. Additionally, the findings indicate a decline in water availability, particularly under high-emission scenarios, underscoring the urgency of mitigation and adaptation measures to ensure water security in the region.

Keywords: *Regional climate models. Future scenarios. Water resources. Water security.*

1 INTRODUÇÃO

As mudanças climáticas têm gerado impactos profundos na saúde dos ecossistemas, na economia global e na vida cotidiana das populações, sendo amplamente reconhecidas como um dos principais desafios ambientais contemporâneos. Entre os setores mais vulneráveis a essas transformações, destaca-se o de recursos hídricos, que enfrenta consequências diretas na qualidade e na disponibilidade da água (IPCC, 2021; Prado, 2024). Estudos demonstram que alterações nas propriedades físico-químicas da água, influenciadas por fatores climáticos e hidrológicos, podem comprometer não apenas os sistemas naturais, mas também a segurança hídrica das sociedades humanas (Amâncio; Cataldi, 2019; Cravinho *et al.*, 2004).

Eventos climáticos extremos, como o aumento das temperaturas, variações nos padrões de precipitação e outros, exercem influência direta sobre a qualidade e a disponibilidade dos recursos hídricos em escala global (Prado, 2024). De acordo com o Painel Intergovernamental sobre Mudanças Climáticas (IPCC, 2021), observou-se um aumento significativo na frequência desses eventos, o que impõe pressão adicional aos sistemas de saneamento básico e de abastecimento de água. Exemplos recentes incluem a crise hídrica ocorrida no Brasil em 2014, que trouxe grandes alterações nas seguranças hídrica, energética e alimentar (Canamary *et al.*, 2023; Nobre *et al.*, 2016).

No contexto da Bacia do Rio Paraíba do Sul, a bacia apresenta elevada vulnerabilidade hidrológica. Amâncio e Cataldi (2019) alertam que, a partir da década de 2070, há uma tendência clara de redução das vazões na bacia, independentemente do cenário climático analisado. Desse modo, compreender as variações na qualidade da água e os desafios associados ao seu tratamento é essencial para a formulação de estratégias eficazes de gestão, assegurando o acesso à água potável à população. Para tanto, foram utilizados modelos climáticos do Instituto Nacional de Pesquisas Espaciais (Inpe), incluindo *EtaHadGEM2-ES*, *EtaMIROC5* e *EtaCanESM2*, com o intuito de projetar cenários futuros e avaliar potenciais impactos na qualidade da água na bacia.

As alterações climáticas previstas para as próximas décadas impõem desafios técnicos e impactos financeiros aos sistemas de abastecimento e de tratamento de água. Estudos corroboram essas projeções (Delpla *et al.*, 2009; Whitehead *et al.*, 2009), indicando que mudanças climáticas tendem a deteriorar a qualidade da água superficial, aumentando os desafios para o tratamento convencional. Essas alterações podem demandar investimentos em tecnologias de tratamento, monitoramento e controle operacional.

As mudanças climáticas elevam os custos operacionais dos sistemas de tratamento de água devido à maior necessidade de insumos químicos e à adoção de tecnologias avançadas, como a filtração por membranas. Estimativas apontam aumentos de até 20% nesses custos em cenários de estresse climático, segundo a Water Environment Federation (WEF, 2023) e o *United Nations World Water Development Report* (WWAP, 2022). Além disso, exigem-se investimentos estruturais em modernização, monitoramento automatizado e capacitação técnica (Vörösmarty *et al.*, 2010). Incorporar o risco climático ao planejamento financeiro do saneamento torna-se relevante, considerando impactos

diretos e indiretos sobre a saúde, o meio ambiente e a economia regional (Organisation for Economic Co-Operation and Development - OECD, 2018).

2 ÁREA DE ESTUDO

O presente trabalho tem foco na porção paulista da Bacia Hidrográfica do Rio Paraíba do Sul, localizada aproximadamente entre 22°00'S e 23°30'S de latitude e 44°00'W e 45°52'W de longitude, abrangendo o Vale do Paraíba, no estado de São Paulo. Essa região é delimitada pela Serra da Mantiqueira ao norte e pela Serra do Mar ao sul, estendendo-se desde as cabeceiras do rio Paraíba do Sul, formadas pela confluência dos rios Paraibuna e Paraitinga, até a divisa com o estado do Rio de Janeiro.

Na Figura 1, abaixo, observam-se as dimensões da porção paulista da Bacia do Rio Paraíba do Sul.

A Bacia do Rio Paraíba do Sul possui área de drenagem com cerca de 55.500 km², compreendendo os estados de São Paulo (13.900 km²), do Rio de Janeiro (20.900 km²) e Minas Gerais (20.700 km²). É limitada ao norte pelas bacias dos rios Grande e Doce e pelas serras da Mantiqueira, Caparaó e Santo Eduardo.

Ao nordeste, a bacia é limitada pelo rio Itabapoana; ao sul, pelas Serras dos Órgãos e do Mar. A oeste, a bacia é limita pelo rio Tietê, separada por ramificações da Serra do Mar e da Serra da Mantiqueira. O rio Paraíba do Sul é formado pela união dos rios Paraibuna e Paraitinga, com extensão superior a 1.100 km (ANA, 2011).

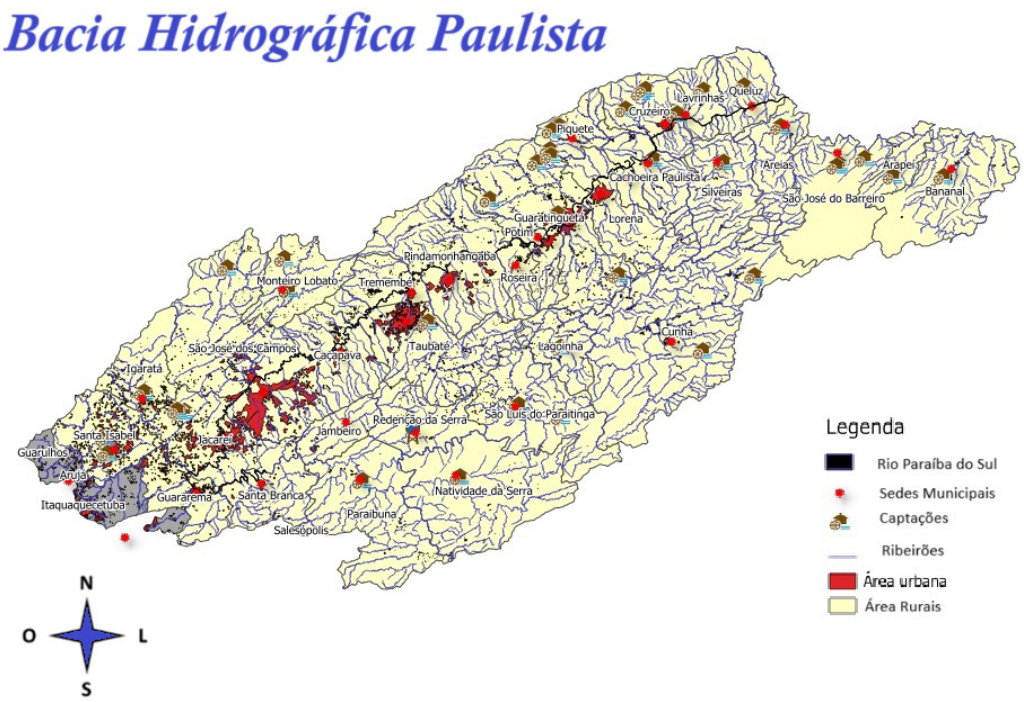


Figura 1 – Bacia Hidrográfica Paulista, considerada neste estudo, indicando as sedes municipais, as captações, o Rio Paraíba do Sul e as áreas urbanas e rurais.

Fonte: Produzido pelo autor (2025)

3 METODOLOGIA

No estudo atual, foram utilizados métodos integrados de modelos climáticos, de modelagem hidrológica e de técnicas de aprendizado de máquina para avaliar os efeitos das mudanças climáticas nos parâmetros de qualidade da água da porção paulista da Bacia do Rio Paraíba do Sul.

Os modelos climáticos representam abordagens numéricas baseadas em equações físicas e são empregados para visualizar os processos básicos que produzem os sistemas climáticos da Terra, como a função da atmosfera, oceanos, superfície terrestre e biosfera. Princípios fundamentais da física, como a conservação de massa, energia e momento, são empregados nesses modelos para simular o clima em diferentes escalas de tempo e espaço (IPCC, 2021). A partir dessas simulações, também é possível prever mudanças futuras em fatores meteorológicos críticos, como temperatura, precipitação e radiação solar, bem como avaliar os potenciais impactos ambientais e hidrológicos das mudanças climáticas.

Os modelos climáticos podem ser divididos em modelos climáticos globais (GCMs) e modelos climáticos regionais (RCMs). Os GCMs são modelos climáticos planetários que modelam a circulação atmosférica global, a oceânica e as dinâmicas de interação de vários elementos do sistema climático. No entanto, eles apresentam limitações para análises em nível regional ou local devido à sua resolução espacial relativamente baixa. Essa limitação pode ser superada pelo uso de modelos climáticos regionais, que realizam práticas de regionalização climática, ajudando a ajustar espacialmente as projeções globais, denominadas *downscaling* climático. Isso permite a disponibilidade de projeções climáticas com maior resolução espacial e maior representatividade das condições climáticas regionais, particularmente em regiões onde topografia e hidrologia complexas convergem, como as bacias hidrográficas (Almagro *et al.*, 2020).

No Brasil, o modelo climático regional Eta é amplamente utilizado na regionalização de cenários climáticos globais. As projeções climáticas regionalizadas do Eta permitem uma resolução espacial mais detalhada ao calcular os impactos das mudanças climáticas em sistemas hidrológicos e ambientais.

Neste estudo, foram utilizados modelos climáticos globais do Projeto de Intercomparação de Modelos Acoplados Fase 5 (CMIP5) para realizar as projeções que foram então convertidas para o modelo Eta.

Os modelos escolhidos foram HadGEM2-ES, MIROC5 e CanESM2, modelos de variabilidade climática e de emissões de gases de efeito estufa, bem estabelecidos por sua capacidade de capturar diversos padrões de variabilidade climática. Eles fornecem simulações de várias trajetórias climáticas no futuro, com base em diferentes cenários de concentração de gases de efeito estufa, denominados Cenários de Concentração Representativa (RCPs).

Para o modelo hidrológico MHD-Inpe, foram usadas projeções climáticas regionalizadas como entradas, incluindo principalmente processos hidrológicos como precipitação, infiltração, evapotranspiração, escoamento superficial e fluxo de água subterrânea. O modelo MHD baseia-se em princípios físicos e matemáticos que permitem modelar a dinâmica hidrológica em escala de bacia hidrográfica, fornecendo, por sua vez, informações relevantes para a análise da disponibilidade de água e condições ambientais do sistema (Paiva *et al.*, 2023).

Para explorar o impacto dos fatores climáticos nos parâmetros de qualidade da água do rio Paraíba do Sul, a modelagem climática e a modelagem hidrológica, juntamente com técnicas de aprendizado de máquina, foram empregadas, permitindo uma avaliação integrada, bem como a análise das possíveis consequências a jusante das mudanças climáticas nos recursos hídricos da região.

Portanto, embora os modelos climáticos tenham sido amplamente adotados para simulações ambientais, essas ferramentas são inerentemente limitadas devido às simplificações necessárias para descrever o funcionamento complexo do sistema climático.

As projeções sobre o clima enfrentam diferentes fontes de incerteza, que decorrem de:

- Limitações estruturais dos modelos, relacionadas à representação de processos atmosféricos e oceânicos.
- Diferenças entre modelos climáticos globais na simulação da variabilidade climática.
- Incertezas dos cenários futuros das emissões de gases de efeito estufa (IPCC, 2021).
- Outra fonte importante de incerteza está relacionada ao processo de *downscaling* climático, que aplica limites regionais às estimativas globais com base em condições de contorno de modelos globais (por exemplo, o modelo climático Eta).

Dessa forma, quaisquer erros ou vieses nos modelos globais podem se refletir localmente nas simulações. Em determinados casos, a resolução espacial em microescala pode falhar em capturar processos locais importantes, como eventos convectivos intensos e a variabilidade hidrológica.

Devido a essas limitações, a aplicação de múltiplos modelos climáticos, como os adotados neste estudo (HadGEM2-ES, MIROC5, CanESM2), é atualmente considerada uma das estratégias mais comuns na literatura científica para minimizar a dependência excessiva de um único modelo climático e aumentar a robustez das projeções climáticas. Essa abordagem permite avaliar a sensibilidade dos resultados a diferentes representações dos processos climáticos e, assim, realizar uma análise mais abrangente dos cenários atuais e futuros possíveis (Almagro *et al.*, 2020; IPCC, 2021).

3.1 CENÁRIOS DAS MUDANÇAS CLIMÁTICAS

Os modelos climáticos selecionados para o estudo em questão foram o *HadGEM2-ES*, o *MIROC5* e o *CanESM2*. Esses modelos foram escolhidos por sua reconhecida credibilidade e por sua notável capacidade de simular diversos cenários climáticos futuros (Almagro *et al.*, 2020). O modelo *HadGEM2-ES*, desenvolvido pelo Met Office Hadley Centre, oferece uma visão particularmente detalhada e abrangente das mudanças climáticas que podem ocorrer ao longo do tempo. Por outro lado, o *MIROC5*, fruto do trabalho da Japan Agency for Marine-Earth Science and Technology, e o *CanESM2*, desenvolvido pelo Canadian Centre for Climate Modelling and Analysis, apresentam diferentes abordagens e perspectivas para a análise dos fenômenos climáticos. A utilização combinada desses três modelos permitiu uma comparação robusta, resultando em uma melhor compreensão dos impactos das mudanças climáticas na qualidade da água do rio Paraíba do Sul, bem como de suas possíveis implicações para o meio ambiente e a sociedade (Rodrigues, 2022).

3.2 SIMULAÇÃO DA TEMPERATURA DA ÁGUA

O cálculo da temperatura da água baseia-se no princípio da temperatura de equilíbrio (Edinger *et al.*, 1968). Esse tipo de formulação tem sido utilizado em vários modelos hidrológicos, como o *CE-QUAL-W2* (Cole; Wells, 2006) e o *MIKE SHE* (Dhi, 2017), devido à sua simplicidade e estabilidade numérica.

No caso de temperatura uniforme, os gradientes em relação à distância são iguais a zero; a equação (1) de transporte de calor unidimensional pode ser escrita como:

$$\rho_w c_{pw} \frac{dTw}{dt} = \frac{q_{net}}{depth} \qquad (1)$$

Sendo ρ_w a densidade da água; c_{pw} o calor específico da água; q_{net} a radiação líquida à superfície; Tw a temperatura; e $depth$ a profundidade da água.

A radiação líquida é composta por fluxos provenientes de diferentes processos físicos, especificamente: a radiação solar líquida; a radiação atmosférica de onda longa; a radiação de onda longa emitida pela superfície da água; o fluxo de calor evaporativo; o fluxo de calor convectivo; e o fluxo de calor devido à precipitação. De todas essas componentes, o fluxo mais importante corresponde ao termo de radiação solar líquida q_{atm}. Portanto, a equação anterior pode ser simplificada como:

$$\rho_w c_{pw} \frac{dTw}{dt} = \frac{q_{atm} + \varepsilon_q}{depth} \qquad (2)$$

Sendo ε_q um parâmetro que incorpora os demais termos da radiação.

Edinger *et al.* (1968) definiram a temperatura de equilíbrio como a temperatura da água em que o fluxo de calor atmosférico líquido (q_{atm}) é igual a zero. Nessas condições, o balanço de radiação pode ser escrito como:

$$q_{atm} = K(Te - Tw) \qquad (3)$$

Sendo Te a temperatura de equilíbrio e K coeficiente global de troca de calor superficial. O coeficiente de troca de calor da superfície total, K, pode ser calculado a partir das equações empíricas de Edinger. K é uma função da temperatura da água, da temperatura do ponto de orvalho $Tdew$ e da velocidade do vento w usando:

$$K = 4.48 + (\beta + 0.47) f_w + 0.05 Tw$$

sendo

$$f_w = 9.2 + 0.46 w^2$$

$$\beta = 0.35 + 0.015 \left(\frac{Tdew + Tw}{2}\right) + 0.0012 \left(\frac{Tdew + Tw}{2}\right)^2$$

$$Te = Tdew + \frac{S}{K} + \varepsilon_t \qquad (4)$$

Sendo S a radiação incidente de onda curta e ε_t um parâmetro de ajuste. Combinando as duas equações anteriores, resulta em:

$$\rho_w c_{pw} \frac{dTw}{dt} = \frac{K(Te - Tw) + \varepsilon_q}{depth} \qquad (5)$$

Integrando no intervalo de tempo temos:

$$Tw_{t+\Delta t} = Te\left(1 - e^{-\frac{Kt_{res}}{\rho_w c_{pw} depth}}\right) + Tw_{in,t} e^{-\frac{Kt_{res}}{\rho_w c_{pw} depth}} + \frac{\varepsilon_q}{K}\left(1 - e^{-\frac{Kt_{res}}{\rho_w c_{pw} depth}}\right) \qquad (6)$$

Sendo Tw, in a entrada de calor vinda de outras células contíguas. Essa equação é muito similar à encontrada por Bogan *et al.* (2004).

3.3 SIMULAÇÃO EM PYTHON COM MODELO HISTGRADIENTBOOSTINGREGRESSOR

A presente análise foi conduzida em Python, utilizando o algoritmo *HistGradientBoostingRegressor*, implementado na biblioteca *scikit-learn*, com o objetivo de estimar parâmetros físico-químicos da água do rio Paraíba do Sul.

As variáveis preditoras compreenderam indicadores climáticos e hidrológicos — como temperatura do ar, precipitação e vazão —, enquanto as variáveis-resposta incluíram indicadores-chave de qualidade da água: pH, turbidez, cor aparente e nitrogênio amoniacal (NHH3).

As séries temporais utilizadas para treinamento do modelo foram obtidas a partir de bases de dados disponibilizadas por instituições oficiais, tais como o Instituto Nacional de Pesquisas Espaciais (Inpe), a Agência Nacional de Águas e Saneamento Básico (ANA) e o Instituto Nacional de Meteorologia (Inmet). Essa abordagem possibilitou a avaliação quantitativa da influência de fatores climáticos e hidrológicos sobre os parâmetros de qualidade da água, oferecendo subsídios relevantes para a projeção de cenários futuros sob os efeitos das mudanças climáticas.

Estudos recentes corroboram a eficácia de modelos baseados em aprendizado de máquina para fins semelhantes. Khan *et al.* (2021) aplicaram regressão por componentes principais (*Principal Component Regression* – PCR) associada ao algoritmo *Gradient Boosting* para prever e classificar a qualidade da água, atingindo acurácia de 95% e 100%, respectivamente, na estimativa do Índice de Qualidade da Água (IQA), com base em variáveis como pH, turbidez e oxigênio dissolvido (OD).

De forma complementar, Manikandan *et al.* (2024) demonstraram que algoritmos de *Gradient Boosting* podem estimar o IQA com elevada precisão a partir de 20 características físico-químicas de amostras hídricas. Os autores evidenciam a relação direta entre a degradação da qualidade da água e os riscos à segurança hídrica.

Ainda nesse contexto, Wang *et al.* (2017) aplicaram o método de *Support Vector Regression* (SVR) para previsão do IQA, alcançando acurácia superior a 90% a partir de 22 variáveis de entrada.

Os resultados confirmam a eficácia do modelo HistGradientBoostingRegressor na previsão da qualidade da água, demonstrando sua aptidão para lidar com dados multidimensionais e com relações complexas entre variáveis ambientais e químicas.

3.4 CENÁRIOS DA QUALIDADE DA ÁGUA

Para a elaboração dos mapas de uso e cobertura da terra, considerou-se o estudo de Rezende *et al.* (2018), que delineou três cenários futuros de mudanças no uso e na ocupação do solo entre 2010 e 2050. Esse estudo enfatizou as transições entre as categorias de silvicultura, floresta e pastagem. Posteriormente, essas projeções foram revisadas por Paiva *et al.* (2023), que incorporaram a expansão das áreas urbanas ao modelo. Adicionalmente, os cenários de Rezende *et al.* (2018) foram aprimorados com a inclusão de pressupostos relacionados ao comportamento das demandas de água para abastecimento humano e industrial, com cenários otimista, pessimista e atual (Canamary *et al.*, 2023). Agora são adicionadas informações de qualidade da água, com os seguintes parâmetros: temperatura da água ºC (físico), temperatura do ar ºC (físico), fósforo mg/L (químico), DBO5 mg/L O2 (químico), pH U.pH (químico), turbidez NTU (físico) e OD mg/L (químico). Os cenários foram projetados para três

períodos: Histórico, Atual e Futuro, e, para cada período, atual e futuro, três cenários foram projetados: otimista, pessimista e atual.

- Período Histórico de 1976 até 2015
- Período Atual: 2016 até 2035
- Período Futuro: 2036 até 2055

a) Cenário otimista (O): reflete um aumento significativo no acesso aos serviços de abastecimento público, acompanhado de uma redução no consumo *per capita* de água, impulsionada por maior conscientização sobre a preservação dos recursos hídricos.

b) Cenário pessimista (P): considera melhorias nos níveis de acesso ao abastecimento de água, mas com crescimento da demanda *per capita*.

c) Cenário atual (A): baseia-se nas tendências de consumo e de ocupação observadas no momento.

O estudo conduzido por Martins *et al.* (2023) também está incorporado neste modelo, em que é abordada a demanda hídrica na agricultura na porção paulista da bacia do rio Paraíba do Sul. Existe também a projeção sob dois cenários de emissões de gases de efeito estufa, *RCP 4.5* e *RCP 8.5*, com o objetivo de analisar os impactos potenciais das mudanças climáticas na disponibilidade e no consumo de recursos hídricos para a produção agrícola na região.

4 RESULTADOS

Os resultados obtidos por meio da modelagem executada foram apresentados de forma gráfica com o auxílio de tabelas numéricas e de comparações de dados ao longo das décadas pesquisadas. A análise permitiu verificar as progressões, inclusões e exclusões de cada parâmetro no tratamento de água bruta ao longo dos anos estudados. Para confirmar a precisão do modelo, foi realizada uma análise estatística comparativa entre os dados mensurados durante os tratamentos de água bruta (dados históricos, chamados de *baseline*) e os dados simulados pelo modelo hidrológico.

4.1 TEMPERATURA DO AR E DA ÁGUA

As projeções dos modelos climáticos CAM, MIROC e HADGEN indicam um aumento progressivo da temperatura do ar nos municípios paulistas entre os períodos de 2035 e 2055. O cenário de referência *baseline* apresenta as menores medianas, com valores concentrados entre 21°C e 22°C nos três modelos. Em 2035, as temperaturas se elevam levemente em relação ao histórico, com diferenças mínimas entre os cenários (atual, otimista e pessimista). Já em 2055, observa-se um aumento mais expressivo, com os cenários pessimistas indicando as maiores medianas, o que indica tendência de aquecimento. Abaixo, apresenta-se um gráfico com os dados e realizam-se uma análise estatística descritiva, a variância e o teste de *Tukey*.

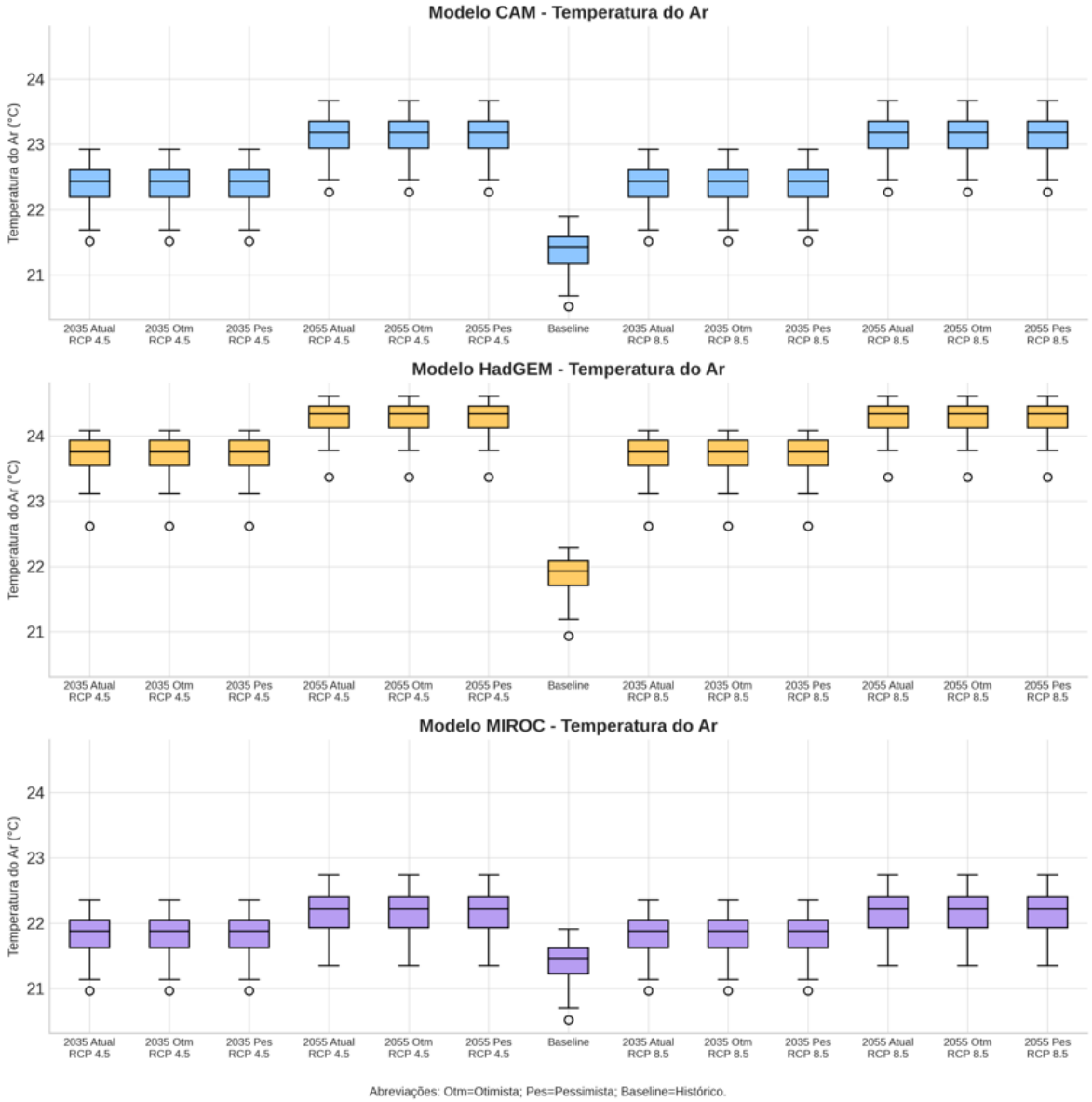


Figura 2 – Projeções da temperatura do ar a partir dos modelos climáticos regionais (Eta–CMIP5)

Fonte: Produzido pelos autores (2025)

A análise *pós-hoc* confirmou diferenças estatisticamente significativas entre todos os modelos climáticos, o que indica a relevância de múltiplas abordagens na projeção de cenários ambientais. As projeções para 2035 e 2055 indicam um aumento gradual da temperatura da água em relação ao cenário de referência. Em 2035, as variações entre os cenários são discretas, enquanto, em 2055, observa-se uma elevação mais acentuada, especialmente no cenário pessimista (RPC 8.5), que indica maior impacto climático e possíveis impactos adicionais sobre os sistemas hídricos.

Tabela 1 – Análise estatística para o parâmetro temperatura do ar

Estatística descritiva para o parâmetro temperatura do ar				
Modelo Climático	*Média de Temperatura (°C)*	*Desvio-Padrão Médio*	*Amplitude Média*	*Observações*
CAM	22,644	0,342	1,402	Variabilidade moderada entre os cenários.
HadGEM	23,809	0,300	1,352	Variabilidade ligeiramente inferior ao CAM.
MIROC	21,941	0,350	1,391	Variabilidade comparável ao modelo CAM.
Análise de variância (ANOVA) - Temperatura do ar entre os cenários dentro de cada modelo				
Modelo Climático	*Estatística F*	*Valor-p*	*Significância Estatística*	*Interpretação*
CAM	83,520	< 0,0001	Sim	Diferenças estatisticamente significativas entre os cenários do modelo.
HadGEM	161,210	< 0,0001	Sim	Diferenças estatisticamente significativas entre os cenários simulados.
MIROC	15,720	< 0,0001	Sim	Todos os cenários apresentaram variações estatisticamente relevantes.
Teste de Tukey para comparação de médias da temperatura do ar entre os modelos				
Group 1	*Group 2*	*Mean Difference*	*p-Value*	*Statistical Significance*
CAM	HadGEM	+1,1649	< 0.001	Sim
CAM	MIROC	−0,7030	< 0.001	Sim
HadGEM	MIROC	−1,8679	< 0.001	Sim

Fonte: Produzido pelos autores (2025)

O comportamento térmico da água segue, de forma atenuada, o padrão observado na temperatura do ar, refletindo o acoplamento entre a atmosfera e a superfície hídrica. Nos cenários futuros, as medianas aumentam discretamente, e a amplitude térmica cresce nos cenários pessimistas de 2055. Essas observações podem ser verificadas na Figura 3, logo abaixo:

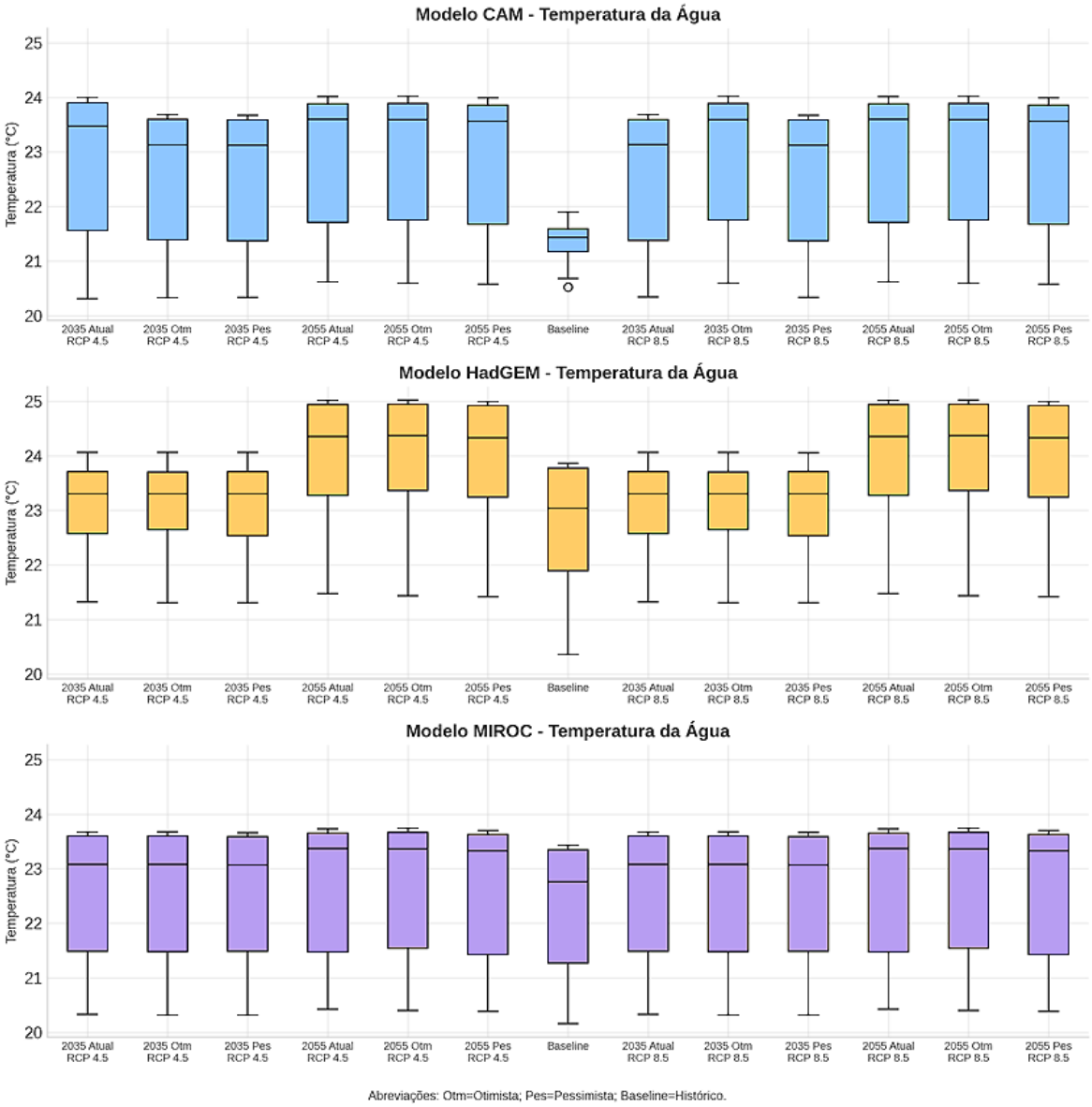


Figura 3 – Projeções da temperatura da água estimadas pelo modelo hidrológico MHD-Inpe.

Fonte: Produzido pelos autores (2025)

A análise estatística do parâmetro Temperatura da Água (Tabela 2) evidencia padrões térmicos distintos entre os modelos climáticos Eta-CamESM2, HadGEM e MIROC, refletindo diferenças estruturais na representação dos processos de troca de energia entre a atmosfera e a superfície hídrica. As médias variaram entre 23,1°C (MIROC) e 24,0°C (HadGEM), com o CAM apresentando um valor intermediário de 23,5°C. Essa diferença de até 0,9°C entre os extremos confirma a presença de um gradiente térmico intermodelo estatisticamente significativo.

Tabela 2 – Análise estatística para o parâmetro temperatura da água

Estatística descritiva para o parâmetro temperatura da água				
Modelo Climático	*Média de Temperatura (°C)*	*Desvio-Padrão Médio*	*Amplitude Média*	*Observações*
CAM	23,500	0,342	1,402	Dispersão moderada; variabilidade considerável entre os cenários.
HADGEM	24,000	0,300	1,352	Média superior ao CAM; variabilidade interna significativa.
MIROC	23,100	0,350	1,391	Variabilidade superior ao HADGEM; distribuição homogênea.
Análise de variância (Anova) - temperatura da água entre os cenários dentro de cada modelo				
Modelo Climático	*Estatística F*	*Valor-p*	*Significância Estatística*	*Interpretação*
CAM	4,765	< 0,0001	Sim	Diferenças estatisticamente significativas entre os cenários do modelo.
HADGEM	8,747	< 0,0001	Sim	Diferenças estatisticamente significativas entre os cenários simulados.
MIROC	0,254	> 0,0001	Não	Sem diferenças estatisticamente significativas.
Teste de Tukey para comparação de médias da temperatura da água entre os modelos				
Grupo 1	*Grupo 2*	*Diferença de Média (cº)*	*Valor-p*	*Diferença Significativa*
CAM	HADGEM	+0,774	< 0.001	Sim
CAM	MIROC	- 0,084	>0.05	Não
HADGEM	MIROC	-0,858	< 0.001	Sim

Fonte: Produzido pelos autores (2025).

4.2 ESTIMATIVAS DOS PARÂMETROS DA QUALIDADE DA ÁGUA – PH, COR, TURBIDEZ E NH_3.

Para as simulações apresentadas, utilizaram-se como dados de entrada as temperaturas de água e de ar, obtidas a partir das simulações dos modelos climáticos integrados ao modelo hidrológico (MHD) e inseridas no software *Python*. Nos gráficos abaixo, apresentamos os quatro parâmetros da qualidade da água analisados.

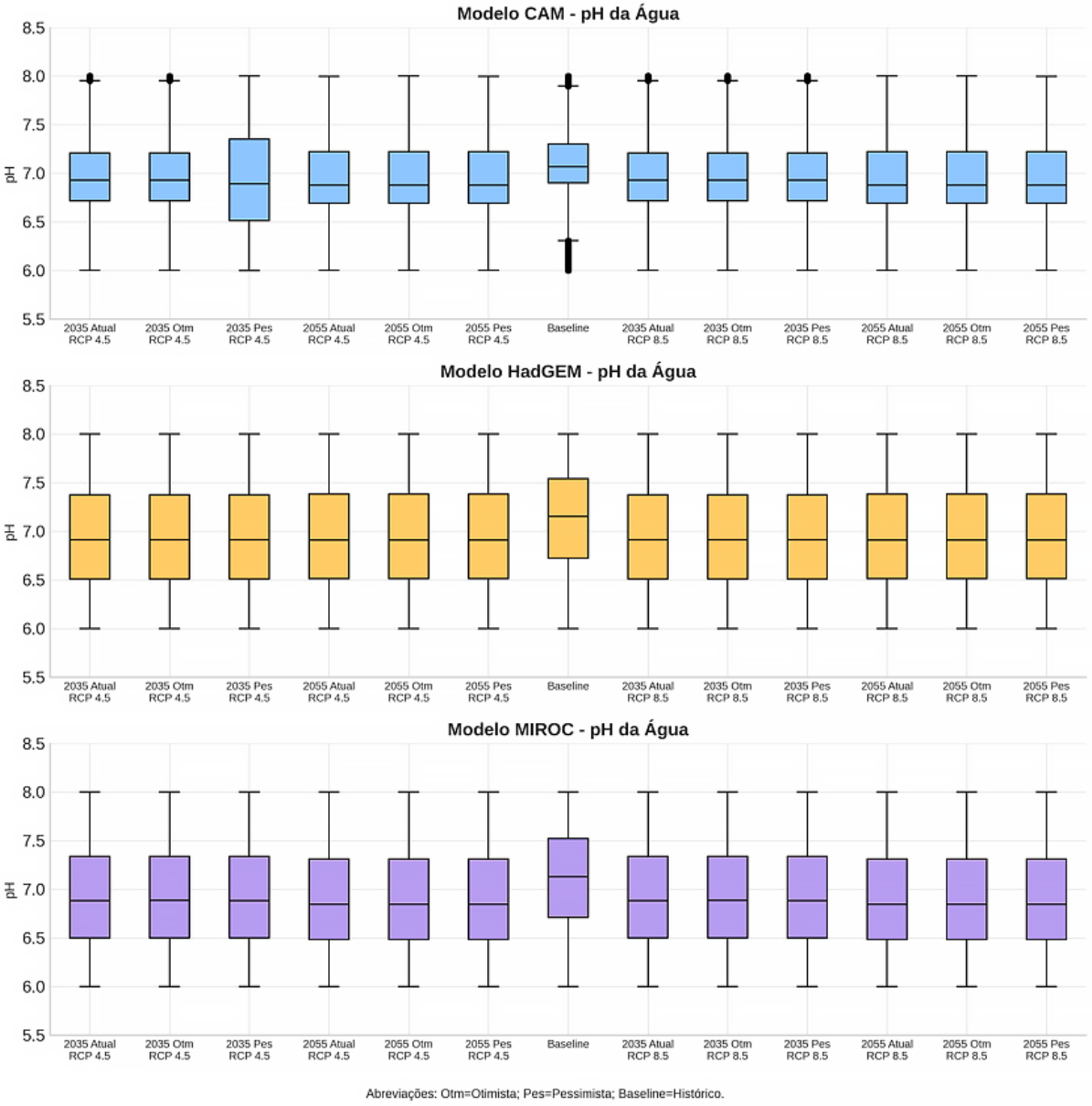


Figura 4 – Projeções do pH da água (Gradient Boosting) sob variavéis climáticas (Eta–CMIP5) e hidrológicas (MHD-Inpe) para 2035 e 2055

Fonte: Produzidos pelo autores (2025).

Para o pH, conforme análise gráfica, não houve mudanças significativas; a média ficou próxima de 7,0, indicando pH neutro, sem grandes alterações ao longo de todos os períodos.

O modelo *CAM* apresentou variabilidade moderada, com pH entre 6.7 e 7.7 em diferentes cenários. Observa-se uma tendência de redução do pH nos cenários de 2055, sem *outliers* expressivos. O modelo sugere um comportamento estável, porém ligeiramente mais ácido no futuro.

Entre os modelos climáticos analisados, o *HADGEM* apresentou maior estabilidade nas projeções de pH, com medianas próximas de 7, baixa variabilidade e ausência de valores anômalos.

Em contraste, o *MIROC* exibiu maior variabilidade e tendência de queda do pH nos cenários de 2055, especialmente sob a condição pessimista, o que se reflete maior variabilidade nas projeções. A tendência geral indica uma leve redução do pH até 2055 nos modelos *MIROC* e *CAM*, enquanto o

HADGEM permanece praticamente inalterado. O cenário de altas emissões (RCP 8.5) não resultou em acidificação significativa, exceto no modelo *CAM*. A análise estatística confirmou diferenças significativas entre os modelos, indicando a importância de considerar múltiplas abordagens de modelagem nas projeções ambientais.

Tabela 3 – Análise estatística para o parâmetro pH da água

Estatística descritiva para o parâmetro pH				
Modelo Climático	*Média de pH*	*Desvio-Padrão*	*Amplitude*	*Observações*
CAM	6,975	0,365	1,999	Baixa dispersão; valores concentrados próximos à neutralidade.
HADGEM	6,960	0,543	6,931	Maior dispersão influenciada por valores extremos.
MIROC	6,930	0,536	6,858	Variabilidade semelhante à do HADGEM; presença de extremos.
Análise de variância (ANOVA) - pH entre os cenários dentro de cada modelo				
Modelo Climático	*Estatística F*	*Valor-p*	*Significância Estatística*	*Interpretação*
CAM	1387,44	< 0,0001	Sim	Diferenças estatisticamente significativas, porém, com efeito pequeno.
HADGEM	697,85	< 0,0001	Sim	Significativo; magnitude de efeito muito pequena.
MIROC	905,09	< 0,0001	Sim	Significativo; efeito reduzido.
Teste de Tukey para comparação de médias de pH entre os modelos				
Grupo 1	*Grupo 2*	*Diferença de Média*	*Valor-p*	*Diferença Significativa*
CAM	HADGEM	+ 0,01451	< 0,001	Sim
CAM	MIROC	+ 0,04487	< 0,001	Sim
HADGEM	MIROC	+ 0,03035	< 0,001	Sim

Fonte: Produzido pelos autores (2025).

O parâmetro Turbidez apresentou grandes *outliers* (pontos fora da média), expressivos. Na *base de linha*, a mediana de turbidez está próxima de 20, mas há registros de amostras com valores entre 40 e 80, possivelmente decorrentes de chuvas intensas e enxurradas.

No período 2035 (A, O, P), a mediana sobe ligeiramente, mas os *outliers* permanecem expressivos. Já na previsão de 2055 (A, O, P), observa-se um pequeno aumento na mediana, o que indica que eventos de turbidez podem se tornar mais frequentes.

O grande número de *outliers* (fora da média) em todos os períodos sugere que o controle da turbidez será um desafio constante, o que pode implicar ajustes operacionais futuros, conforme a Figura 5.

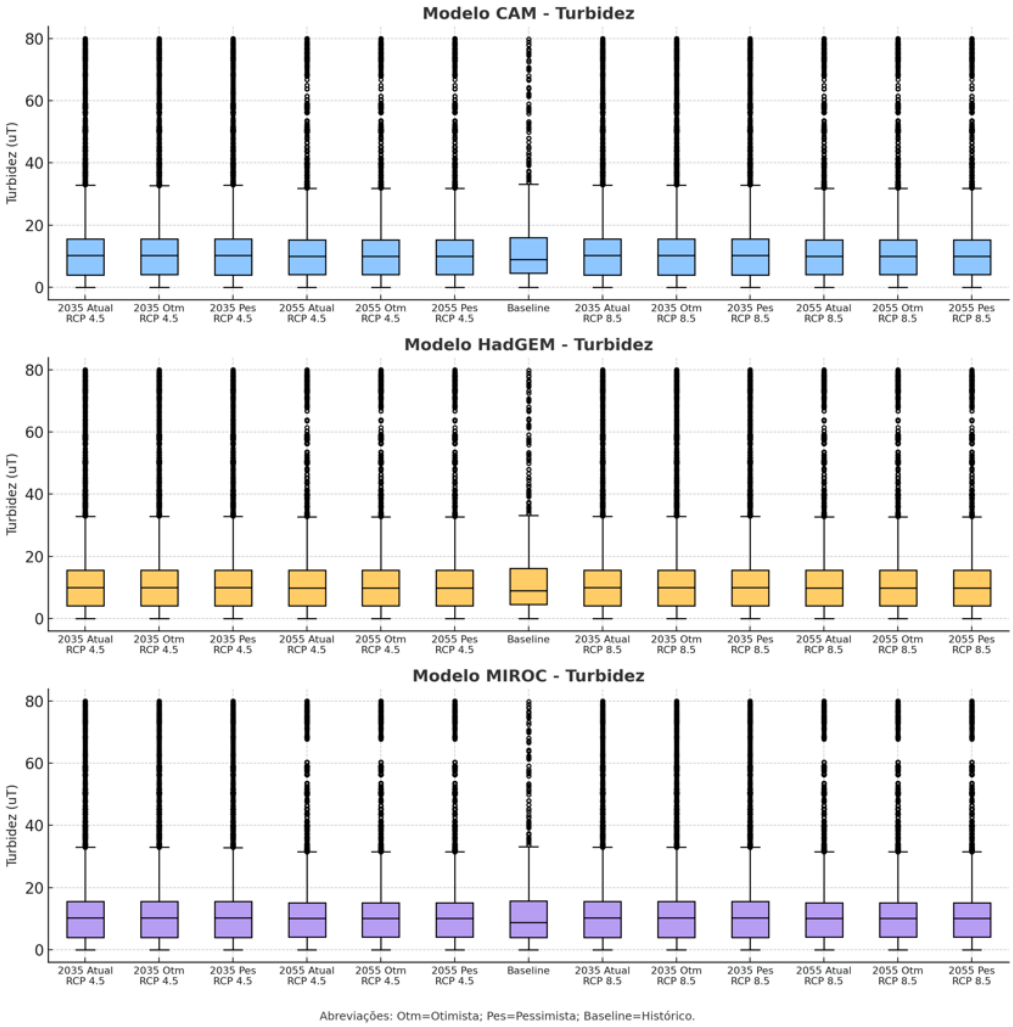


Figura 5 – Projeções da turbidez da água (Gradient Boosting) sob variáveis climáticas (Eta–CMIP5) e hidrológicas (MHD-Inpe) para 2035 e 2055.

Fonte: Produzido pelos autores (2025).

Na estatística descritiva, observa-se heterogeneidade entre os modelos, em que os desvios-padrão variaram entre 11,77 e 12,64 UNT, com amplitudes máximas próximas de 80 UNT em todos os modelos, indicando a presença recorrente de valores extremos. Contudo, as médias globais foram bastante próximas (≈12,5 a 12,8 UNT), sugerindo baixa diferença estrutural entre os regimes médios simulados.

Tabela 4 – Análise estatística para o parâmetro turbidez

Estatística descritiva para o parâmetro turbidez			
Modelo Climático	*Média de pH*	*Amplitude*	*Observações*
CAM	12,188	79,999	Distribuição assimétrica; presença de valores extremos elevados
HADGEM	12,636	79,997	Maior média entre os modelos; dispersão ligeiramente maior.
MIROC	11,769	79,939	Média inferior; variabilidade comparável à do CAM.

Análise de variância (ANOVA) - Turbidez entre os cenários dentro de cada modelo				
Modelo Climático	Estatística F	Valor-p	Significância Estatística	Interpretação
CAM	0,182	0,9991	Não	Ausência de diferenças entre cenários.
HADGEM	5,933	< 0,0001	Sim	Diferença estatística com efeito extremamente pequeno.
MIROC	0,068	0,999	Não	Ausência de diferenças entre cenários.
Teste de Tukey para comparação de médias de turbidez entre os modelos				
Grupo 1	Grupo 2	Diferença de Média	Valor-p	Diferença Significativa
CAM	HADGEM	+0,1225	< 0.001	Sim
CAM	MIROC	−0,1069	< 0.001	Sim
HADGEM	MIROC	−0,2294	< 0.001	Sim

Fonte: Produzido pelos autores (2025)

A análise do parâmetro Cor aparente da água, apresentada na Figura 6 abaixo, com base nos modelos climáticos CAM, HADGEM e MIROC, indica uma tendência de maior variabilidade e dispersão nas projeções futuras (2035 e 2055), em comparação ao cenário de referência (*baseline*), cuja média está em torno de 100 unidades. Esse aumento de variações, especialmente nos cenários pessimistas, sugere um risco crescente de instabilidade na cor da água, o que pode representar um desafio operacional contínuo, principalmente por sua relação direta com o parâmetro de Turbidez.

Entre os modelos, o *HADGEM* destacou-se por sua baixa variabilidade, menor dispersão interquartil e medianas mais baixas, sendo o mais conservador e confiável para aplicações que exigem maior precisão regulatória. O *CAM* apresentou projeções moderadamente estáveis, com medianas consistentes ao longo dos cenários, enquanto o *MIROC* indicou maior suscetibilidade a variações, especialmente no longo prazo.

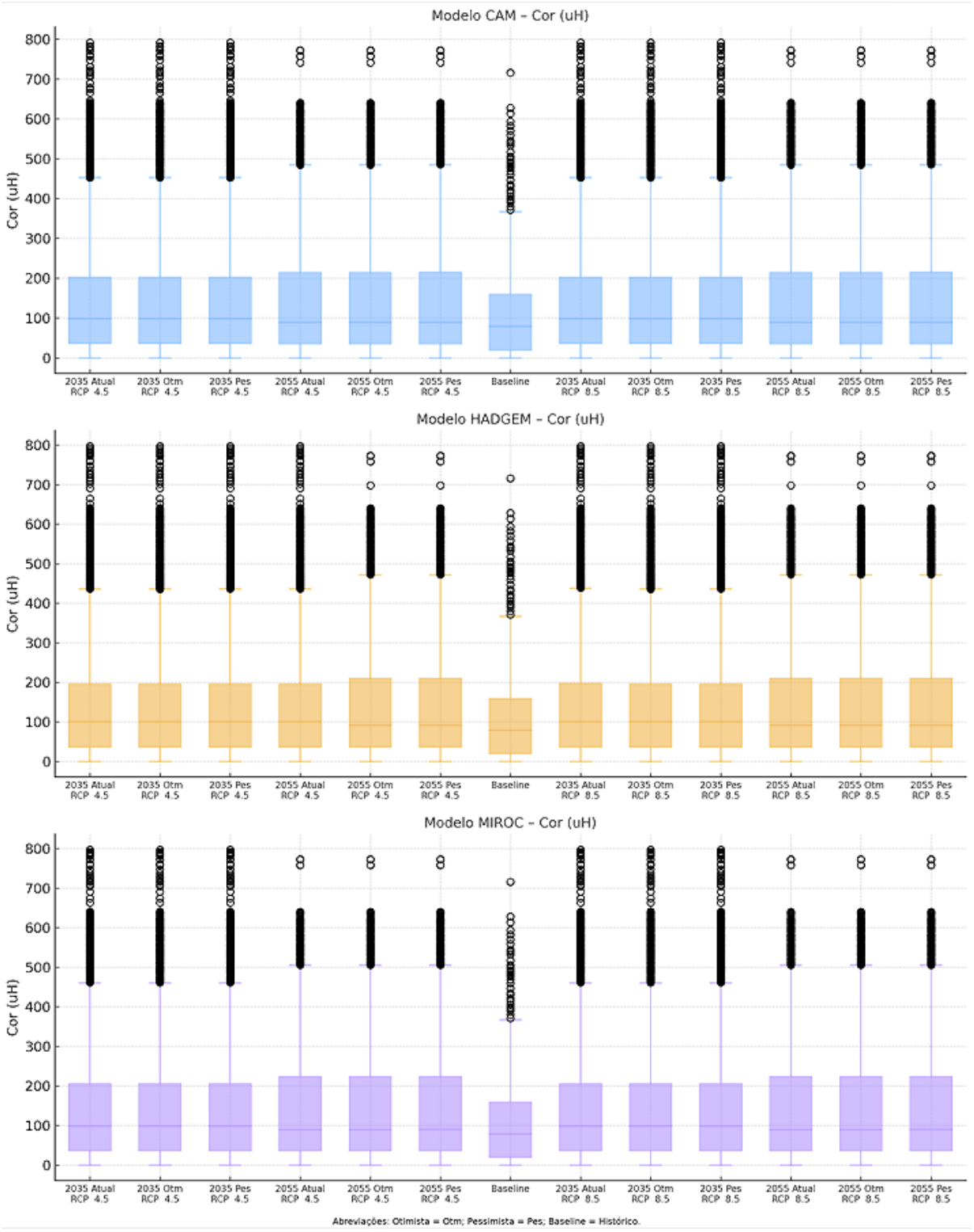


Figura 6 – Projeções da Cor aparente da água (Gradient Boosting) sob variáveis climáticas (Eta–CMIP5) e hidrológicas (MHD--Inpe) para 2035 e 2055.

Fonte: Produzido pelos autores (2025).

A análise estatística do parâmetro Cor (uH) fornece subsídios quantitativos para a interpretação dos efeitos climáticos na qualidade da água.

O modelo Eta-CamESM2 apresentou maior amplitude interquartil e maior proporção de valores anômalos, indicando maior variabilidade interna. Entretanto, a Anova entre os cenários do modelo

CAM não indicou diferença estatisticamente significativa (F = 0,294; p = 0,995), sugerindo que a variação observada decorre predominantemente da variabilidade interna da série, e não de deslocamentos sistemáticos entre os cenários climáticos. Em contrapartida, o modelo MIROC apresentou menor dispersão e valores medianos mais próximos do *baseline*, evidenciando maior estabilidade relativa. O HadGEM apresentou comportamento intermediário, com valores medianos ligeiramente superiores ao *baseline* e variabilidade moderada.

Tabela 5 – Análise estatística para o parâmetro cor aparente

Estatística descritiva para o parâmetro cor aparente				
Modelo Climático	*Média de pH*	*Amplitude*	*Observações*	
CAM	32,418	199,998	Distribuição assimétrica; presença recorrente de valores extremos elevados.	
HADGEM	33,104	199,997	Maior média entre os modelos; dispersão ligeiramente maior.	
MIROC	31,884	199,995	Média inferior; variabilidade comparável à do CAM.	
Análise de variância (ANOVA) - Cor entre os cenários dentro de cada modelo				
Modelo Climático	*Estatística F*	*Valor-p*	*Significância Estatística*	*Interpretação*
CAM	0,294	0,995	Não	Ausência de diferenças entre cenários.
HADGEM	7,814	< 0,0001	Sim	Diferença estatística com efeito extremamente pequeno.
MIROC	0,117	0,999	Não	Ausência de diferenças entre cenários.
Teste de Tukey para comparação de médias de cor aparente entre os modelos				
Grupo 1	*Grupo 2*	*Diferença de Média*	*Valor-p*	*Diferença Significativa*
CAM	HADGEM	+0,724	< 0,001	Sim
CAM	MIROC	-0,335	< 0,001	Sim
HADGEM	MIROC	-1,059	< 0,001	Sim

Fonte: Produzido pelos autores (2025).

A Figura 7 apresenta o comportamento do parâmetro NH_3–N (nitrogênio amoniacal) sob diferentes cenários climáticos, segundo os modelos Eta-CamESM2, HADGEM e MIROC. Observa-se que, de modo geral, as concentrações projetadas de NH_3–N tendem a aumentar nos cenários futuros, com destaque para o RCP 8.5 (Pessimista), o que indica maior vulnerabilidade da qualidade da água diante das condições de aquecimento e das variações hidrológicas.

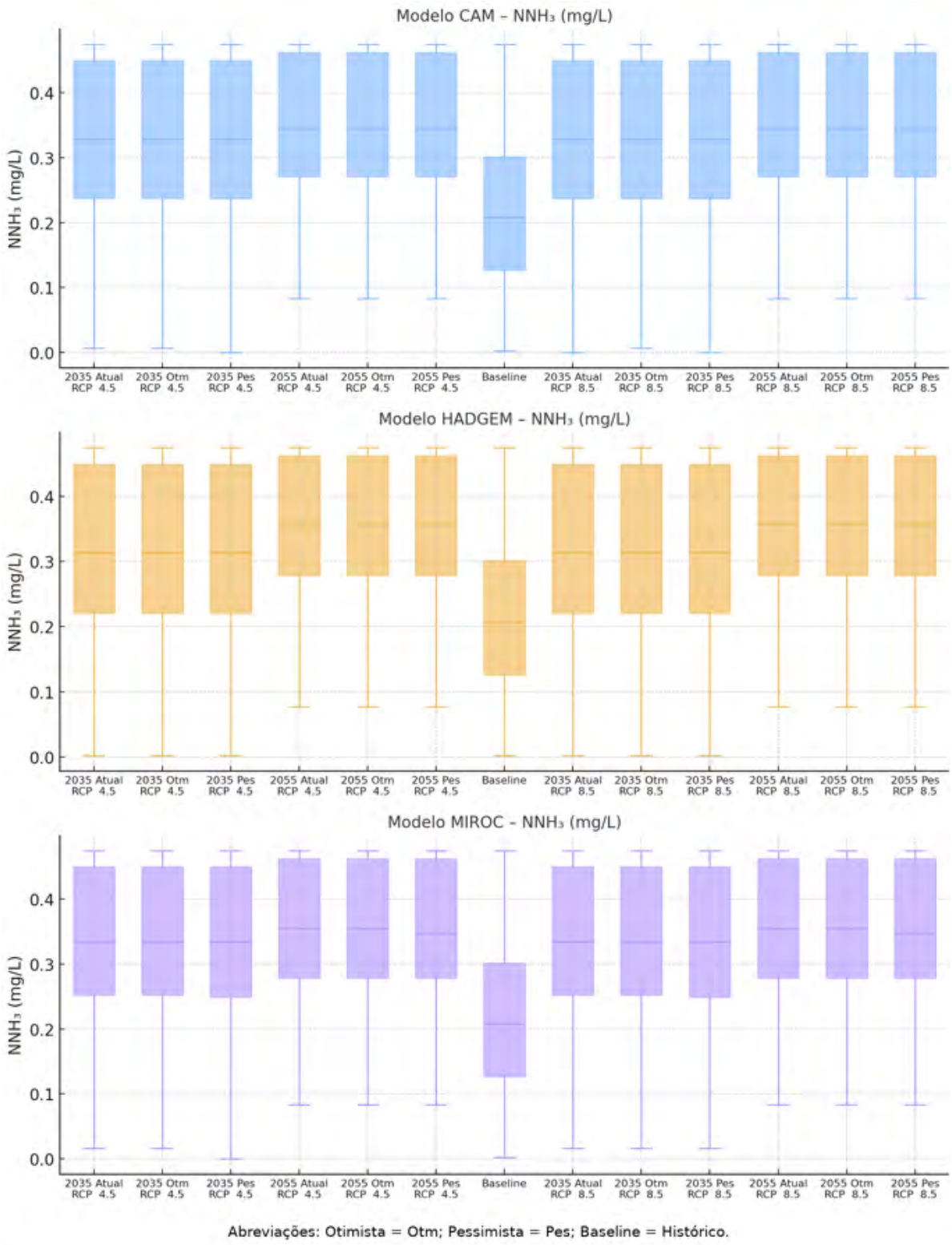


Figura 7 – Projeções do NH_3–N da água (Gradient Boosting) sob variáveis climáticas (Eta–CMIP5) e hidrológicas (MHD-Inpe) para 2035 e 2055.

Fonte: Produzido pelos autores (2025).

De forma integrada, os resultados indicam que o Eta-CamESM2 apresenta maior sensibilidade à variabilidade interna, o HADGEM mantém um comportamento mais concentrado e o MIROC combina estabilidade central com ocorrência de extremos pontuais.

Contudo, a variabilidade global do NH_3–N é explicada pela dinâmica interna da série e pela ocorrência de eventos extremos, e não por diferenças estruturais robustas entre modelos ou cenários.

Tabela 6 – Análise estatística para o parâmetro NH_3–N

Estatística descritiva para o parâmetro NH_3–N			
Modelo Climático	*Média de pH*	*Amplitude*	*Observações*
CAM	0,1086	0,477	Variabilidade moderada; presença de outliers pontuais; distribuição relativamente estável entre os cenários.
HADGEM	0,1051	0,472	Dispersão semelhante ao CAM; comportamento central concentrado.
MIROC	0,104	0,472	Menor dispersão relativa; ocorrência pontual de extremos.

Análise de variância (ANOVA) - NH_3–N entre os cenários dentro de cada modelo				
Modelo Climático	*Estatística F*	*Valor-p*	*Significância Estatística*	*Interpretação*
CAM	2,873	< 0,0001	Sim	Diferença estatisticamente detectável, porém, pequena e baixa relevância prática.
HADGEM	4,912	< 0,0001	Sim	Diferença estatisticamente detectável; magnitude do efeito reduzida.
MIROC	1,964	< 0,0001	Sim	Diferença estatisticamente detectável; variação explicada pelos cenários é pequena.

Teste de Tukey para comparação de médias de NH_3–N entre os modelos				
Grupo 1	*Grupo 2*	*Diferença de Média*	*Valor-p*	*Diferença Significativa*
CAM	HADGEM	+0,0037	< 0,001	Sim
CAM	MIROC	−0,0052	< 0,001	Sim
HADGEM	MIROC	−0,0089	< 0,001	Sim

Fonte: Produzido pelos autores (2025).

A simulação em *Python* do parâmetro NH_3–N mostra um aumento percentual considerável em relação à *baseline*, que está em torno de 0,2 mg/L. Os resultados do período de 2035 (A, O, P) apresentam um valor mediano de cerca de 0,25 mg/L, o que representa um acréscimo de 25%. No período de 2055 (A, O, P), a mediana permanece estável, mas as variações continuam presentes.

A escolha do modelo climático exerce impacto direto sobre as projeções de amônia (NNH3) nos cenários futuros, sendo recomendada uma análise integrada e cautelosa, considerando os objetivos da gestão e os níveis de risco aceitáveis.

5 DISCUSSÕES

Os resultados das simulações indicam que as mudanças climáticas podem influenciar os desafios relacionados à qualidade da água na Bacia do Rio Paraíba do Sul. A análise dos dados revela correlações

diretas entre o aumento das temperaturas do ar e da água, bem como impactos significativos nos parâmetros de qualidade, como pH, turbidez, cor e amônia (NNH3).

As projeções indicam que eventos climáticos extremos, como secas prolongadas e chuvas intensas, podem alterar significativamente a dinâmica hídrica da região, aumentando a concentração de poluentes e sedimentos, e demandando ajustes nos processos de tratamento. Já o aumento da temperatura favorece a proliferação de algas e a produção de toxinas, elevando a DBO e os desafios operacionais.

Estudos anteriores corroboram as informações encontradas. Em Andrade *et al.* (2016), a urbanização, a agricultura e o desmatamento afetam o ciclo hidrológico na Bacia do Rio Paraíba do Sul, impactando diretamente a qualidade da água disponível. Além disso, Gonçalves *et al.* (2015) utilizaram o Índice de Qualidade das Águas (IQA) para avaliar a contaminação por esgotos domésticos e por outras fontes poluidoras, o que evidencia a importância de medidas adicionais de gestão.

Coliformes termotolerantes e fósforo total apresentaram índices de desconformidade de 54% e 12%, respectivamente, na região do baixo Paraíba do Sul, entre 2012 e 2019, evidenciando a necessidade de medidas de gestão mais eficazes (Nunes *et al.*, 2024).

Alvarenga *et al.* (2012) ressaltam que práticas conservacionistas e ações de recuperação ambiental na microbacia do Ribeirão dos Macacos contribuíram para a melhoria da qualidade da água e a sustentabilidade hídrica, sendo a temperatura o parâmetro mais afetado pela sazonalidade da vazão.

Canamary *et al.* (2023), a respeito da segurança alimentar e energética com as mudanças climáticas na Bacia do Rio Paraíba do Sul, utilizam os mesmos modelos hidrológicos determinísticos. Assim, seguem algumas medidas que podem auxiliar nas mitigações desses impactos:

- Desenvolver cenários de estresse hídrico para antecipar medidas em situações críticas (ex.: seca severa ou inundação).
- Construção de reservatórios de contingência para garantir a estabilidade do abastecimento em eventos climáticos extremos.
- Buscar novas fontes (ex.: captação subterrânea, dessalinização ou reúso de água) para reduzir dependência de um único manancial.
- Ajustar os protocolos operacionais com base em modelos de previsão climática para que o sistema se adapte ao aumento da variabilidade hídrica.
- Promover campanhas de conscientização para reduzir o impacto das atividades humanas nos corpos de água.
- Reflorestar as áreas de recarga dos aquíferos e as áreas de proteção ambiental na bacia.
- Recuperar áreas degradadas e sem uso plantando árvores.
- Reduzir o desmatamento e fortalecer as políticas de conservação ambiental.
- Tratar 100% do esgoto doméstico e industrial.
- Reduzir o uso de combustíveis fósseis.
- Intensificar o monitoramento dos parâmetros físicos e químicos da qualidade da água na bacia.

Essas ações podem fortalecer a resiliência dos sistemas de tratamento de água, garantindo que, mesmo em cenários de mudanças climáticas, a qualidade da água tratada atenda aos padrões exigidos, porém, sempre haverá impactos financeiros, o que fará com que os tratamentos de água fiquem mais caros.

6 CONCLUSÕES

Este estudo teve como objetivo avaliar os impactos das mudanças climáticas na qualidade da água na Bacia do Rio Paraíba do Sul, utilizando modelos climáticos (*CAM*, *HADGEM* e *MIROC*) e técnicas de *machine learning*. Os resultados obtidos confirmam os objetivos propostos, indicando associação entre mudanças climáticas e alterações nos parâmetros analisados na qualidade da água e fornecendo subsídios para estratégias de mitigação e adaptação. A análise comparativa entre cenários futuros e o cenário *baseline* (histórico) revelou que as variações climáticas desempenham papel determinante na potabilidade da água e na disponibilidade hídrica.

Há uma tendência de aumento gradual nas temperaturas do ar e da água em cenários futuros, especialmente nos cenários pessimistas de longo prazo, como o de 2055. Esse aquecimento pode comprometer o equilíbrio climático e hidrológico da região, elevando os custos de tratamento de água bruta. Além disso, o aumento da temperatura favorece o crescimento de algas e cianobactérias, que podem produzir toxinas prejudiciais à saúde humana e animal.

O aumento da temperatura e a maior frequência de eventos climáticos extremos, como chuvas intensas e secas prolongadas, favorecem a proliferação de algas nocivas. Esses organismos podem deteriorar a qualidade da água, aumentando a demanda bioquímica de oxigênio (DBO) e reduzindo a concentração de oxigênio dissolvido (OD).

As mudanças climáticas afetam diretamente parâmetros críticos de qualidade da água, como turbidez, cor, amônia (NNH3) e pH. Secas prolongadas reduzem a vazão dos rios, aumentando a concentração de poluentes, enquanto chuvas intensas transportam mais sedimentos e matéria orgânica para os mananciais. A necessidade de tecnologias mais avançadas e o uso intensificado de produtos químicos podem aumentar os custos de tratamento em até 20%.

Diante desses desafios, algumas medidas para mitigar os impactos das mudanças climáticas foram discutidas no tópico anterior.

Essas ações podem fortalecer a resiliência dos sistemas de tratamento de água, garantindo que mesmo em cenários de mudanças climáticas, a qualidade da água tratada atenda aos padrões exigidos. No entanto, é importante destacar que essas medidas terão impactos financeiros, elevando os custos de tratamento.

Este trabalho foi limitado pela dependência de modelos climáticos específicos (*CAM*, *HADGEM*, *MIROC*), que apresentam níveis distintos de sensibilidade e de incerteza. Estudos futuros devem explorar a eficácia de diferentes tecnologias de tratamento em cenários extremos de mudanças climáticas, além de avaliar o impacto de intervenções socioambientais na qualidade da água. A integração de dados de alta resolução temporal e espacial também pode aprimorar a precisão das projeções.

Em suma, este estudo reforça a importância de uma gestão integrada dos recursos hídricos, combinando soluções tecnológicas, técnicas de gestão ambiental e políticas públicas voltadas à segurança hídrica. A implementação de estratégias de mitigação é relevante para garantir a disponibilidade de água de qualidade no futuro.

DECLARAÇÃO SOBRE O USO DE INTELIGÊNCIA ARTIFICIAL

Os autores utilizaram ChatGPT (OpenAI) exclusivamente para edição linguística e aprimoramento estilístico. Todo o conteúdo científico, a análise e a contribuição intelectual foram desenvolvidos e verificados pelos autores, que assumem total responsabilidade pela precisão e integridade do manuscrito.

CONSIDERAÇÕES ÉTICAS

O presente estudo baseou-se exclusivamente na análise de dados ambientais secundários e na modelagem computacional, não envolvendo a coleta de dados com seres humanos ou a experimentação com animais. Dessa forma, não foi necessária a submissão nem a aprovação por um comitê de ética em pesquisa.

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Analysis of grape growers' and wine producers' perceptions in Brazil regarding climate change

Análise da percepção dos produtores de uva e vinho no Brasil em relação às mudanças climáticas

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ABSTRACT

The issue of climate change has received increasing emphasis in studies across various economic sectors, with agriculture being no exception. Among agricultural activities, fruit production is particularly sensitive to climatic variations, and within this sector, viticulture stands out as a segment highly impacted by climate change. In Brazil, grape and wine producers have reported a more frequent occurrence of extreme climatic events, drawing attention to the impacts of these changes on the sector. In this context, this study aimed to analyse grape and wine producers' perceptions across different regions of the country regarding the effects of climate change on viticultural activities, and to identify the adaptation measures they adopt. To this end, a literature review was conducted, followed by a characterisation of Brazil's main grape- and wine-producing regions. Subsequently, primary data were collected through structured questionnaires applied to a sample of 80 producers to assess their perceptions of climate change and adaptation strategies in the sector. The main results indicate that approximately 80% of the surveyed producers report that their production has been affected by climate change in some way, with these impacts linked to productivity and quality. However, adaptation actions remain limited in terms of both the diversity of strategies and their effectiveness. These results highlight the importance of research and climate-monitoring systems in supporting public policy development for the Brazilian grape and wine sector.

Keywords: Climate variability. Adaptive capacity of vitiviniculture. Management strategies. Sustainability.

RESUMO

A questão climática tem ganhado ênfase crescente nos estudos em diversos setores da economia, e a agropecuária não tem sido exceção. Entre as atividades agropecuárias mais sensíveis às variações

climáticas está a fruticultura, e, dentro dela, a vitivinicultura se destaca como um segmento altamente impactado pelas mudanças climáticas. No Brasil, produtores de uva e vinho têm observado uma ocorrência mais frequente de fenômenos climáticos extremos, o que tem chamado atenção para os impactos dessas mudanças no setor. Diante desse cenário, este artigo tem como objetivo analisar a percepção dos produtores de uva e vinho nas diferentes regiões do país sobre os efeitos das mudanças climáticas na atividade vitivinícola, bem como identificar as ações de adaptação adotadas por esses produtores. Para tanto, foi realizada uma revisão da literatura, seguida da caracterização das principais macrorregiões produtoras de uva e vinho no Brasil. Posteriormente, por meio de um levantamento de dados primários realizado com a aplicação de questionário estruturado, buscou-se avaliar a percepção sobre as mudanças climáticas e as estratégias de adaptação implementadas pelo setor. Como principais resultados, observou-se que aproximadamente 80% dos produtores participantes da pesquisa afirmam que suas produções têm sido afetadas de alguma forma pelas mudanças climáticas, relacionando problemas de produtividade e qualidade a esses fenômenos. Por outro lado, as ações de adaptação ainda são limitadas, tanto em termos de diversidade de estratégias quanto de efetividade. Esses resultados indicam a importância de pesquisas e do monitoramento climático de precisão a fim de subsidiar novas políticas públicas para o setor vitivinícola brasileiro.

Palavras-chave: *Variabilidade climática. Capacidade adaptativa da vitivinicultura. Estratégias de manejo. Sustentabilidade.*

1 INTRODUCTION

According to projections by the Food and Agriculture Organisation of the United Nations (FAO, 2021), agriculture in the 21st century will face multiple challenges, including the need to address population growth, which is expected to increase the global population from the current 7.8 billion to approximately 9 billion by 2050. This scenario implies the need to increase production of food, fibre, and energy while simultaneously facing emerging challenges related to carbon emissions, water availability, and climate change, as well as issues such as food security, food safety, and traceability.

On the other hand, the development of agriculture is understood as an evolutionary process that has responded to the challenges of each historical period. Evidence of this can be seen in Brazilian agriculture, which represents a rare case at the global level: through research and innovation, the country, in less than 30 years, has shifted from being a net importer of a large share of domestically consumed products to becoming a major producer across several global agricultural value chains, even achieving a leading position in many of them (Embrapa, 2014).

Within this framework, according to Pillon (2016), the past decades of agricultural production worldwide can be understood as being shaped by three major waves. The first was characterised by the Green Revolution, which followed a monodisciplinary approach, focusing on monoculture, the use of synthetic inputs, and adaptive research, taking place between 1960 and 1990 (Borlaug, 1971).

The second wave began in the 1990s, with the emergence of integrated systems approaches that emphasise sustainable intensification, multidisciplinarity, production efficiency, and systems-based research (Alves *et al.*, 2015). The third wave, projected for the coming years, refers to a biologically based agriculture, focusing on complex systems, interdisciplinarity, the use of biological inputs, and open research and innovation (Soares, 2020).

However, issues that were previously less evident to the general public have become part of the global discussion agenda, particularly climate change and its impacts across different sectors of the economy. Thus, without delving into the causes of climate change, it is understood that there is a growing perception of more frequent extreme weather events across regions worldwide, including Brazil.

This increased occurrence of such phenomena — or at least the perception of a greater intensity of climate-related events affecting production regions — has not always led to proportional actions to address the challenges of mitigation and, especially, adaptation. This may result either from a lack of knowledge regarding which actions are most effective in minimising impacts or enhancing adaptation, or from the absence of clearer guidelines from relevant public authorities (Nascimento; Bursztyn, 2011).

In global forums addressing climate change, such as the recent United Nations Climate Change Conferences (COP 26, held in Glasgow, in 2021; COP 27, held in Sharm El-Sheikh, Egypt, in November 2022; and COP 28, held in Dubai in December 2023), new commitments to reduce greenhouse gas emissions have been discussed and adopted by countries each year for the coming decade. At the same time, increasing emphasis has been placed on the importance of adaptation actions.

An important element in recent discussions has been the recognition that agricultural activities, often perceived as major contributors to greenhouse gas emissions, should also be viewed as part of the solution. In this context, adaptation has gained increasing relevance in the debate (FAO, 2023a; FAO, 2023b; Kissel *et al.*, 2023).

According to the United Nations (UN, 2022), one of the main outcomes of COP 27 was the strengthening of the adaptation agenda in response to climate change impacts. In this sense, economic sectors are expected to face growing pressure to adopt adaptive practices. At COP 28, negotiators agreed to establish global targets with specific timelines for different themes and economic sectors; however, adaptation targets were not quantified and did not include clear guidelines on how this process will be financed, particularly in developing countries.

In any case, there is a clear increase in attention to the need for adaptation financing mechanisms, which, in turn, require the development and adoption of practices, technologies, and processes that rural producers can implement in the context of climate change adaptation in agriculture.

Concerning climate change in viticulture, there has been a growing body of scientific literature worldwide, including studies on climate change, carbon, water, and sustainability in relation to the wine sector, as evidenced by the proceedings of the International Organisation of Vine and Wine (OIV, 2021).

As demonstrated in the literature review presented in this article, variations in temperature, precipitation, thermal amplitude, and other factors can significantly affect the performance of grape varieties across different *terroirs*.

Considering Brazil's continental dimensions and its increasingly diversified wine sector, with production taking place in regions with markedly distinct characteristics, understanding which climatic factors are most relevant to viticulture is essential. Furthermore, assessing how producers in each region have perceived changes in these phenomena in recent years is crucial to establishing a more accurate diagnosis and supporting more comprehensive conclusions aimed at adaptation and mitigation strategies for the Brazilian wine sector.

Within this context, the objective of this study is to investigate how climate change has affected Brazilian viticulture across its regions, from the perspective of grape and wine producers, and to analyse how these actors have responded by adopting adaptation measures in their activities.

Thus, the relevance of the topic is justified, as well as the importance of studies that assess the current situation of different producing regions in Brazil in relation to these variables. Identifying signals of significant change and providing information to support decision-making in both the public and private

sectors, thereby enhancing their capacity to respond to emerging opportunities and risks, constitutes a crucial input for the technological and sustainable development of agriculture in the future.

2 LITERATURE REVIEW

2.1 CLIMATE CHANGE AND VITICULTURE

Climate change has become a central topic in political and scientific debates since the early 2000s, particularly following major natural disasters such as Hurricane Katrina, which struck the United States in 2005. The awarding of the Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) and to Al Gore in 2007 further reinforced the political relevance of the issue; however, part of the literature indicates that effective adaptation measures have not matched this increased international visibility in productive sectors, including the wine sector (Nascimento; Bursztyn, 2011).

Since then, progress has been made, and the main international forum addressing the issue has been the Conference of the Parties (COP), whose most recent edition was held in Dubai in November 2023.

As a result, several economic sectors have begun to assess how they are being affected by, or will be affected by, climate change. This is also the case in the wine sector, which is highly sensitive to climatic variability. The International Organisation of Vine and Wine (OIV) has incorporated specific sections in its conferences and publications addressing climate-related issues in viticulture and winemaking.

Numerous studies have investigated the influence of climate on grape quality, as well as on must and wine characteristics. Araújo *et al.* (2016) highlight the effect of temperature on vine metabolism. Rufato *et al.* (2021) expand the analysis by emphasising the interaction between climate, topography, and soil, suggesting that the sensitivity of viticulture cannot be understood solely in thermal terms. This perspective aligns with Gambetta *et al.* (2020), who emphasise the difficulty of predicting crop responses in complex scenarios, generating uncertainty for both producers and policymakers in regions dependent on this economic activity.

Understanding past climatic conditions and future projections, and estimating their impacts on agro-meteorological indices applied to grapevines, is therefore a key strategy for the development of the Brazilian wine sector. This need is particularly relevant given Brazil's tropical climate, where viticulture is distributed across diverse climatic regimes.

According to recent IPCC reports (IPCC, 2021; IPCC, 2022), projections indicate that climate change impacts will intensify throughout this century, affecting ecosystems worldwide. In this context, multiple future scenarios are being modelled to assess the magnitude of these impacts and to guide mitigation and, especially, adaptation strategies.

Among the observed effects of climate change are increased rainfall intensity in many regions, more frequent heat waves, and extreme cold events. Additional impacts include large-scale wildfires in the western United States, Australia, and Portugal, which have affected grape cultivation and wine production. One example is the growing incidence of smoke-tainted wines in the western United States, Canada, and Australia. Many mountainous regions have also shown trends of earlier snowmelt and reduced snow accumulation, affecting water availability for agriculture and contributing to increased drought frequency (Jones *et al.*, 2022).

On the other hand, Xyrafis *et al.* (2022) argue that temperature anomalies and changes in precipitation patterns may have both positive and negative effects on agricultural production at regional or local scales, depending on the affected area. This contrasts with Jones *et al.* (2022), who emphasise

predominantly negative impacts, such as droughts and wildfires, suggesting that assessments must be contextualised by region and grape variety.

Recent studies indicate that climate change is altering the climatic suitability for viticulture, making some traditional regions less suitable while favouring new areas, such as those at higher altitudes or latitudes (Leeuwen *et al.*, 2024). This demonstrates that impacts are not homogeneous and requires the sector to consider not only local adaptations but also the potential relocation of production as a long-term strategy.

Leeuwen *et al.* (2019) identify several adaptation strategies for viticulture, including the development of late-ripening varieties, clones, and rootstocks; increasing trunk height; reducing the leaf area-to-fruit weight ratio; late pruning; shifting cultivation to higher altitudes; and combining different strategies for gradual implementation. Some of these practices require minimal changes in vineyard management, while others may involve vineyard replanting or varietal substitution, potentially affecting terroir typicity.

According to Angelotti (2011), some adaptation measures require long-term research, particularly the development of new grape varieties. Thus, although a wide range of adaptation strategies exists, many require decades of research, highlighting the tension between short-term measures and long-term structural solutions.

Complementarily, Leeuwen *et al.* (2024) emphasise that while some adaptation strategies—such as selecting heat-tolerant varieties, adjusting canopy management, and optimising irrigation—can mitigate the impacts of global warming, these measures have limitations, particularly in regions severely affected by droughts or heat waves. In such cases, the economic viability of viticulture may be compromised, necessitating more substantial adjustments, including relocation to more suitable climatic regions.

Pandolfo (2010), as cited in Rufato *et al.* (2021), projected that in the Serra Catarinense region of southern Brazil, rising temperatures could reduce the areas currently suitable for grape cultivation by more than 50% by 2050 and 2070. According to these authors, earlier budburst and shorter ripening periods are also expected, potentially leading to a decline in wine quality. Monitoring the spatial shift of suitable areas and investing in regionally adapted varieties and genetic improvement are therefore essential.

Furthermore, changes in vineyard management directly affect grape processing, requiring new techniques to maintain wine quality or to develop new products adapted to changing conditions. In summary, climate change has gained significant attention over the past decades; however, as noted by Nascimento and Bursztyn (2011), although awareness has increased, adaptation and mitigation actions have not progressed at the same pace.

2.2 PRODUCERS' PERCEPTIONS OF CLIMATE CHANGE

Several studies have focused on producers' perceptions of the impacts of climate change on grape and wine production. For example, Ryan (2019) investigated the perceptions of producers in New Zealand; Zuniga *et al.* (2024) examined producers' perceptions in Southern California, United States; Battaglini *et al.* (2009) analysed the perceptions of European producers (Italy, France, and Germany); and Vega-Bayo *et al.* (2023) assessed the mitigation strategies adopted by producers in the Rioja region of Spain.

According to Ryan (2019), climate change may affect both the quality and quantity of grapes used for wine production, as well as overall wine production in the study region. The author investigated adaptation planning within the New Zealand wine industry, examining growers' decision-making

processes and their perceptions of climate change. The findings indicate that winegrowers are partially informed about climate change, with some adaptation planning underway; however, most still lack structured adaptation plans.

In Brazil, Vieira, Garcia, and Bruch (2015) conducted a similar analysis in the Vales da Uva Goethe region, in the state of Santa Catarina, southern Brazil. The study aimed to develop an exploratory assessment of the potential impacts of changes in climate dynamics on viticulture within the area defined at the time by the Geographical Indication of the Vales da Uva Goethe. The results showed that only a portion of producers associate variations in grape quantity and quality with the effects of climate change.

Beyond the wine sector, Tanure *et al.* (2024), in a study analysing how farmers' perceptions of climate change influence the adoption of sustainable agricultural technologies in Brazil—particularly in the Amazon and Atlantic Forest biomes—found that farmers' motivations to adopt more sustainable practices are strongly driven by economic incentives. In addition, the overall level of adoption of such technologies remains low, mainly due to a lack of technical knowledge and financial support.

While in Brazil, Vieira *et al.* (2015) identify a weak association between climate variability and grape quality, studies in countries such as New Zealand (Ryan, 2019) show that even in regions highly dependent on viticulture, producers' perceptions of climate risks remain limited. This convergence points to a global challenge: the gap between producers' perceptions and the urgency highlighted in IPCC reports (2021, 2022). In this context, by examining different Brazilian regions, this study contributes to addressing a gap that remains underexplored in the international literature: how producers operating in tropical and subtropical contexts perceive and respond to climate change.

2.3 WINE-PRODUCING REGIONS IN BRAZIL

Changes in temperature, variations in solar radiation levels, and increased atmospheric CO_2 concentrations are expected to influence vine productivity, with direct impacts on grape and wine quality. According to Costa *et al.* (2016), as cited in Xyrafis *et al.* (2022), changes in these environmental factors are likely to affect wine-producing regions differently over the coming decades.

Due to its continental dimensions, Brazil presents a unique viticultural landscape worldwide, as wine production is distributed across three distinct macro-regions. According to Pereira (2021) and Pereira *et al.* (2020), these macro-regions can be classified as follows: the Southern region, representing traditional viticulture; winter wine production in the Southeast and Central-West regions; and tropical wine production in the Northeast region (Figure 1).

According to these authors, traditional viticulture is located in the South and Southeast regions of Brazil, tropical viticulture is concentrated in the Northeast, and the most recent system—winter viticulture—occurs in the Southeast, Central-West, and Northeast regions, in vineyards located at altitudes above 700 meters.

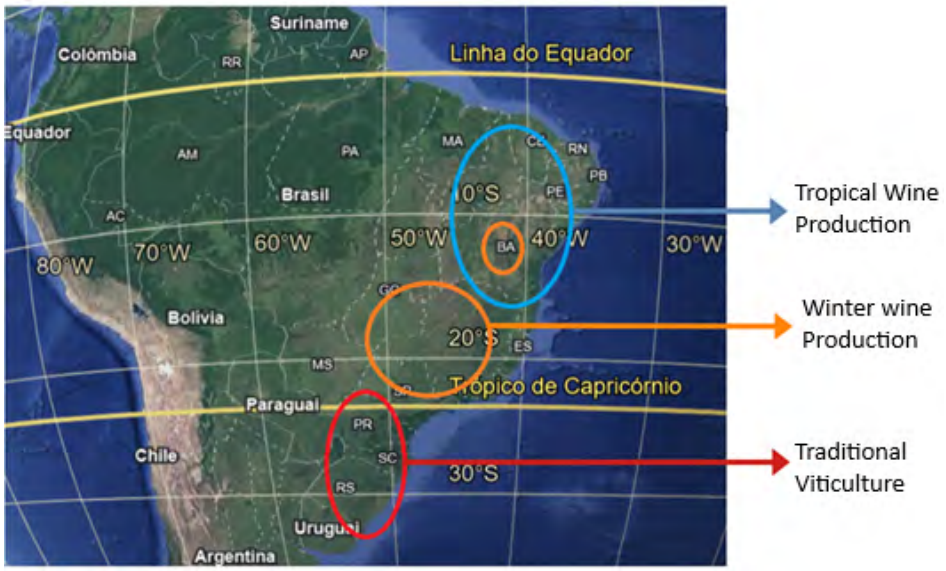


Figure 1 – Three Brazilian wine-producing regions, classified according to climatic production and management characteristics

Source: Adapted from Google Earth and Pereira et al. (2020)

This is, evidently, a macro-level analysis; a more detailed examination of each region would reveal numerous characteristics and nuances that differentiate local terroirs, as highlighted by Leeuwen (2004).

Nevertheless, it is important to recognise that each macro-region presents a distinct set of characteristics, including the historical development of the activity, cultural aspects, cultivation techniques, planting periods, and product-specific features, both in terms of grape varieties and processing outcomes, such as juices and wines.

3 MATERIALS AND METHODS

This study is exploratory and descriptive in nature, based on the collection of primary data through a survey questionnaire. The instrument was developed based on theoretical frameworks related to viticulture, climate change, and producers' perceptions, and was structured to include open-ended, multiple-choice, and multiple-selection questions. The questionnaire was organised into sections covering the following topics: respondent identification; property location and characteristics; perceptions of climate and viticulture; perceptions of climate change; qualitative and economic impacts of climate change on production; and actions or investments aimed at mitigation.

The research was conducted in accordance with ethical principles applicable to studies involving human subjects. All participants were informed about the objectives of the study and participated voluntarily, providing informed consent at the beginning of the questionnaire. The study was submitted to the Human Research Ethics Committee of the Federal Institute of Santa Catarina (CEPSH-IFSC) and was approved under protocol number CAAE 68133023.4.0000.0185. The questionnaire was administered digitally via Google Forms and remained open from August to October 2023.

The sample consisted of 80 grape and wine producers from different regions of Brazil, recruited through voluntary participation following dissemination via academic and sectoral networks, including producers' associations and educational and research institutions. Of the total responses, 79 were considered valid, with one excluded due to incomplete data.

Following the literature review, the three main Brazilian wine-producing macro-regions were characterised. Subsequently, based on the survey results, data were tabulated and analysed using both qualitative and quantitative approaches. Qualitative data were categorised through content analysis, while quantitative analysis was conducted using Microsoft Excel.

4 RESULTS AND DISCUSSION

4.1 CHARACTERISATION OF THE SAMPLE OF GRAPE AND WINE PRODUCERS

The regional distribution of survey respondents was as follows: 70.8% from the Southern region (n = 56), 10.1% from the Northeast (n = 8), 15.1% from the Southeast (n = 12), and 3.7% from the Central-West (n = 3). No respondents were recorded from the Northern region of Brazil. This distribution is consistent with the structure of Brazilian viticulture, according to official data on cultivated area, in which the Southern region accounts for 73.4% of total production area (55,710 hectares), followed by the Northeast with 14.68% (11,153 hectares), the Southeast with 11.5% (8,717 hectares), the Central-West with 0.4% (257 hectares), and the North with 0.03% (26 hectares) (IBGE, 2020). For analytical purposes, the three main Brazilian wine-producing macro-regions were considered (South, Southeast/Central-West, and Northeast).

Regarding the profile of participants, among the 79 valid respondents, 78.5% were male and 21.5% female. In terms of age distribution, 26.6% were between 30 and 39 years old; 24.1% between 50 and 59; 20.3% were over 60; 17.7% between 40 and 49; and 11.4% between 18 and 29 years old.

With respect to education level, 11.4% reported having completed secondary education; 11.4% had incomplete higher education; 29.1% had completed higher education; and 44.3% held postgraduate degrees. Participants identified themselves as rural producers (40.5%), entrepreneurs (22.8%), private-sector employees (16.5%), public servants (8.9%), self-employed workers (6.3%), and retirees (3.8%).

These profile data reflect the characteristics of grape and wine producers across different Brazilian regions and corroborate the findings of Ryan (2019) in New Zealand, where producers also exhibit a high level of qualification (74%) and where diverse professional backgrounds contribute to a wide range of expertise within the wine sector, enhancing the robustness of the data collected.

4.2 PRODUCTION AND FARM CHARACTERISTICS OF RESPONDENTS

Regarding the length of time producers have been engaged in viticultural or winemaking activities, a relatively balanced distribution across experience levels is observed: up to 5 years (24.1%), 6 to 10 years (17.7%), 11 to 20 years (24.1%), and over 30 years (13.9%). Studies indicate that producers with higher levels of education or greater experience tend to perceive and adopt adaptation measures more effectively (Tanure *et al.*, 2024; Vieira *et al.*, 2015).

In terms of farm size, 68.5% of respondents own properties smaller than 50 hectares, while 11.4% have farms ranging from 50 to 100 hectares, and 20% exceed 100 hectares. Regarding the area planted with grapes, 40.5% of producers cultivate less than 3 hectares; 38% between 4 and 10 hectares; 10.1% between 11 and 20 hectares; 3.8% between 21 and 50 hectares; and 7.6% cultivate more than 50 hectares.

These findings reinforce the predominance of small-scale production in Brazilian viticulture. This is particularly relevant because smaller cultivated areas, depending on management practices, tend to make variations in productivity, anomalies, and the impacts of climatic events more noticeable, as

well as the need for adjustments in cultivation techniques. This, in turn, enhances the sensitivity and reliability of the perceptions reported by producers in the survey.

4.3 PERCEPTIONS AND IMPACTS OF CLIMATE CHANGE ON VITICULTURE AND WINE MAKING

To investigate producers' perceptions of climate-related events and their impacts on production, specific questions were applied, the results of which are presented in Figures 2 to 4 and discussed below. A total of 94.9% of respondents considered climate to be highly relevant for grape production. This finding is consistent with other studies conducted in Brazil, which show that producers—even those operating small-scale farms—recognise climate as a key determinant of viticulture (Vieira *et al.*, 2015).

When asked about observed changes in climate patterns in their production regions, 81% of respondents reported noticing such variations. This result indicates that Brazilian producers are aligned with the perceptions of producers in other countries, such as New Zealand, where most respondents in Ryan (2019) acknowledged that climate change is real and already occurring. Similar findings have been reported among Argentine producers, who have observed an increase in extreme events (Straffelini *et al.*, 2023), as well as among producers in Southern California (Zuniga *et al.*, 2024) and in Germany, France, and Italy, who highlight changes since the 1990s, particularly related to temperature and precipitation (Battaglini *et al.*, 2009).

However, given Brazil's continental scale, response patterns varied across regions. For instance, none of the respondents from the Central-West region reported observing climate change; however, all of them have been engaged in viticulture for less than five years, which may explain their lower perception of climate variability. This is likely because identifying climate trends generally requires longer time series, as demonstrated by studies from the Brazilian National Institute for Space Research (Inpe), which have documented climate changes across all regions of the country over the past three decades.

According to Inpe studies, the average number of days with heatwave events in Brazil increased from 7 to 53 between 2011 and 2020. The Southern region experienced less severe drought impacts; however, it also recorded above-average rainfall anomalies. The study further indicates that factors such as urbanisation and land-use and land-cover changes have contributed to rising temperatures (MCTI, 2023).

Nevertheless, temperature is not the only relevant factor, as extreme climate events may result from multiple interacting variables. For producers, these events tend to be more noticeable and impactful than gradual changes in average temperatures. Straffelini *et al.* (2023), in a study on climate change in Argentina, report that rising temperatures, heatwaves, droughts, hail, and intense rainfall have led winegrowers to relocate vineyards to higher altitudes in search of more favourable conditions. Similarly, among producers in Southern California, increasing temperatures combined with drought periods have caused phenological shifts in grapevines, such as earlier budburst and harvest, directly affecting vineyard management (Zuniga *et al.*, 2024).

Among the participants in this study who reported observing climate change (n = 73), respondents were also asked when they began to perceive these variations in their production regions. More than 60% indicated that they have noticed such changes within the past five years, as illustrated in Figure 2.

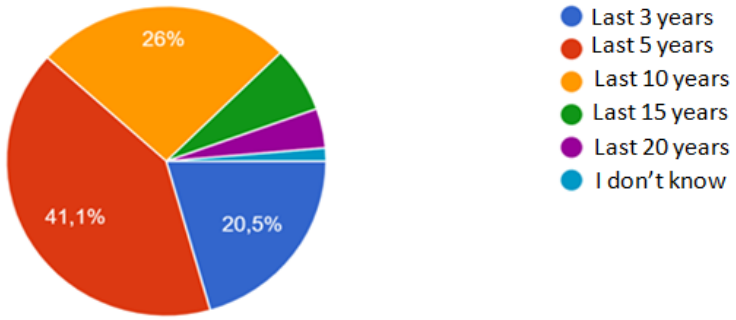


Figure 2 – Duration of Producers' Perception of Climate Variability in Their Production Regions

Source: The authors

Regarding the most frequently observed types of events in the production regions, producers highlighted different climatic phenomena, as shown in Figure 3, with a predominance of perceived temperature variations outside the historical patterns of the region (25.68%); heavy rainfall (25.13%); hail (19.67%); frost (14.20%); and, to a lesser extent, strong winds and flooding (3.82% each).

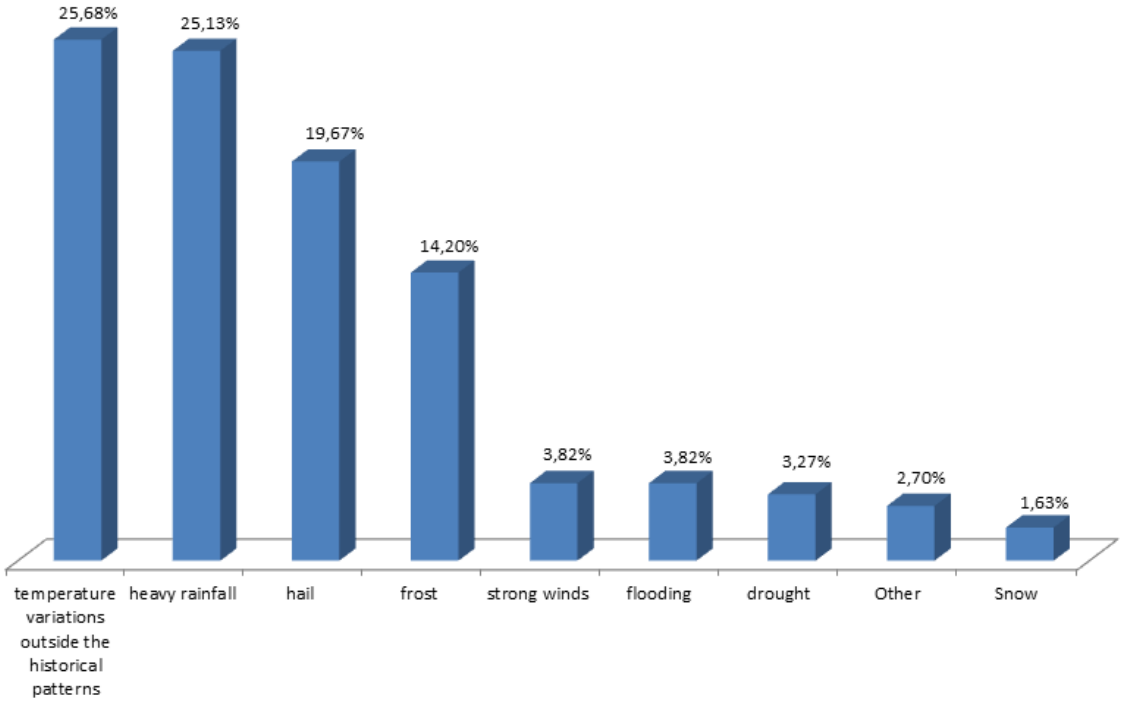


Figure 3 – Producers' Perceptions of the Main Climatic Events Observed as Indicators of Climate Change in Their Production Regions

Source: The authors

The perception of increased temperatures outside historical patterns among Brazilian producers may reflect their level of experience and familiarity with the issue, as it aligns with findings from New Zealand reported by Ryan (2019), where producers identified rising local temperatures as the main impact and most direct consequence of climate change. Despite concerns regarding temperature changes, producers do not always perceive this climatic factor as negative, since solar radiation is associated with the production of high-quality grapes (Ryan, 2019).

In Europe, Battaglini *et al.* (2009) had already indicated that the main climate changes perceived by producers were related to increasing temperatures, hotter summers, and extreme events such as prolonged droughts (Italy) and intense rainfall and flooding (France).

On the other hand, extreme climate events such as heavy rainfall, hail, frost, strong winds, and droughts are a concern not only for Brazilian producers but also for those in New Zealand and Argentina, as they are associated with negative impacts on grape quality (Ryan, 2019; Straffelini *et al.*, 2023). The results further indicate that 90% of Brazilian respondents perceived an increase in the frequency of extreme climatic events. Moreover, they reported that both the number and intensity of such events have increased over the past decade, with a marked intensification in the last five years.

Regarding the degree of impact of climate events on grape production, 80% of respondents stated that their production has been affected in some way by climate change in their region, while 70% classified these impacts as high, based on a scale ranging from high to low. The Southern and Northeastern regions were the main contributors to this result, which may be explained by their longer history and greater experience in viticulture compared to other regions, such as the Central-West, considered a new viticultural frontier in Brazil (Pereira *et al.*, 2020), where respondents reported a moderate level of impact.

Given the high level of perceived impact of climate change on grape production, this study also sought to understand how these events affect production quality (Figure 4). The impacts reported by producers can be grouped into two main categories. The first relates to productivity, highlighting reductions in yield per plant, deterioration in grape health (higher incidence of rot), and consequently, increased use of pesticides. The second category relates to the physicochemical quality of grapes, particularly variations in ripening levels, including increases or decreases in sugar content depending on climatic conditions.

These findings are consistent with perceptions reported by producers in both Old World and New World wine regions, who identify reduced yields, compromised grape health, and declines in both quantity and quality as the main negative impacts of climate change (Battaglini *et al.*, 2009; Ryan, 2019).

Furthermore, studies by Straffelini *et al.* (2023) and Zuniga *et al.* (2024), focusing on Argentina and Southern California, respectively, are consistent with the results of this study, indicating that the main impacts of climate change include reduced productivity and grape quality, as well as compromised vineyard health, particularly due to increased disease incidence under humid conditions.

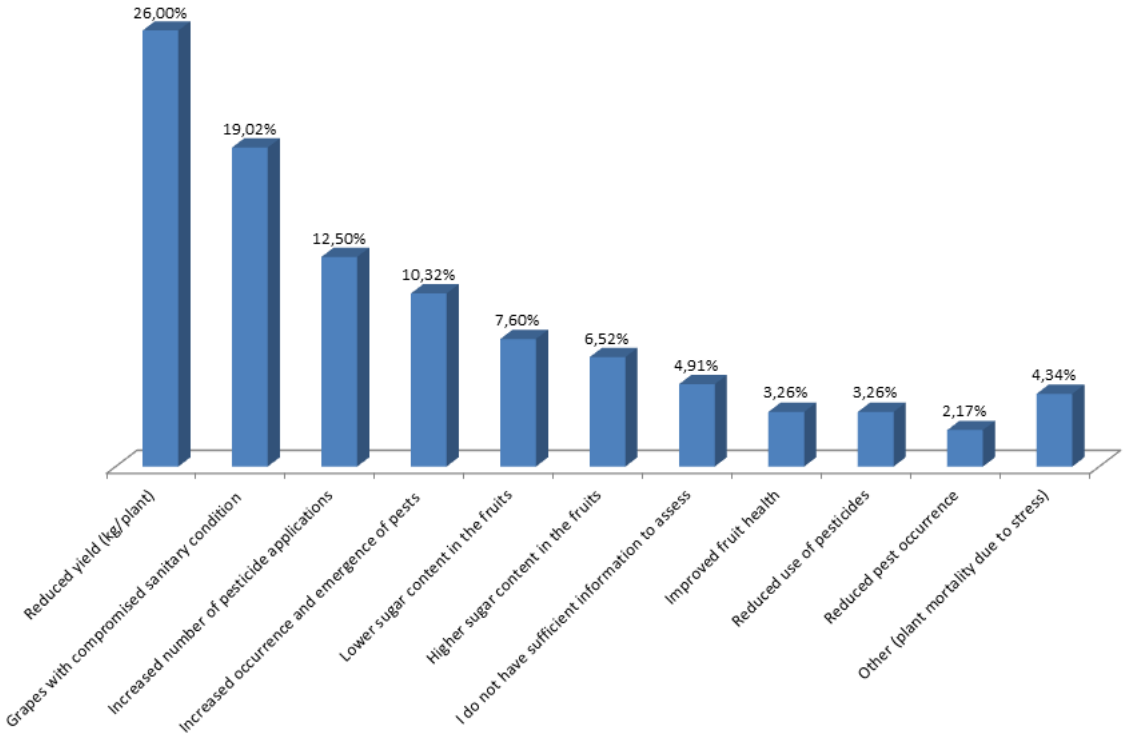


Figure 4 – Producers' Perceptions of the Impacts of Climatic Events on the Quality of Grapes Produced

Source: The authors

In addition to production impacts, producers also reported their perceptions regarding the financial impacts of climate events. More than 80% of respondents indicated that they had experienced economic losses. Estimated damages over the past five years varied considerably: 15.9% reported losses between BRL 26,000 and BRL 50,000; 14.5% between BRL 51,000 and BRL 100,000; and 25% reported losses exceeding BRL 100,000.

Given producers' awareness of the impacts of climate change on viticulture in their regions, this study sought to understand how they have responded. A total of 69.6% of respondents reported adopting adaptation measures. The main strategies identified include: (a) adjusted vineyard management practices, such as late pruning; (b) installation of physical barriers, including windbreaks and plastic covers; (c) increased use of pesticides treatments; (d) adoption of more resilient grape varieties; (e) seeking additional information on local climate conditions; and (f) agricultural insurance.

Compared with New Zealand, where only 32% of producers are considering adaptation plans, Brazilian producers show greater engagement in adaptive actions. However, these are often not structured within medium- or long-term planning frameworks. Nevertheless, across countries, adaptation strategies tend to converge, particularly in vineyard and water management, as well as varietal selection or replacement (Ryan, 2019).

In Europe, varietal change has also been discussed as an adaptation strategy, being more accepted in Germany, while other countries face regulatory constraints related to geographical indications. Additionally, increased disease and pest control and greater demand for technical information on climate and grape varieties have been identified as important responses in countries such as Germany, France, and Italy (Battaglini *et al.*, 2009).

In Argentina, other adaptation strategies have been implemented, including relocating vineyards to higher altitudes (2,000–3,000 m), irrigation under water scarcity conditions, soil and drainage management, vegetation cover, structural support in sloped areas, and the use of sensors and remote monitoring technologies for water and climate management, as well as practices aligned with the Sustainable Development Goals (Straffelini *et al.*, 2023).

In Southern California, adaptation strategies primarily focus on coping with high temperatures, including optimised irrigation management, the use of drought- and heat-resistant varieties and rootstocks, canopy management and shading practices, climate-monitoring technologies, and adjustments to the agricultural calendar (Zuniga *et al.*, 2024). Overall, despite differences in planning and investment levels across regions, there is a clear convergence in adaptation strategies, reflecting a growing concern within the global wine sector.

To assess progress in adaptation planning, producers were asked about barriers limiting implementation. The main constraints identified were budget limitations (50.7%), lack of specific financing (28.8%), and insufficient local climate information (23.3%). These findings are consistent with studies in New Zealand, where lack of information and uncertainty are also major constraints, followed by financial limitations (Ryan, 2019).

Similarly, in Argentina, high costs of adaptive technologies and socioeconomic impacts associated with relocating production areas are key barriers (Straffelini *et al.*, 2023). In Southern California, producers also highlighted limited institutional support and a lack of public policies, as well as financial and informational constraints (Zuniga *et al.*, 2024). In Europe, regulatory constraints related to geographical indications further limit adaptation options (Battaglini *et al.*, 2009). These findings highlight the global complexity of climate change adaptation in the wine sector.

Finally, regarding investment capacity, 69.9% of respondents indicated they would invest if specific credit lines were available, and nearly 70% reported willingness to invest their own resources. For

approximately 60% of producers, the maximum investment would be up to BRL 50,000. These findings reinforce the predominance of small-scale production in Brazilian viticulture, which faces greater financial constraints and, consequently, higher vulnerability to climate change compared to larger enterprises—a pattern also observed in New Zealand and Australia (Galbreath, 2011; Ryan, 2019).

5 FINAL CONSIDERATIONS

The results of this study indicate that producers' perceptions of the impacts of climate change on viticulture have increased significantly. More than 80% reported that their production has been affected, corroborating findings from the Brazilian National Institute for Space Research (Inpe) (MCTI, 2023), which indicate climate changes across all regions of the country over the past 30 years. The impacts were more pronounced in the Southern and Northeastern regions—traditionally important grape-producing areas—where financial losses exceeding BRL 100,000 were reported by approximately one-quarter of respondents.

Despite this growing awareness, the identified adaptation measures remain limited in scope and largely focused on incremental adjustments in vineyard management and increased pesticide use. This raises environmental and economic concerns, as such approaches do not ensure long-term resilience and may generate adverse effects on the environmental and economic sustainability of the wine sector.

These findings highlight the need for public policies, targeted financing mechanisms, and the development of more effective adaptive technologies capable of enhancing resilience and sustainability in Brazilian viticulture. However, it is important to acknowledge the limitations of this study, including the restricted sample size and the exploratory nature of the analysis, which do not allow for generalisation across the entire production chain. Future research should expand the methodological scope by incorporating comparative analyses across countries or regions, as well as technical indicators of climate impacts, in order to support more effective and sustainability-oriented adaptation strategies.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (GPT-5.3, OpenAI) for language editing and stylistic

polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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Análise da percepção dos produtores de uva e vinho no Brasil em relação às mudanças climáticas

Analysis of grape growers' and wine producers' perceptions in Brazil regarding climate change

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ARTICLE- VARIA

RESUMO

A questão climática tem ganhado crescente ênfase nos estudos em diversos setores da economia, e a agropecuária não tem sido exceção. Entre as atividades agropecuárias mais sensíveis às variações climáticas está a fruticultura, e, dentro dela, a vitivinicultura se destaca como um segmento altamente impactado pelas mudanças no clima. No Brasil, produtores de uva e vinho têm percebido uma ocorrência mais frequente de fenômenos climáticos extremos, o que tem chamado atenção para os impactos dessas mudanças no setor. Diante desse cenário, este artigo teve como objetivo analisar a percepção dos produtores de uva e vinho nas diferentes regiões do país sobre os efeitos das mudanças climáticas na atividade vitivinícola, bem como identificar as ações de adaptação adotadas por esses produtores. Para tanto, foi realizada uma revisão da literatura, seguida da caracterização das principais macrorregiões produtoras de uva e vinho no Brasil. Posteriormente, por meio de um levantamento de dados primários realizado com a aplicação de questionário estruturado, buscou-se avaliar a percepção sobre as mudanças climáticas e as estratégias de adaptação implementadas pelo setor. Como principais resultados, observou-se que aproximadamente 80% dos produtores participantes da pesquisa afirmam que suas produções têm sido afetadas de alguma forma pelas mudanças climáticas, relacionando problemas de produtividade e qualidade a esses fenômenos. Por outro lado, as ações de adaptação ainda são limitadas, tanto em termos de diversidade de estratégias quanto de efetividade. Esses resultados indicam a importância de pesquisas e do monitoramento climático de precisão a fim de subsidiar novas políticas públicas para o setor vitivinícola brasileiro.

Palavras-chave: Variabilidade climática. Capacidade adaptativa da vitivinicultura. Estratégias de manejo. Sustentabilidade.

ABSTRACT

The issue of climate change has received increasing emphasis in studies across various economic sectors, with agriculture being no exception. Among agricultural activities, fruit production is particularly sensitive to climatic variations, and within this sector, viticulture stands out as a segment highly impacted by climate change. In Brazil, grape and wine producers have reported a more frequent occurrence of extreme climatic events, drawing attention to the impacts of these changes on the sector. In this context, this study aimed to analyse grape and wine producers' perceptions across different regions of the country regarding the effects of climate change on viticultural activities, and to identify the adaptation measures they adopt. To this end, a literature review was conducted, followed by a characterisation of Brazil's main grape- and wine-producing regions. Subsequently, primary data were collected through structured questionnaires applied to a sample of 80 producers to assess their perceptions of climate change and adaptation strategies in the sector. The main results indicate that approximately 80% of the surveyed producers report that their production has been affected by climate change in some way, with these impacts linked to productivity and quality. However, adaptation actions remain limited in terms of both the diversity of strategies and their effectiveness. These results highlight the importance of research and climate-monitoring systems in supporting public policy development for the Brazilian grape and wine sector.

Keywords: *Climate variability. Adaptive capacity of vitiviniculture. Management strategies. Sustainability.*

1 INTRODUÇÃO

Conforme projeções da FAO (2021), a agricultura no século XXI enfrentará múltiplos desafios, uma vez que terá de lidar com o crescimento populacional, que deverá elevar a população mundial dos atuais 7,8 bilhões para cerca de 9 bilhões de habitantes até 2050. Esse cenário implica a necessidade de aumento da produção de alimentos, fibras e energia, ao mesmo tempo que surgem novos desafios relacionados às emissões de carbono, à disponibilidade de água e às mudanças climáticas, além de questões como segurança dos alimentos, inocuidade e rastreabilidade.

Por outro lado, sabe-se que o desenvolvimento da agricultura é um processo evolutivo que tem apresentado respostas aos desafios de cada período histórico. Prova disso é a própria agropecuária brasileira, que constitui um caso raro no mundo, no qual, por meio de pesquisa e inovação, o Brasil, em menos de 30 anos, deixou de ser um importador líquido de grande parte dos produtos consumidos internamente para se tornar um importante produtor em diversas cadeias agropecuárias globais, sendo, inclusive, líder em várias delas (Embrapa, 2014).

Nessa lógica, de acordo com Pillon (2016), pode-se afirmar que as últimas décadas da produção agropecuária no mundo foram marcadas por três grandes ondas. A primeira caracterizou-se pela Revolução Verde, de caráter monodisciplinar, focada na monocultura, no uso de insumos sintéticos e na pesquisa adaptativa, ocorrida entre 1960 e 1990 (Borlaug, 1971).

A segunda onda teve início nos anos 1990, com a agenda de sistemas integrados, focada na intensificação sustentável da produção, na multidisciplinaridade, na eficiência produtiva e na pesquisa sistêmica (Alves et al., 2015). Já a terceira onda, vislumbrada para os anos futuros, refere-se a uma agricultura de base biológica, ou seja, focada em sistemas complexos, na interdisciplinaridade, no uso de insumos biológicos e na pesquisa e inovação aberta (Soares, 2020).

Entretanto, elementos que antes não eram tão evidentes ao grande público passaram a integrar a agenda de discussão global, como é o caso da questão climática e seus impactos nos diferentes setores da economia. Assim, sem pretender aprofundar a discussão das causas das mudanças climáticas,

entende-se que há, atualmente, uma percepção cada vez maior da ocorrência de eventos climáticos extremos em diferentes regiões do globo e também no Brasil.

Essa maior ocorrência de fenômenos ou, ao menos, a percepção de maior intensidade de eventos climáticos impactando as regiões produtoras nem sempre tem gerado ações proporcionais para enfrentar o desafio da mitigação e, principalmente, da adaptação. Isso ocorre seja pela falta de conhecimento sobre quais ações são efetivamente relevantes para minimizar os impactos ou promover a adaptação, seja pela ausência de diretrizes mais claras por parte dos órgãos competentes (Nascimento; Bursztyn, 2011).

Nos fóruns globais de discussão das mudanças climáticas, como as recentes Conferências do Clima das Nações Unidas (COP 26, realizada em Glasgow, no final de 2021; COP 27, realizada no Egito, em Sharm El Sheikh, em novembro de 2022; e COP 28, realizada em Dubai, em dezembro de 2023), a cada ano, novos compromissos de redução das emissões de gases de efeito estufa têm sido discutidos e assumidos pelos países para a próxima década. Ao mesmo tempo, tem sido dada maior ênfase à importância de ações de adaptação.

Um elemento importante nas discussões recentes tem sido a visão de que as atividades agropecuárias, muitas vezes percebidas como vilãs no debate climático devido às emissões de gases, devem ser encaradas como parte da solução. Dessa forma, a questão da adaptação ganha crescente relevância no debate (FAOa, 2023; FAOb, 2023; KISSEL et al., 2023).

De acordo com a UN (2022), um dos principais resultados da COP 27 foi o fortalecimento da agenda de adaptação aos impactos das mudanças climáticas. Nesse sentido, os diversos setores econômicos serão progressivamente pressionados a adotar práticas adaptativas. Na COP 28, os negociadores concordaram em definir metas globais, com prazos específicos para temas e setores da economia; no entanto, as metas de adaptação não foram quantificadas nem incluíram diretrizes claras sobre como esse processo será financiado, especialmente nos países em desenvolvimento.

De qualquer forma, fica evidente o crescimento da atenção para a necessidade de mecanismos de financiamento da adaptação, os quais, por sua vez, demandam o desenvolvimento e a adoção de práticas, tecnologias e processos aplicáveis pelos produtores rurais no contexto da adaptação às mudanças climáticas na agricultura.

No tocante à temática das mudanças climáticas na vitivinicultura, percebe-se um crescimento na produção científica mundial, com trabalhos, artigos e estudos que abordam temas como mudanças climáticas, carbono, água e sustentabilidade aplicados à vitivinicultura, como se observa nos anais dos congressos da OIV (2021).

Conforme se demonstra na revisão da literatura deste artigo, é evidente que variações na temperatura, na pluviosidade, na amplitude térmica, entre outros fatores, podem afetar consideravelmente o desempenho das variedades de uva em seus diferentes *terroirs*.

No tocante à abrangência territorial do Brasil, país de dimensões continentais e com uma vitivinicultura cada vez mais diversificada, com produção em regiões de características bastante distintas, compreender quais fatores climáticos são relevantes para a produção vitivinícola é fundamental. Além disso, averiguar como produtores de cada região têm percebido as mudanças desses fenômenos nos últimos anos é essencial para estabelecer um diagnóstico mais preciso e subsidiar conclusões mais abrangentes, voltadas à adaptação e à mitigação dos impactos das mudanças climáticas no setor vitivinícola brasileiro.

Dentro desse contexto, o objetivo deste trabalho é investigar como o cenário de mudanças climáticas tem afetado a vitivinicultura brasileira em suas diferentes regiões, a partir da perspectiva de produtores

de uva e vinho, bem como analisar como esses agentes têm se posicionado quanto à adoção de ações de adaptação em suas atividades.

Justifica-se, assim, a relevância do tema e a importância de estudos que apontem a situação atual das diversas regiões produtoras do Brasil perante essas variáveis. Identificar sinais de mudanças relevantes e fornecer informações que apoiem a tomada de decisão nos setores público e privado, ampliando a capacidade de resposta às oportunidades e aos riscos emergentes, constitui um insumo crucial para o desenvolvimento tecnológico e sustentável da agropecuária no futuro.

2 REVISÃO DA LITERATURA

2.1 MUDANÇAS CLIMÁTICAS E VITICULTURA

A questão das mudanças climáticas passou a fazer parte do debate político e científico com maior força a partir dos anos 2000, especialmente após alguns desastres naturais, como o furacão Katrina, que atingiu os Estados Unidos em 2005. O reconhecimento com o Prêmio Nobel da Paz ao Painel Intergovernamental sobre Mudanças Climáticas (IPCC) e a Al Gore, em 2007, reforçou a centralidade política do tema. No entanto, parte da literatura aponta que essa visibilidade internacional não foi acompanhada, no mesmo ritmo, por medidas efetivas de adaptação nos setores produtivos, inclusive na vitivinicultura (Nascimento; Bursztyn, 2011).

Desde então, avanços ocorreram, e o principal evento internacional sobre o tema tem sido a Conferência das Partes (COP), cuja última edição foi realizada em novembro de 2023, em Dubai.

Como decorrência, diversos setores da economia passaram a avaliar como estão sendo ou serão impactados pelas mudanças climáticas. Não tem sido diferente na vitivinicultura, um setor altamente sensível às variações do clima. A própria Organização Internacional da Uva e do Vinho (OIV) passou a incluir seções específicas em seus congressos e publicações voltadas à questão climática na vitivinicultura.

Diversos estudos investigam a influência do clima sobre a qualidade das uvas, de seus mostos e dos vinhos. Enquanto Araújo et al. (2016) destacam o efeito da temperatura no metabolismo da videira, Rufato et al. (2021) ampliam a análise ao apontar a interação entre clima, relevo e solo, sugerindo que a sensibilidade da viticultura não pode ser compreendida apenas em termos térmicos. Essa visão converge com Gambetta et al. (2020), que ressaltam a dificuldade de prever as respostas das culturas agrícolas em cenários complexos, o que gera, especialmente no caso da viticultura, incerteza tanto para produtores quanto para governos de regiões dependentes dessa atividade econômica.

Assim, conhecer as condições climáticas ao longo das últimas décadas e suas projeções futuras, de modo a estimar os impactos dessas mudanças nos índices agrometeorológicos aplicados à videira, constitui uma importante estratégia para o desenvolvimento do setor vitícola do país. Essa necessidade é ainda mais relevante considerando o contexto de clima tropical do Brasil, onde a vitivinicultura se distribui por diferentes regimes climáticos.

De acordo com os últimos relatórios do IPCC (IPCC, 2021; IPCC, 2022), as projeções indicam que os efeitos das mudanças climáticas se intensificarão ao longo deste século, causando impactos em diversos ecossistemas ao redor do mundo. Nesse sentido, vários cenários futuros estão sendo simulados para avaliar o nível de intensidade desses impactos e orientar formas de mitigação e, principalmente, de adaptação a essas mudanças.

Alguns dos efeitos das mudanças climáticas incluem o aumento da intensidade das chuvas em muitas regiões do mundo, ondas de calor mais frequentes e eventos de frio extremo. Impactos adicionais têm sido observados na incidência de grandes incêndios no oeste dos Estados Unidos, na Austrália e em Portugal, que afetaram o cultivo de uvas e a produção de vinho em algumas regiões. Um exemplo desse impacto é o aumento da frequência de vinhos contaminados por fumaça no oeste dos Estados Unidos e do Canadá, bem como na Austrália. Muitas regiões montanhosas têm apresentado tendências de derretimento precoce e redução do acúmulo de neve, o que afeta os recursos hídricos para a agricultura e contribui para o aumento da frequência de secas (Jones et al., 2022).

Por outro lado, Xyrafis et al. (2022) argumentam que anomalias de temperatura e alterações nos padrões de precipitação podem gerar impactos tanto positivos quanto negativos na produção agrícola, em escala regional ou local, dependendo da área afetada. Essa posição contrasta com Jones et al. (2022), que enfatizam predominantemente impactos negativos, como secas e incêndios, sugerindo que a avaliação dos efeitos deve ser contextualizada por região e variedade de uva.

Estudos recentes indicam que as mudanças climáticas estão alterando a aptidão climática para a viticultura, tornando algumas regiões tradicionais menos adequadas e favorecendo novas áreas, como regiões de maior altitude ou latitude (Leeuwen et al., 2024). Isso evidencia que os impactos não são homogêneos e exigem que o setor considere, além de adaptações locais, a possível migração da atividade como estratégia de longo prazo.

Leeuwen et al. (2019) apontam algumas estratégias para adaptação às mudanças climáticas na atividade vitícola, tais como: desenvolvimento de variedades, clones e porta-enxertos de maturação tardia; aumento da altura do tronco; redução da relação entre área foliar e peso do fruto; poda tardia; mudança do cultivo para altitudes mais elevadas; e combinação de diferentes estratégias de adaptação, permitindo sua implementação progressiva. Ainda segundo os autores, algumas dessas práticas não requerem mudanças significativas no manejo vitícola, como a poda tardia, enquanto outras podem exigir o replantio de vinhas ou a substituição de variedades, o que pode acarretar alterações relevantes na tipicidade do *terroir*.

Na visão de Angelotti (2011), algumas medidas demandam longo tempo de pesquisa, como o desenvolvimento de novas variedades. Nesse sentido, a autora já apontava, em 2011, a necessidade de estudos sobre os impactos das mudanças climáticas em diversas áreas do setor agrícola no Brasil. Assim, embora exista um conjunto amplo de estratégias adaptativas, muitas delas demandam décadas de pesquisa, evidenciando a tensão entre medidas de curto prazo e soluções estruturais de longo prazo.

De forma complementar, Leeuwen et al. (2024) destacam que, embora algumas estratégias de adaptação possam mitigar os impactos do aquecimento global — como a escolha de variedades mais tolerantes ao calor, ajustes no manejo do dossel e uso racional da irrigação —, essas medidas apresentam limites, especialmente em regiões altamente afetadas por secas ou ondas de calor. Nessas situações, a própria viabilidade econômica da viticultura pode ser comprometida, exigindo reconfigurações mais profundas, como a migração da produção para áreas com condições climáticas mais favoráveis. Isso reforça a necessidade de planejamento adaptativo que considere tanto ações pontuais quanto mudanças estruturais de longo prazo.

Pandolfo (2010) *apud* Rufato et al. (2021), ao projetar cenários para a viticultura na Serra Catarinense, indicou que, nos anos de 2050 e 2070, o aumento da temperatura poderá restringir em mais de 50% as áreas atualmente adequadas ao cultivo das variedades utilizadas na região. Segundo os mesmos autores, é provável que ocorra antecipação da brotação e redução do período de maturação, o que pode resultar em diminuição da qualidade dos vinhos. Em função disso, apontam ser fundamental o acompanhamento do deslocamento das áreas potenciais, além do uso de variedades mais adaptadas regionalmente, destacando a importância de pesquisas em melhoramento genético.

Além disso, mudanças no cultivo dos vinhedos impactam diretamente as formas de processamento da uva, exigindo novas técnicas para manter a qualidade dos vinhos ou desenvolver novos produtos adaptados às novas condições. Em síntese, a temática das mudanças climáticas tem ganhado grande repercussão nas últimas décadas. Contudo, como apontado por Nascimento e Bursztyn (2011), embora haja maior percepção sobre seus impactos, as ações de adaptação e mitigação nem sempre avançam no mesmo ritmo.

2.2 PERCEPÇÃO DAS MUDANÇAS CLIMÁTICAS PELOS PRODUTORES

Diversos trabalhos têm sido elaborados com enfoque na percepção dos produtores a respeito dos impactos das mudanças climáticas na produção de uvas e vinhos, como, por exemplo, Ryan (2019), que investigou a percepção dos produtores da Nova Zelândia; Zuniga et al. (2024), que estudaram a percepção dos produtores da região sul da Califórnia (Estados Unidos); Battaglini et al. (2009), que analisaram a percepção de produtores europeus (Itália, França e Alemanha); e Vega-Bayo et al. (2023), que avaliaram as estratégias de mitigação adotadas pelos produtores da região de Rioja, na Espanha.

Para Ryan (2019), os efeitos das mudanças climáticas podem afetar a qualidade e a quantidade de uvas destinadas à produção de vinho, bem como a própria produção vinícola na região de estudo. Durante seu trabalho, a autora investigou o planejamento de adaptação na indústria vinícola da Nova Zelândia, avaliando os processos de tomada de decisão dos viticultores e suas percepções sobre as mudanças climáticas. Como resultado, identificou que os viticultores estão parcialmente informados sobre as mudanças climáticas, com algum planejamento de adaptação em curso. No entanto, a maioria ainda não possui planos estruturados de adaptação.

No Brasil, Vieira, Garcia e Bruch (2015) realizaram uma análise sob a mesma perspectiva nos Vales da Uva Goethe, em Santa Catarina. O objetivo do trabalho foi desenvolver uma análise exploratória a respeito dos potenciais impactos decorrentes das mudanças na dinâmica climática sobre a vitivinicultura na região delimitada, à época, pela Indicação de Procedência dos Vales da Uva Goethe. Os resultados indicaram que apenas uma parcela dos produtores associa as variações na quantidade e na qualidade das uvas aos efeitos das mudanças climáticas.

Para além da vitivinicultura, Tanure et al. (2024), em estudo que analisou como as percepções dos agricultores sobre as mudanças climáticas influenciam a adoção de tecnologias agrícolas sustentáveis no Brasil, especialmente nos biomas Amazônia e Mata Atlântica, apontam que as motivações dos agricultores para adotar práticas mais sustentáveis são fortemente influenciadas por incentivos econômicos. Além disso, o nível de adoção dessas tecnologias permanece, em geral, baixo, devido à falta de conhecimento técnico e de apoio financeiro.

Enquanto, no Brasil, Vieira et al. (2015) identificam baixa associação entre variabilidade climática e qualidade da uva, estudos em países como a Nova Zelândia (Ryan, 2019) mostram que, mesmo em regiões altamente dependentes da vitivinicultura, a percepção dos produtores sobre os riscos climáticos ainda é limitada. Essa convergência sugere um desafio global: a defasagem entre a percepção dos produtores e a urgência apontada pelos relatórios do IPCC (2021; 2022). Nesse sentido, ao investigar diferentes regiões brasileiras, este estudo contribui para preencher uma lacuna ainda pouco explorada na literatura internacional: como produtores inseridos em contextos tropicais e subtropicais percebem e respondem às mudanças climáticas.

2.3 REGIÕES PRODUTORAS DE VINHO NO BRASIL

Mudanças nas temperaturas, alterações nos níveis de radiação solar e o aumento da concentração atmosférica de CO_2 certamente influenciarão o rendimento das videiras, com impactos na qualidade

da uva e do vinho. Na visão de Costa et al. (2016), apud Xyrafis et al. (2022), alterações nesses fatores ambientais tendem a afetar de maneira distinta as diferentes regiões produtoras de vinho ao longo das próximas décadas.

O Brasil, por suas dimensões continentais, apresenta um cenário vitivinícola único no mundo, uma vez que possui produção distribuída em três diferentes macrorregiões. Conforme Pereira et al. (2020) e Pereira (2021), essas macrorregiões podem ser classificadas como: a Região Sul, que representa a viticultura tradicional; os vinhos de inverno, nas regiões Sudeste e Centro-Oeste; e os vinhos tropicais, na Região Nordeste (Figura 1).

Segundo os autores, a viticultura tradicional está localizada nas regiões Sul e Sudeste do Brasil; a viticultura tropical concentra-se no Nordeste do país; e, a mais recente dessas modalidades, a viticultura de inverno, ocorre nas regiões Sudeste, Centro-Oeste e Nordeste, em vinhedos situados em altitudes superiores a 700 m.



Figura 1 – Três regiões vitivinícolas brasileiras divididas conforme características climáticas de produção e manejo

Fonte: Adaptado de Google Earth e Pereira et al. (2020)

Obviamente, trata-se de um recorte em nível macro e, caso seja realizado um aprofundamento em cada uma dessas regiões, serão identificadas diversas características e nuances que diferenciam os *terroirs* em escala local, como aponta Leeuwen (2004).

De qualquer forma, é importante reconhecer que cada uma dessas macrorregiões apresenta um conjunto de características bastante distinto, incluindo o período de início das atividades, aspectos culturais, diferentes técnicas de cultivo, épocas de plantio e, ainda, as especificidades dos produtos, tanto em termos de variedades de uva quanto dos resultados do processamento, como sucos e vinhos.

3 MATERIAL E MÉTODOS

Este estudo possui caráter exploratório e descritivo, tendo como base a coleta de dados primários por meio da aplicação de um questionário do tipo *survey*. O instrumento foi elaborado a partir de referenciais teóricos sobre viticultura, mudanças climáticas e percepção de produtores, sendo estruturado em questões que incluíram perguntas abertas, de múltipla escolha e itens de seleção múltipla. As perguntas foram divididas em seções que abordam os seguintes temas: identificação do respondente; localização e características da propriedade; percepção sobre o clima e a viticultura; percepção sobre as mudanças climáticas; impactos qualitativos e econômicos na produção decorrente das mudanças climáticas; e ações ou investimentos para mitigação.

A pesquisa foi conduzida em conformidade com os princípios éticos aplicáveis a estudos com seres humanos. Todos os participantes foram informados sobre os objetivos da investigação e participaram de forma livre e voluntária, mediante consentimento informado no início do questionário. O estudo foi submetido ao Comitê de Ética em Pesquisa com Seres Humanos (CEPSH-IFSC), tendo sido aprovado sob o número CAAE 68133023.4.0000.0185. O questionário foi disponibilizado em formato digital (Google *forms*) e permaneceu aberto entre agosto e outubro de 2023.

A amostra foi composta por 80 produtores de uva e vinho de diferentes regiões do Brasil, obtidos por adesão voluntária mediante divulgação em redes de contato acadêmicas e setoriais (associações de produtores e instituições de ensino e pesquisa). Do total, 79 respostas foram consideradas válidas, sendo uma excluída por insuficiência de preenchimento.

Como procedimentos de análise, após a revisão da literatura acerca dos temas tratados neste estudo, foi realizada a caracterização das três principais macrorregiões vitivinícolas brasileiras. Na sequência, com base nos resultados do *survey*, foram realizadas a tabulação e a análise dos dados, tanto qualitativa quanto quantitativamente, utilizando-se categorização por meio de análise de conteúdo e o software Microsoft Excel, respectivamente.

4 RESULTADOS E DISCUSSÃO

4.1 CARACTERIZAÇÃO DA AMOSTRA DE PRODUTORES DE UVA E VINHO

A distribuição regional dos respondentes participantes da pesquisa foi de 70,8% na Região Sul (n = 56), 10,1% na Região Nordeste (n = 8), 15,1% na Região Sudeste (n = 12) e 3,7% na Região Centro-Oeste (n = 3). Não houve respondentes da Região Norte do país. Essa distribuição mostrou-se proporcional à realidade da viticultura brasileira, conforme dados oficiais de área cultivada, nos quais a Região Sul concentra 73,4% do volume (55.710 hectares), seguida pela Região Nordeste com 14,68% (11.153 hectares), Região Sudeste com 11,5% (8.717 hectares), Região Centro-Oeste com 0,4% (257 hectares) e Região Norte com 0,03% (26 hectares) (IBGE, 2020). Para fins de análise, consideraram-se as três principais macrorregiões vitivinícolas do Brasil (Sul, Sudeste/Centro-Oeste e Nordeste).

Em relação ao perfil dos participantes da pesquisa, dos 79 respondentes válidos considerados na tabulação, no que diz respeito ao gênero, 78,5% eram homens e 21,5% mulheres. Em relação à faixa etária, 26,6% informaram ter entre 30 e 39 anos; 24,1% entre 50 e 59 anos; 20,3% acima de 60 anos; 17,7% entre 40 e 49 anos; e 11,4% entre 18 e 29 anos.

Quanto à escolaridade, 11,4% afirmaram ter ensino médio completo; 11,4% ensino superior incompleto; 29,1% ensino superior completo; e 44,3% pós-graduação. Os participantes se identificaram como produtores rurais (40,5%), empresários (22,8%), trabalhadores de empresas privadas (16,5%), servidores públicos (8,9%), autônomos (6,3%) e aposentados (3,8%).

Esses dados de perfil demonstram as características dos produtores de uva e vinho no Brasil nas diferentes regiões produtoras e corroboram as observações de Ryan (2019), realizadas na Nova Zelândia, onde o perfil dos produtores também é altamente qualificado (74%) e há diversidade de perfis profissionais atuando na vitivinicultura, o que proporciona uma ampla gama de experiências e contribui para a qualidade dos dados obtidos (Ryan, 2019).

4.2 DADOS DE PRODUÇÃO E DA PROPRIEDADE RURAL DOS RESPONDENTES

No que diz respeito ao tempo em que o produtor desenvolve a atividade vitícola ou vitivinícola, observa-se uma distribuição relativamente equilibrada entre os diferentes períodos de atuação: até 5 anos (24,1%), de 6 a 10 anos (17,7%), de 11 a 20 anos (24,1%) e acima de 30 anos (13,9%). Estudos indicam que produtores com maior escolaridade ou mais experiência tendem a perceber e adotar medidas de adaptação com maior eficácia (Tanure et al., 2024; Vieira et al., 2015).

Em relação ao tamanho da propriedade, 68,5% dos respondentes possuem áreas inferiores a 50 hectares, enquanto 11,4% possuem propriedades entre 50 e 100 hectares e 20% acima de 100 hectares. Quanto à área plantada com uva, observa-se que 40,5% dos produtores cultivam em menos de 3 hectares da propriedade; 38% em áreas entre 4 e 10 hectares; 10,1% entre 11 e 20 hectares; 3,8% entre 21 e 50 hectares; e 7,6% em áreas superiores a 50 hectares.

Essas informações reforçam a predominância de pequenas propriedades na vitivinicultura brasileira. Esse dado é relevante, pois quanto menor a área cultivada, dependendo das técnicas de manejo empregadas, mais evidentes tendem a ser as variações produtivas, anomalias e impactos de fenômenos climáticos, bem como a necessidade de ajustes nas práticas de cultivo, o que confere maior sensibilidade às percepções dos produtores captadas na pesquisa.

4.3 PERCEPÇÕES E IMPACTOS DAS MUDANÇAS DO CLIMA SOBRE A VITIVINICULTURA

Para investigar a percepção dos produtores sobre a ocorrência de eventos climáticos, bem como seus impactos na produção, foram aplicadas perguntas específicas, cujos resultados podem ser observados nas Figuras 2 a 4 e são discutidos a seguir. Do total de respondentes, 94,9% consideraram o clima como altamente relevante para a produção de uvas. Essa informação coincide com outros estudos sobre o tema no Brasil, nos quais os produtores, mesmo em pequenas propriedades, reconhecem o clima como fator determinante para a vitivinicultura (Vieira et al., 2015).

Quando questionados sobre a observação de alterações no padrão climático em suas regiões de cultivo, 81% dos respondentes relataram observar tais variações. Esse resultado demonstra que os produtores brasileiros estão alinhados à percepção de produtores de outros países, como os da Nova Zelândia, que, na pesquisa realizada por Ryan (2019), indicaram, em sua maioria, que as mudanças climáticas são reais e já estão em curso. O mesmo se observa entre produtores argentinos, que relatam a ocorrência de eventos extremos (Straffelini et al., 2023), bem como entre produtores do sul da Califórnia (Zuniga et al., 2024) e da Alemanha, França e Itália, que destacam mudanças observadas desde a década de 1990, especialmente relacionadas à temperatura e à precipitação (Battaglini et al., 2009).

Observa-se, porém, que, dada a dimensão continental do Brasil, o padrão de respostas variou conforme a região. Por exemplo, entre os respondentes da região Centro-Oeste, nenhum relatou observar mudanças climáticas; entretanto, todos esses produtores estão na atividade vitivinícola há menos de cinco anos, o que pode explicar a menor percepção de alterações no clima. Isso ocorre porque a identificação de mudanças climáticas geralmente requer séries históricas mais longas, conforme evidenciado por estudos do Instituto Nacional de Pesquisas Espaciais (Inpe), que já comprovaram alterações climáticas nas últimas três décadas em todas as regiões do país.

De acordo com estudo do Inpe, a média de dias com registro de ondas de calor no território brasileiro aumentou de 7 para 53 no período de 2011 a 2020. A única região com impacto menos severo de seca foi a Região Sul, que, por outro lado, apresentou anomalias de precipitação acima da média. Ainda segundo o estudo, fatores como urbanização e mudanças no uso e cobertura da terra têm contribuído para o aumento das temperaturas (MCTI, 2023).

No entanto, a temperatura não é o único fator relevante, uma vez que eventos climáticos extremos podem resultar de múltiplas variáveis. Para os produtores, esses eventos tendem a ser mais perceptíveis e emblemáticos do que alterações graduais nas médias de temperatura. Straffelini et al. (2023), em estudo sobre mudanças climáticas na Argentina, indicam que o aumento das temperaturas, ondas de calor, secas, granizo e chuvas intensas têm levado viticultores a deslocar vinhedos para altitudes mais elevadas em busca de condições mais favoráveis. De forma semelhante, entre produtores do sul da Califórnia, o aumento das temperaturas, associado a períodos de seca, tem provocado alterações fenológicas nas videiras, como brotação e colheita mais precoces, impactando diretamente o manejo (Zuniga et al., 2024).

No âmbito dos participantes deste estudo que relataram observar mudanças climáticas (n = 73), foram também questionados sobre o período a partir do qual passaram a perceber essas variações em suas regiões produtoras. Mais de 60% dos respondentes indicaram que têm notado essas mudanças nos últimos cinco anos, conforme ilustrado na Figura 3.



Figura 3 – Percepção de tempo em que os produtores têm observado variações climáticas na sua região produtora

Fonte: Autores

Em relação ao tipo de evento mais recorrente que tem sido observado na região de cultivo, os produtores destacaram diferentes fenômenos, conforme demonstra a Figura 4, com predominância da percepção em relação às variações de temperaturas fora do padrão histórico da região (25,68%); chuvas fortes (25,13%); granizo (19,67%); geadas (14,20%), vendaval e enchentes (3,82% cada).

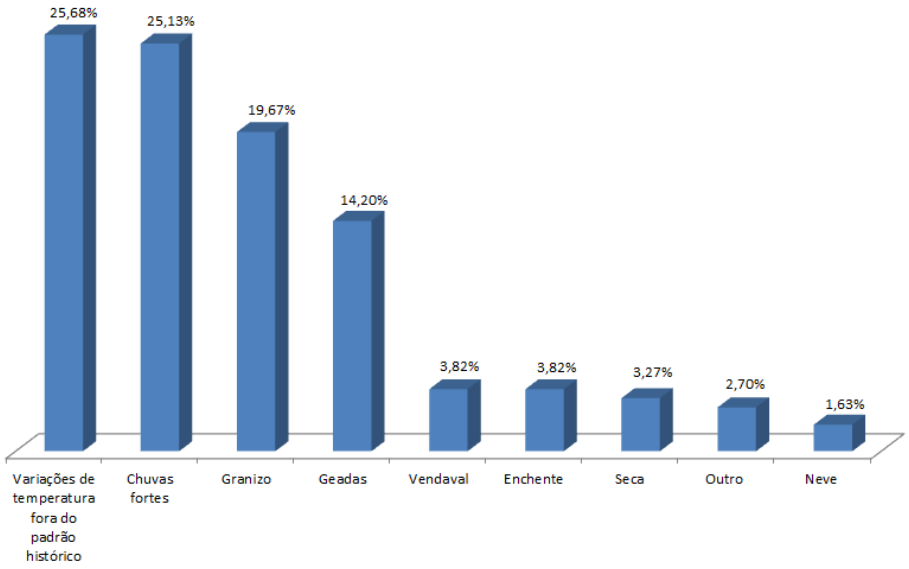


Figura 4 – Percepção dos produtores entrevistados quanto aos principais eventos climáticos observados como fatores de mudança climática em suas regiões de cultivo

Fonte: Autores

A percepção de aumento da temperatura fora do padrão histórico entre os produtores brasileiros pode refletir o grau de maturidade e experiência com o tema, pois corrobora os dados observados na Nova Zelândia por Ryan (2019), onde os produtores daquele país consideram o aumento das temperaturas locais como o principal impacto e a consequência mais direta das mudanças climáticas. Apesar da preocupação quanto às mudanças de temperatura, os produtores nem sempre associam esse evento climático a um efeito negativo, visto que a insolação está relacionada à produção de uvas de qualidade (Ryan, 2019).

Na Europa, o estudo de Battaglini et al. (2009) já indicava que as principais mudanças climáticas percebidas pelos produtores estavam relacionadas ao aumento das temperaturas, verões mais quentes e eventos extremos, como secas prolongadas (Itália) e chuvas intensas e enchentes (França).

Por outro lado, eventos climáticos extremos, como chuvas fortes, granizo, geadas, vendavais e secas, preocupam não só os produtores brasileiros, como também os neozelandeses e argentinos, pois estão associados a impactos negativos sobre a qualidade da uva (Ryan, 2019; Straffelini et al., 2023). Os resultados demonstraram ainda que 90% dos produtores brasileiros respondentes da pesquisa perceberam maior frequência de eventos climáticos extremos. Além disso, relataram que o número desses eventos aumentou nos últimos 10 anos e que sua intensidade se intensificou, especialmente nos últimos 5 anos.

Em relação ao grau de impacto dos eventos climáticos sobre a produção de uvas, 80% dos respondentes afirmaram que sua produção tem sido impactada de alguma maneira pelas mudanças climáticas na região; e 70% consideram esses impactos como altos, em uma escala que variou entre alta, média e baixa. As regiões Sul e Nordeste foram as principais responsáveis por esse resultado, o que se justifica pelo maior tempo de cultivo e experiência com a vitivinicultura nessas regiões, em comparação com outras áreas do país, como o Centro-Oeste, considerado uma nova fronteira vitivinícola nacional (Pereira et al., 2020), onde os respondentes indicaram impacto médio das mudanças climáticas sobre a produção de uvas.

Considerando o alto impacto das mudanças climáticas sobre a produção de uvas, percebido pela maioria dos produtores, buscou-se compreender como esses eventos climáticos têm afetado a qualidade da produção (Figura 5). Os impactos mais mencionados pelos produtores podem ser agrupados em dois grandes conjuntos: o primeiro, relacionado à produtividade, destacou a redução do número de quilos de uva por planta, o comprometimento da sanidade das uvas (maiores índices de podridão) e, consequentemente, a maior necessidade de aplicação de defensivos agrícolas; o segundo grupo está relacionado à qualidade físico-química da uva, especialmente às variações no grau de maturação (aumento ou redução de açúcares, conforme o evento climático).

Esses dados corroboram as percepções observadas por produtores do Velho e do Novo Mundo, que apontam a redução do rendimento, o comprometimento da sanidade da uva e a diminuição da quantidade e da qualidade da produção como os principais impactos negativos decorrentes das mudanças climáticas (Battaglini et al., 2009; Ryan, 2019).

Além disso, os estudos de Straffelini et al. (2023) e Zuniga et al. (2024), sobre os efeitos das mudanças climáticas na Argentina e no sul da Califórnia, respectivamente, estão em consonância com os dados observados nesta pesquisa, indicando que os principais impactos incluem a redução da produtividade e da qualidade das uvas, bem como o comprometimento da sanidade do vinhedo, com maior incidência de doenças em condições úmidas.

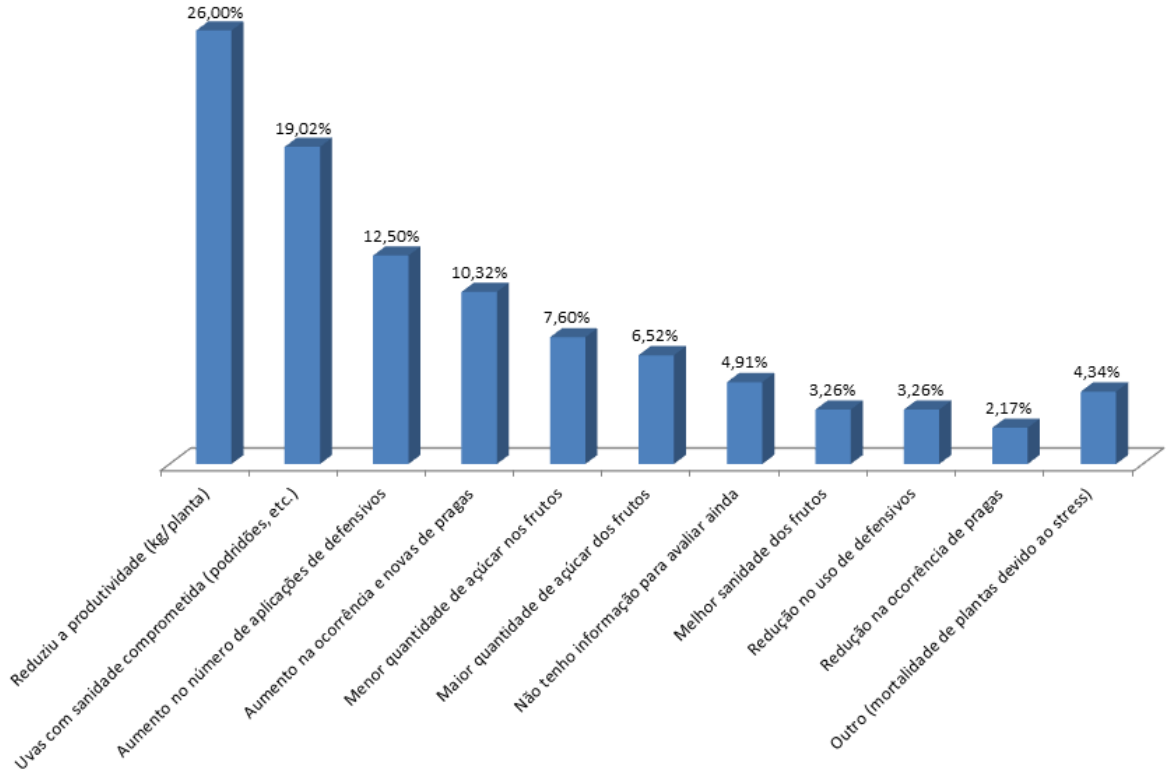


Figura 5 – Percepção dos produtores sobre o impacto dos eventos climáticos na qualidade das uvas produzidas

Fonte: Autores

Além dos impactos produtivos, os produtores indicaram sua percepção quanto aos impactos financeiros desses eventos climáticos e, para mais de 80% dos respondentes, houve prejuízos econômicos. Os valores estimados de danos em cada propriedade nos últimos cinco anos são variados e, entre os respondentes que conseguiram estimar, 15,9% apontaram prejuízos entre R$ 26.000,00 e R$ 50.000,00; 14,5% entre R$ 51.000,00 e R$ 100.000,00; e 25% acima de R$ 100.000,00.

Considerando a consciência dos produtores quanto aos impactos das mudanças climáticas sobre a vitivinicultura em suas regiões, buscou-se compreender como estes têm atuado para enfrentar a situação. Observou-se que 69,6% dos respondentes indicaram ter adotado medidas de adaptação aos impactos decorrentes dos eventos climáticos. Entre as principais medidas identificadas, destacam-se: (a) adoção de manejo adaptado, como podas tardias ou pré-podas; (b) instalação de barreiras físicas, como quebra-ventos e cobertura plástica; (c) aumento no uso de tratamentos químicos; (d) utilização de variedades mais resistentes; (e) busca por mais informações sobre o clima local; e (f) contratação de seguro agrícola.

Em comparação com os produtores neozelandeses, entre os quais apenas 32% consideram planos de adaptação, os produtores brasileiros demonstram maior preocupação com ações de enfrentamento, ainda que, em muitos casos, essas ações não estejam estruturadas em planejamentos de médio e longo prazo. No entanto, independentemente do país, os produtores que buscam adaptação tendem a destacar estratégias semelhantes, principalmente relacionadas ao manejo do vinhedo e da água, bem como à seleção ou substituição de variedades (Ryan, 2019).

Quanto à estratégia de mudança de variedades de uva, essa prática também vem sendo discutida na Europa, sendo mais aceita na Alemanha, enquanto outros países enfrentam restrições associadas às indicações geográficas. Além disso, a intensificação do controle de doenças e pragas, bem como o maior interesse em acessar informações técnicas sobre clima e variedades, tem sido apontada como estratégia relevante em países como Alemanha, França e Itália (Battaglini et al., 2009).

Por outro lado, conforme estudo realizado por Straffelini et al. (2023) na Argentina, outras estratégias de adaptação vêm sendo implementadas, como: (a) deslocamento de vinhedos para altitudes mais elevadas (2.000–3.000 m); (b) uso de irrigação em contextos de escassez hídrica; (c) sistemas de drenagem e manejo do solo para reduzir erosão e acúmulo de água; (d) cobertura vegetal e proteção do solo; (e) estruturas de contenção em áreas inclinadas; (f) uso de sensores e monitoramento remoto para gestão hídrica e climática; e (g) adoção de práticas alinhadas aos Objetivos de Desenvolvimento Sustentável (ODS).

Na região sul da Califórnia, destacam-se ações de adaptação relacionadas principalmente aos efeitos das altas temperaturas, como o manejo da irrigação para otimização do uso da água, o uso de variedades e porta-enxertos mais resistentes à seca e ao calor, práticas de sombreamento e manejo do dossel para reduzir o estresse térmico, além da adoção de tecnologias de monitoramento climático e ajustes no calendário agrícola (Zuniga et al., 2024). Observa-se que, embora existam diferenças no nível de planejamento e investimento entre países, há uma convergência nas estratégias adotadas, refletindo a crescente preocupação do setor vitivinícola com os impactos das mudanças climáticas.

Para avaliar o avanço do planejamento adaptativo, buscou-se compreender a percepção dos produtores quanto às barreiras que limitam a implementação dessas ações. Entre os principais fatores restritivos apontados, destacam-se: (a) restrição orçamentária (50,7%); (b) ausência de financiamento específico (28,8%); e (c) falta de informações sobre mudanças climáticas em escala local (23,3%). Esses dados corroboram estudos realizados com produtores neozelandeses, que também apontam a carência de informações específicas e a incerteza como fatores limitantes, seguidos por restrições financeiras (Ryan, 2019).

De forma semelhante, na Argentina, os principais entraves incluem os elevados custos das tecnologias adaptativas e os impactos socioeconômicos associados ao deslocamento das regiões produtoras (Straffelini et al., 2023). Na região sul da Califórnia, além da limitação de informações técnicas acessíveis e dos altos custos, destaca-se a ausência de apoio institucional e de políticas públicas específicas (Zuniga et al., 2024). Já na Europa, além da necessidade de informações confiáveis, as restrições regulatórias associadas às indicações geográficas representam importantes limitações (Battaglini et al., 2009). Esses achados evidenciam a complexidade e os desafios globais da adaptação às mudanças climáticas no setor vitivinícola.

Considerando os desafios econômicos para a implementação de estratégias de adaptação, os participantes foram questionados sobre sua disposição para investir. Observou-se que 69,9% dos respondentes indicaram que realizariam investimentos caso houvesse linhas de crédito específicas, e aproximadamente 70% afirmaram estar dispostos a investir recursos próprios para minimizar os impactos climáticos. Para cerca de 60% dos produtores, o valor máximo de investimento seria de até R$ 50.000,00.

Esses resultados reforçam a característica predominante da vitivinicultura brasileira, baseada em pequenas propriedades, as quais enfrentam maiores restrições de investimento e, consequentemente, maior vulnerabilidade às mudanças climáticas quando comparadas a grandes empresas — situação semelhante à observada na Nova Zelândia e na Austrália (Galbreath, 2011; Ryan, 2019).

5 CONSIDERAÇÕES FINAIS

Os resultados desta pesquisa demonstram que a percepção dos produtores sobre os impactos das mudanças climáticas na vitivinicultura tem aumentado de forma significativa. Mais de 80% relataram que sua produção foi afetada, corroborando os dados do Inpe (MCTI, 2023), que apontam alterações climáticas em todas as regiões do país nos últimos 30 anos. Os impactos mostraram-se mais expressivos

nas regiões Sul e Nordeste, tradicionais na produção de uvas, onde prejuízos financeiros superiores a R$ 100.000,00 foram relatados por um quarto dos respondentes.

Apesar dessa crescente consciência, as medidas de adaptação identificadas permanecem limitadas e de alcance restrito, predominantemente centradas em ajustes pontuais de manejo e no aumento do uso de defensivos agrícolas, o que levanta preocupações ambientais e econômicas. Essa tendência, além de não garantir resiliência no longo prazo, pode gerar efeitos adversos à sustentabilidade ambiental e econômica da vitivinicultura.

Esses resultados reforçam a necessidade de políticas públicas, linhas de financiamento e desenvolvimento de tecnologias adaptativas mais eficazes, capazes de promover maior resiliência e sustentabilidade para a vitivinicultura brasileira. No entanto, é importante reconhecer as limitações deste estudo, como a abrangência restrita da amostra e o caráter exploratório da análise, que não permite generalizações para toda a cadeia produtiva. Pesquisas futuras podem ampliar o escopo metodológico, incorporando análises comparativas entre países ou regiões, bem como indicadores técnicos de impacto climático, de modo a subsidiar estratégias adaptativas mais eficazes e alinhadas aos princípios da sustentabilidade.

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Deforestation in the Amazon and macroeconomic variables: evidence from time-series analysis (2000–2023)

O desmatamento na Amazônia e variáveis macroeconômicas: evidências de análises de séries de tempo entre 2000 e 2023

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ARTICLE- VARIA

ABSTRACT

Building on the premise that macroeconomic variables – such as prices, agricultural income, and the real exchange rate – are associated with deforestation dynamics, this study investigates both the long-run relationship between these variables and deforestation, as well as the effects of macroeconomic shocks on its temporal evolution. The empirical strategy is grounded in a time-series framework using annual data from 2000 to 2023 and employs unit root tests, the Johansen cointegration approach, and a Vector Error Correction Model (VECM). The results provide evidence of cointegration among the variables, indicating the existence of a long-run equilibrium relationship between macroeconomic conditions and deforestation. Granger causality tests underscore the predictive relevance of the real exchange rate within the system, particularly in relation to deforestation and agricultural variables. Variance decomposition analysis reveals that exchange rate shocks account for a substantial share of the fluctuations in deforestation, whereas agricultural prices and agricultural GDP contribute to a lesser extent. Furthermore, impulse–response functions indicate that positive shocks in prices and the real exchange rate generate positive cumulative effects on deforestation over time. These findings suggest

that external competitiveness and the profitability of agricultural activities constitute key economic drivers of land-use expansion in the Amazon. At the same time, the results highlight the importance of the institutional environment, as conservation policies and monitoring mechanisms may mitigate the environmental pressures associated with favourable macroeconomic conditions. Overall, this study contributes to the literature by emphasising the interaction between macroeconomic dynamics and environmental outcomes in the Amazon region.

Keywords: Agriculture. Deforestation. Amazon. Macroeconomic Variables.

RESUMO

Partindo da premissa de que variáveis macroeconômicas – como preços, renda agrícola e a taxa de câmbio real – estão associadas à dinâmica do desmatamento, este estudo investiga tanto a relação de longo prazo entre essas variáveis e o desmatamento quanto os efeitos de choques macroeconômicos sobre sua evolução temporal. A estratégia empírica baseia-se em uma abordagem de séries temporais, utilizando dados anuais de 2000 a 2023, e emprega testes de raiz unitária, o método de cointegração de Johansen e o Modelo de Correção de Erros Vetorial (VECM). Os resultados fornecem evidências de cointegração entre as variáveis, indicando a existência de uma relação de equilíbrio de longo prazo entre as condições macroeconômicas e o desmatamento. Testes de causalidade de Granger destacam a relevância preditiva da taxa de câmbio real no sistema, particularmente em relação ao desmatamento e às variáveis agrícolas. A análise de decomposição da variância revela que choques na taxa de câmbio respondem por uma parcela substancial das flutuações no desmatamento, enquanto os preços agrícolas e o Produto Interno Bruto agrícola contribuem em menor medida. Além disso, as funções impulso-resposta indicam que choques positivos nos preços e na taxa de câmbio real geram efeitos cumulativos positivos sobre o desmatamento ao longo do tempo. Esses achados sugerem que a competitividade externa e a rentabilidade das atividades agrícolas constituem importantes motores econômicos da expansão do uso da terra na Amazônia. Ao mesmo tempo, os resultados ressaltam a importância do ambiente institucional, uma vez que políticas de conservação e mecanismos de monitoramento podem mitigar as pressões ambientais associadas a condições macroeconômicas favoráveis. De modo geral, este estudo contribui para a literatura ao enfatizar a interação entre a dinâmica macroeconômica e os resultados ambientais na região amazônica.

Palavras-chave: *Agricultura. Desmatamento. Amazônia. Variáveis Macroeconômicas.*

1 INTRODUCTION

Over the past few decades, Brazil has emerged as a key global supplier in meeting the increasing demand for food, with approximately 49% of the country's total exports originating from agribusiness (Brasil, 2024). In this context, Brazilian agribusiness plays a central role in global food provision and, importantly, has the potential to expand production without necessarily contributing to increased deforestation, particularly in the Amazon Biome. According to Abramovay (2019), between 1991 and 2017, agricultural and livestock production increased by 312%, while the total cultivated area expanded at a substantially lower rate of 61%. These figures, which refer specifically to the Amazon Biome, suggest significant gains in productivity. In addition, Rodrigues (2018) reports that only 13% of the total area allocated to grain production is located within the Amazon Biome, with most of this land already previously cleared for low-productivity pasture. Therefore, both within the Amazon Biome and across the country as a whole, there is no structural requirement for further deforestation to meet global food demand, as existing technologies enable productivity gains without expanding cultivated areas.

Moreover, Brazil has faced increasing pressure from international *trading partners* – particularly the European Union – to impose restrictions on products associated with deforestation. One prominent example is the "Soy Moratorium," a multi-stakeholder agreement involving public- and private-sector stakeholders, as well as non-governmental organisations. This initiative seeks to enhance the export

potential of Brazilian agricultural and livestock products while ensuring traceability and sustainability in production processes (Abramovay, 2019).

Brazil's international commitments in recent years, especially under the Paris Agreement – ratified in 2016 – represent an additional step toward strengthening its global environmental credibility and promoting long-term policies related to deforestation, greenhouse gas emissions, and sustainability. According to the Ministry of Environment (2024), Brazil has committed to: (i) reducing greenhouse gas emissions by 37% below 2005 levels by 2025; (ii) reducing emissions by 43% below 2005 levels by 2030; (iii) increasing the share of sustainable bioenergy to 18% by 2030; and (iv) restoring approximately 12 million hectares of forest, while ensuring that around 45% of its energy matrix consists of renewable sources by 2030.

Within this framework, changes in agricultural and livestock production systems are particularly relevant, given that land-use change – including deforestation across all Brazilian biomes – accounts for approximately 48% of total greenhouse gas emissions. Additionally, agricultural and livestock activities account for 27% of Brazil's total emissions (Seeg, 2024).

Despite these commitments, recent evidence indicates a deterioration in environmental performance. According to the Institute of Energy and Environment (2022), Brazil's total emissions increased by 21.4% between 2015 and 2021. The Climate Observatory further emphasises that achieving the targets established under the Paris Agreement requires a substantial reduction in deforestation, mitigation of methane emissions, and the adoption of low-carbon technologies in agricultural and livestock production.

Regarding deforestation, the Amazon Biome has shown an upward trend since 2016. Data from Inpe (2024) indicate that deforestation increased at an average annual rate of 6.53% between 2016 and 2023. In parallel, the frequency of wildfires has also intensified. Although fire-related emissions are not yet fully incorporated into the national emissions inventory, the Amazon Biome is becoming increasingly vulnerable to fire events, further exacerbating Brazil's overall emissions profile (Instituto de Energia e Meio Ambiente, 2022).

In recent years, Brazil's environmental conservation policies have not consistently aligned with the commitments established under international agreements. Nevertheless, historical evidence demonstrates the country's capacity to significantly reduce deforestation, particularly following the implementation of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). Established in 2004, the PPCDAm was instrumental in reducing deforestation by approximately 83% between 2004 and 2012. The plan was structured around four key pillars: (i) promotion of sustainable production activities; (ii) strengthening of environmental monitoring and enforcement; (iii) land-use and territorial planning; and (iv) implementation of regulatory and economic instruments aimed at curbing deforestation. This multidimensional approach – particularly the integration of economic instruments – is critical, as deforestation is closely linked to agricultural and livestock expansion. Given the sector's strong integration into global markets, fluctuations in agricultural prices, exchange rates, and sectoral income can exert significant pressure on deforestation dynamics, both at the national level and within the Amazon Biome (Ministério do Meio Ambiente e Mudança do Clima, 2024).

Although the PPCDAm was revoked in 2019, it was reinstated in 2023, preserving the comprehensive structure of the original 2004 plan, including economic and regulatory instruments to mitigate deforestation. Given the economic drivers of deforestation, it is essential to examine how macroeconomic variables shape these dynamics. This issue is particularly relevant in the Amazon Biome, where unregulated land occupation remains a persistent challenge and a major concern for both domestic and international stakeholders, given the region's critical role in climate regulation and biodiversity conservation.

A growing body of literature has examined the determinants of deforestation, including conservation policies, price mechanisms, and public policy design. Studies such as Assunção *et al.* (2015), Carvalho

and Domingues (2016), Diniz *et al.* (2009), Ferreira and Coelho (2012) and Mello Júnior *et al.* (2023) highlight the importance of economic variables and external market conditions in shaping deforestation dynamics. In particular, Assunção *et al.* (2015) provide evidence that deforestation responds to agricultural commodity prices, with higher prices increasing incentives for forest clearing. However, their findings also demonstrate that the substantial decline in deforestation observed during the 2000s was primarily driven by command-and-control policies implemented in Brazil, rather than by price dynamics alone, underscoring the effectiveness of environmental enforcement mechanisms. In line with this literature, the present study aims to investigate how macroeconomic variables influence deforestation dynamics, with a particular focus on the Amazon Biome, which remains central to national and international debates on conservation, biodiversity, and sustainability.

Given the importance of understanding the interaction between macroeconomic conditions and deforestation, this study aims to assess whether a long-run relationship exists between selected economic variables – namely, agricultural and livestock prices, the real exchange rate, and agricultural and livestock GDP – and deforestation in the Legal Amazon. Specifically, the study pursues three main objectives: (i) to evaluate the evolution of deforestation in the Legal Amazon between 2000 and 2023; (ii) to analyse the long-run relationship between deforestation and selected macroeconomic variables (prices, exchange rate, and income); and (iii) to examine the dynamic responses of deforestation to shocks in these variables.

This paper is structured as follows. The introduction outlines the research context and objectives. The second section reviews the relevant literature on deforestation. The third section describes the methodological approach and the dataset employed. The fourth section presents the empirical results and the estimation of the time-series model. Finally, the concluding section summarises the main findings and discusses their policy implications, followed by the references.

2 LITERATURE REVIEW

This section reviews selected studies that examine the relationship between macroeconomic variables and deforestation in Brazil and the Amazon Biome. Box 1 summarises some of these contributions.

Box 1 – Selected articles for studying the relationship between macroeconomic variables and deforestation

Author	*Objective*	*Data*	*Methodology*	*Main results*
Silva *et al.* (2023)	Analyse the impact of conservation policies on private lands and their impact on deforestation between 2003 and 2020.	CAR data on properties MapBiomas data on deforestation	Descriptive Analysis of Variables Spatial Analysis	They noted the importance of the CAR and governance policies. The involvement of private properties is needed to amplify the effect of conservation policies. Expand monitoring.
Carvalho (2021)	Analyse the impact of settlements on deforestation in the Legal Amazon from 2002 to 2014.	Deforestation Data (Prodes), Settlements (Incra) and Commodity Prices	Fixed Effects Differences in Differences	The number of settlements must be combined with control policies to be effective against deforestation.
Ferreira Filho, Ribeira, and Horridge (2016)	Analyse the control over deforestation and agricultural expansion. The economic impact of food supply. The importance of changes in land use.	Satellite Data and the Land Use Transition Matrix from 1994 to 2002.	Term BR	Conservation policies can improve the country's position in international trade. However, it must include a more conscious land use policy. Policies to reduce deforestation will not threaten the supply of food demand.

Author	Objective	Data	Methodology	Main results
Lorenço (2021)	Evaluate the relationship between deforestation and socio-economic indicators.	GDP and price data from IBGE and Firjan. Inpe Deforestation	Spearman Correlation	The importance of conservation policies alongside economic indicators and encouraging sustainable crops.
Mello Júnior *et al.* (2023)	Analyse the effects of the PPCDAm on deforestation	Prodes and PAM data	Differences in Policy Evaluation	Supervision, remote monitoring, and expanding conservation policies are the main instruments for controlling deforestation.
Ferreira and Coelho (2012)	Evaluate the impact of agricultural prices on deforestation from 1999 to 2008.	Prices and GDP (IBGE - PAM) Deforestation (Prodes) Economic data (inflation, government spending, rural credit)	Panel Data	Prices and income growth affect deforestation by increasing demand for food, a pressure that can be mitigated through conservation policies.
Diniz *et al.* (2009)	Estimate the Granger Causality of the main variables that determine deforestation.	Municipal data from 1997 to 2006 for economic and social indicators	Granger Causality	Sustainable practices are required since there is evidence that the variables cause deforestation.
Assunção *et al.* (2015)	Evaluate the impact of conservation policies on deforestation in the Amazon. Evaluate the role of agricultural prices in deforestation trends.	Panel for the 380 municipalities of the Legal Amazon using Inpe and PAM	Fixed Effects	An important role for conservation policies, which can be influenced by prices. As a result, there is a need for greater conservation policies.
Carvalho and Domingues (2016)	Analyse deforestation caused by macroeconomic factors	TerraClass and the Agriculture and Livestock Farming Census	CGE analysis	Predicting growth trends in the biome, without registering that there is pressure for more deforestation to occur.

Source: Prepared by the authors based on the consulted studies.

Taken together, this body of literature indicates that deforestation is shaped not only by macroeconomic variables but also by structural characteristics of the productive system, patterns of domestic demand, institutional capacity, and the effectiveness of environmental enforcement. In addition, prior studies have consistently documented the role of price fluctuations in influencing deforestation dynamics. More recent contributions have further advanced this debate by demonstrating that the relationship between economic dynamics and deforestation is neither linear nor confined to conventional macroeconomic aggregates.

Lima *et al.* (2025), for instance, identify a non-linear relationship between deforestation and economic growth in the Brazilian Legal Amazon, suggesting that forest loss may generate only temporary economic gains that tend to diminish as deforestation intensifies. Similarly, Silveira *et al.* (2025) show that the relationship between economic complexity and deforestation is dynamic and non-linear, indicating that changes in the productive structure may initially intensify forest conversion, but may also contribute to its reduction over time – particularly when accompanied by stronger environmental enforcement mechanisms.

From a broader macro-structural perspective, Haddad *et al.* (2024) emphasise that domestic demand, rather than exports alone, plays a central role in driving deforestation in the Brazilian Amazon, thereby extending the debate beyond commodity-driven explanations. In a related vein, Ferreira Filho and Hanusch (2022) demonstrate that productivity gains concentrated in land-intensive activities, particularly agriculture, tend to increase deforestation. In contrast, productivity improvements in less land-intensive sectors may alleviate pressure on forest areas. Collectively, these studies underscore the importance of productive structure, sectoral composition, and structural transformation in shaping deforestation trajectories.

Recent research has also highlighted the critical role of institutions, monitoring systems, and environmental law enforcement in determining forest outcomes. Nunes *et al.* (2024) document significant changes in command-and-control dynamics in the Brazilian Amazon between 2000 and 2020, providing evidence of a weakening in enforcement capacity in recent years. Assunção, Gandour, and Rocha (2023), in turn, demonstrate that satellite-based monitoring systems – such as Deter – combined with environmental inspections, have played a significant role in reducing deforestation. Their findings provide robust evidence that monitoring effectiveness and enforcement capacity are central components of forest governance.

Although the literature on environmental macroeconomics, the political economy of deforestation, institutions, enforcement, and governance is extensive and rapidly evolving, this study does not seek to exhaust these debates. Rather, the selected studies provide an updated and analytically relevant foundation for situating the present investigation within the current state of the art. Building on the contributions summarised in Box 1, this study examines the relationship between macroeconomic variables and deforestation, following the approach of Diniz *et al.* (2009) through the application of Granger causality tests. However, in contrast to that study, we employ a time-series framework to assess the existence of long-run relationships between macroeconomic variables and their dynamic effects on deforestation over time, as detailed in the following methodology section.

3 METHODOLOGY

To achieve the objectives of this study, a time-series econometric approach is employed, incorporating the variables presented in Box 2.

Box 2 – Variables Used in the Time Series Model

Variable	*Description*	*Source*	*Model*
Deforestation	Deforestation in the states of the Legal Amazon in 1000 km²	MapBiomas – Prodes	Def
Agriculture and Livestock Farming Prices	Cepea's IPE considers the prices in FOB dollars (including transportation costs to the ship going to the importing country) of Brazilian agribusiness exports, including fresh and processed agriculture and livestock farming products. In other words, it refers to the prices received by exporters by product category.	Cepea/Esalq/USP	IPE
Real Exchange Rate	The real effective exchange rate is a weighted arithmetic average of the country's bilateral real exchange rates against 23 selected trading partners.	Ipea	Exchange Rate

Variable	Description	Source	Model
Agriculture and Livestock Farming GDP	The agriculture and livestock farming sector refers to GDP calculated from a production accounting perspective and includes agriculture and livestock farming establishments that produce for the market and for their own consumption. This activity covers the following sectors: agriculture, livestock, forestry, fishing, and aquaculture.	IBGE	GDPdef
Action Plan for the Prevention and Control of Deforestation in the Legal Amazon	A binary dummy variable was used, where 0 represents the years without PPCDAm (2000–2003), 1 represents the years of PPCDAm implementation (2004–2018), 0 again for the years when it was discontinued (2019–2022), and 1 for 2023, when the plan was resumed.	*Dummy*	PPCDam

Source: Prepared by the authors based on the consulted sources.

The primary objective of the analysis is to determine whether long-run relationships exist among the selected variables. Accordingly, a time-series framework is adopted. It is important to note that, due to the relatively small sample size associated with the use of annual data, certain variables commonly included in the literature to explain deforestation dynamics – such as rural credit, institutional indicators, and enforcement measures related to environmental policies – are not incorporated into the empirical model. This reflects the specific scope of the present study, which prioritises the role of macroeconomic variables.

For the application of time-series techniques, the statistical properties of the variables must be carefully examined. In particular, the series should be stationary, meaning that their statistical moments – such as mean, variance, and covariance – remain constant over time, and that the roots of the characteristic equation lie outside the unit circle (Lütkepohl, 2004). Box 3 presents the stationarity tests conducted for the variables included in the analysis.

Box 3 – Description of the Unit Root Tests

Test	Description	Null Hypothesis
Dickey-Fuller GLS test	One of the most recent methods is based on the Dickey-Fuller model, where there is a lower probability of making a type II error.	H0: γ = 0 (it has a unit root) H1: γ < 0 (AR (1) stationary)
Ng-Perron test	This test assumes that any possible trend has already been removed. Furthermore, estimates can be made using Monte Carlo simulations, which offer considerable gains.	H0: γ = 0 (it has a unit root) H1: γ < 0 (AR (1) stationary)
Phillips-Perron test	It applies a nonparametric correction to the Dickey-Fuller test, yielding a consistent estimate even in the presence of lagged dependent variables and serial correlation.	H0: γ = 0 (it has a unit root) H1: γ < 0 (AR (1) stationary)

Source: Prepared by the authors based on Bueno (2008).

Macroeconomic time series are typically non-stationary in levels; however, they often become stationary after first differencing, implying that they are integrated of order one, I(1). Although differencing ensures stationarity, it also leads to a loss of long-run information embedded in the data. To address this issue,

and following Engle and Granger (1987), an error correction framework is employed to recover the long-term equilibrium relationships among the variables.

Based on the stationarity results presented in Box 3, the study proceeds to estimate autoregressive vector models using the dataset described in Box 2. As emphasised by Enders (2015), Lütkepohl and Krätzig (2004), Lütkepohl (2005), and Pfaff (2008), Vector Autoregressive (VAR) models have become a standard tool for analysing macroeconomic relationships, particularly following Sims' (1980) critique of large-scale structural models. Sims (1980) argued that traditional models fail to adequately account for the endogenous nature of economic variables, whereas VAR models treat all variables in the system as jointly endogenous.

Furthermore, Lütkepohl and Krätzig (2004) highlight that VAR-type models are particularly suitable for modelling data-generating processes involving a relatively small set of variables. These models also require careful consideration of the individual properties of each time series, including the presence of deterministic trends or potential structural breaks, which may affect model specification and inference.

Figure 1 illustrates the data-processing procedure adopted in this study following data collection, ensuring the application of appropriate econometric methods to identify long-run relationships and estimate autoregressive dynamics.

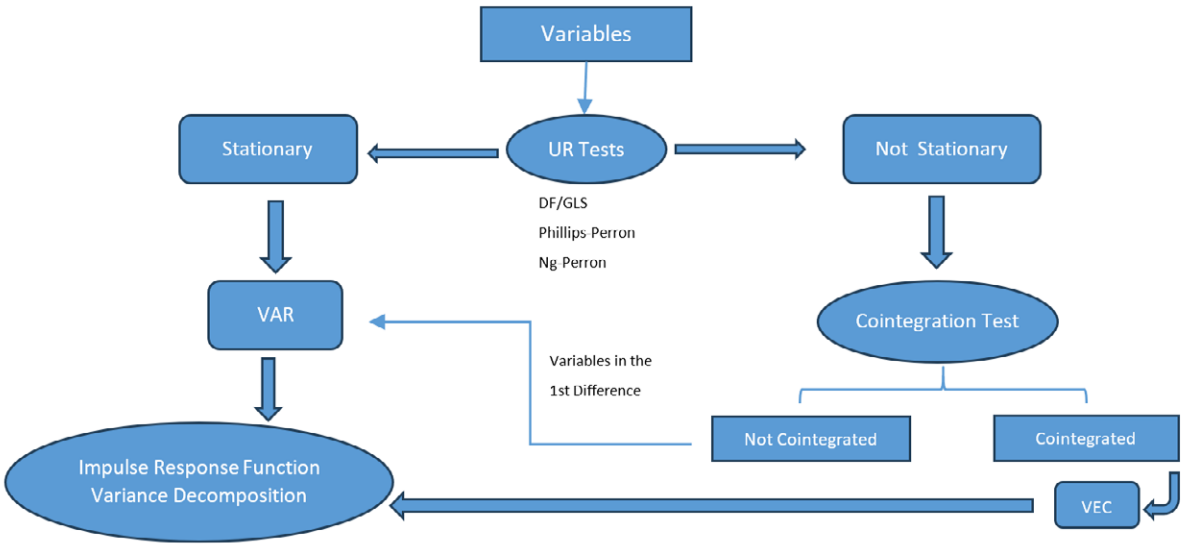


Figure 1 – Steps and Analysis for Building a Time Series Model

Source: Prepared by the authors based on the sources consulted in the methodology.

In addition, the Granger causality test is applied to examine the predictive relationships among the variables. As discussed by Carneiro (1997), this test is based on the principle that future values cannot influence the present or the past; therefore, it evaluates whether lagged values of one variable contain useful information for predicting another variable. A stationary time series is said to Granger-cause another if the inclusion of its lagged values improves the predictive performance of the latter (Carneiro, 1997). For the implementation of the test, non-stationary series are expressed in first differences when necessary. The optimal lag length is determined using the Schwarz Information Criterion (SIC), given its more parsimonious properties in model selection.

Following the presentation of the key elements of the time-series framework, the empirical analysis proceeds to address the research objectives. The EViews software is used to conduct stationarity and Granger causality tests. After identifying which variables in Box 2 exhibit unit roots, the Johansen cointegration test (Trace statistic) is performed using the JMulti software to assess the existence of long-run relationships among the variables. Additionally, JMulti is employed to estimate the most

appropriate model specification based on the cointegration properties of the system. Depending on the results of the Johansen tests, either a Vector Autoregressive (VAR) model or a Vector Error Correction Model (VECM) is estimated.

The Schwarz Information Criterion is again used to determine the optimal lag structure of the model. Following model estimation, a set of diagnostic tests is conducted to assess model adequacy, including normality tests – such as Doornik–Hansen, Lütkepohl, and Jarque–Bera – and the Lagrange Multiplier (LM) test for serial correlation.

4 DISCUSSION OF RESULTS

To address the research questions posed in this study, this section begins with a descriptive analysis of the main variables, namely deforestation, agricultural and livestock prices, the real exchange rate, agricultural and livestock GDP, and the basic interest rate (Selic). Following this characterisation, we examine the predictive relationships among these variables using the Granger causality test. Finally, we investigate the long-run relationships among the variables within a time-series framework.

4.1 DESCRIPTIVE ANALYSIS OF VARIABLES

The evolution of annual deforestation in the Amazon biome since 2000 (Figure 2) constitutes the central focus of this study. This trajectory is analysed in conjunction with the evolution of agricultural and livestock GDP, the real exchange rate (INPC), and agricultural prices (IPE).

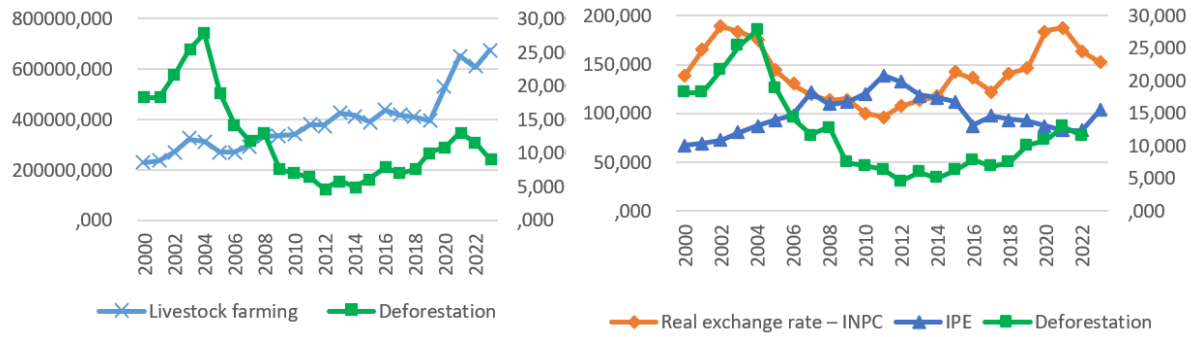


Figure 2 – Evolution of Deforestation in the Amazon Biome (in thousand km²), Agriculture and Livestock Farming GDP (in current BRL at 2023 prices), Real Exchange Rate - INPC, and IPE - Cepea from 2000 to 2023.

Source: Prepared by the authors using data from IBGE, Cepea, and Terra Brasilis.

Note: deforestation data is on the secondary axis.

In general, these variables are often associated with increased agricultural output and, consequently, higher deforestation rates. However, this expected relationship is not clearly supported by the evidence presented in Figure 2. Between 2000 and 2008, deforestation declined significantly, exhibiting a geometric rate of change of approximately −6.16% per year. Over the same period, agricultural and livestock GDP grew at an average annual rate of approximately 3.43%. This pattern persisted between 2008 and 2019, during which agricultural GDP increased at a rate of 2.12% per year, while deforestation continued to decline at an average rate of 0.35% per year.

This decoupling between economic growth and deforestation highlights the effectiveness of the PPCDAm (Action Plan for the Prevention and Control of Deforestation in the Amazon), which coordinated policies aimed at promoting economic activity in the region while simultaneously reducing deforestation rates. The evidence suggests that, during this period, Brazil was able to expand agricultural production without proportionally increasing deforestation.

However, between 2019 and 2022, this pattern reversed. Agricultural and livestock GDP grew at an annual rate of approximately 16.21%, accompanied by an increase in deforestation of approximately 6.10% per year. This shift coincided with the interruption of PPCDAm activities, which were only reinstated in 2023. These results indicate that, for nearly two decades, Brazil successfully implemented policies that allowed for agricultural income growth without exacerbating deforestation. This finding challenges the commonly held assumption that deforestation is a necessary condition for expanding agricultural production.

The relationship between deforestation and variables associated with prices and international competitiveness – captured by the real exchange rate – further reinforces this argument. Between 2000 and 2007, the Brazilian currency (Real) appreciated at an average annual rate of approximately 3.70%, while agricultural prices increased by 8.22% per year. Despite these price increases, deforestation declined at an annual rate of approximately 1.37%. This suggests that higher agricultural prices did not translate into increased deforestation during this period, contradicting the hypothesis that price incentives necessarily lead to forest clearing.

Between 2007 and 2016, the international economic environment remained favourable for Brazilian agricultural exports, although agricultural prices declined at an average rate of 1.53% per year. During this period, the Brazilian currency depreciated by approximately 2.04% annually, enhancing export competitiveness. Despite these favourable conditions for agricultural expansion, deforestation declined sharply at an average rate of 6.75% per year. This finding is consistent with the results of Ferreira Filho, Ribeiro, and Horridge (2015), who demonstrate that Brazil can meet international demand for agricultural products without expanding deforested areas.

In contrast, between 2016 and 2023, deforestation increased at an average annual rate of approximately 6.53%. Over the same period, the exchange rate depreciated by approximately 4.10% per year, increasing the competitiveness of Brazilian products in international markets. Agricultural prices, however, declined slightly at an average rate of 0.16% per year. The combined effect of exchange rate depreciation and relatively lower prices may have stimulated agricultural expansion, thereby increasing pressure on land-use change, particularly through pasture expansion and grain cultivation.

Nevertheless, this expansion strategy raises important concerns. As noted by Abramovay (2019), agricultural productivity in the Amazon region remains relatively low, suggesting that policies should prioritise sustainable intensification rather than the expansion of the agricultural frontier through deforestation.

To further examine the relationships among these variables, the following subsection presents a correlation analysis and the results of the Granger causality tests.

4.2 CORRELATION ANALYSIS AND GRANGER CAUSALITY

Based on the selected dataset, a correlation analysis was conducted, focusing on the relationships between deforestation – the central variable of interest – and the remaining variables (Table 1).

Table 1 – Correlation of the Deforestation Variable with Agriculture and Livestock Farming GDP, Real Exchange Rate, and IPE Variables.

	Agriculture and Livestock Farming GDP	*Real Exchange Rate*	*IPE*
Deforestation	-0.40	0.67	-0.68

Source: Prepared by the authors based on research results.

The results reported in Table 1 indicate a negative correlation between deforestation and both agricultural GDP and agricultural prices (IPE). This finding is consistent with the descriptive evidence presented in Figure 2, where deforestation declined over time despite increases in agricultural income and prices. However, it is important to interpret these results within the context of a policy environment characterised by strong conservation measures, particularly following the implementation of the PPCDAm in 2004.

Regarding the real exchange rate, the results indicate a positive correlation with deforestation. Exchange rate depreciation tends to increase the competitiveness of domestic products in international markets, thereby stimulating exports. In this context, increased external demand for Brazilian agricultural commodities may exert upward pressure on deforestation in the Amazon biome. This pattern may also reflect the expansion of trade with markets that impose relatively less stringent environmental requirements, such as countries in the Middle East and Africa, as well as emerging economies, including China and India.

To further investigate the dynamic relationships among the variables, unit root tests (DF-GLS, Phillips–Perron, and Ng–Perron) were conducted to assess the stationarity of the series. The results, presented in Box 3, indicate that all variables are non-stationary in levels but become stationary after first differencing, suggesting that they are integrated of order one, I(1). Accordingly, the analysis proceeds using first differences where required to ensure stationarity.

Following the stationarity analysis, causal relationships among the variables were examined using a bivariate Granger causality framework. This approach evaluates whether past values of one variable contain useful information for predicting another variable.

Table 2 – Granger Causality Test for the Deforestation, IPE, Real Exchange Rate, and Agriculture and Livestock Farming GDP Variables – with 1 lag* and the variables in the first difference.

Null Hypothesis		*Observations*	*Prob*
Real Exchange Rate does not Cause Granger	Deforestation	22	0.0034
	IPE	22	0.0166
	GDP	22	0.1003

Source: Prepared by the authors based on research data.

**This is consistent with the use of the Schwarz Information Criterion (SIC) to select the optimal lag length.*

Table 2 reports only the statistically significant Granger-causality relationships identified in the analysis.

The results highlight the central role of the real exchange rate in the system, as it Granger-causes the other variables, including deforestation, agricultural prices, and agricultural income. When interpreted alongside the previous findings, these results suggest that the real exchange rate constitutes a key macroeconomic determinant of deforestation dynamics in the Amazon biome.

From an economic perspective, this finding indicates that external market conditions – captured by exchange rate movements – affect both the profitability of agricultural activities and the incentives for production expansion. Exchange rate depreciation, in particular, tends to increase export competitiveness, thereby influencing sectoral prices and income. These mechanisms, in turn, may intensify pressures on land-use expansion and deforestation along the agricultural frontier.

These results are broadly consistent with the literature on the economic drivers of deforestation. Studies such as Assunção *et al.* (2015), Carvalho and Domingues (2016), Diniz *et al.* (2009), and Ferreira Filho, Ribeiro, and Horridge (2015), emphasise the role of macroeconomic conditions and international market incentives in shaping land-use dynamics in Brazil. At the same time, these studies highlight

that the effects of such economic pressures can be mitigated through effective conservation policies and the adoption of sustainable production practices. Thus, economic growth and environmental protection are not necessarily mutually exclusive, provided that appropriate institutional and policy frameworks are in place.

It is important to note, however, the methodological limitations of the Granger Causality Test. While the test identifies predictive relationships based on lagged information, it does not establish structural causality in an economic sense.

Building on these findings, the next section examines the existence of long-run equilibrium relationships among the variables using cointegration techniques within a time-series framework.

4.3 LONG-TERM RELATIONSHIP BETWEEN VARIABLES

Given that the series are non-stationary in levels but integrated of the same order and stationary in first differences, it is appropriate to examine the existence of cointegration among them. To assess whether a linear combination of the variables indicates a long-run equilibrium relationship, the Johansen trace test for cointegration was conducted, as shown in Table 3.

Table 3 – Cointegration Test Results for Selected Variables.

r_0	λ_{trace}	*p-value*	*90%*	*95%*	*99%*
0	58,47**	0.0179	50.50	53.94	60.81
1	33,47***	0.0748	32.25	35.07	40.78
2	14,38	0.2699	17.98	20.16	24.69
3	5,11	0.2814	7.60	9.14	12.53

Source: Research results.

*Note: *significance at 1%, **significance at 5%, and ***significance at 10%.*

The results presented in Table 3 indicate the presence of at least two cointegration vectors among the selected variables, suggesting that they are cointegrated. In other words, the variables exhibit a stable long-term relationship. This finding implies that deforestation dynamics respond, over time, to changes in the selected macroeconomic variables. Formally, the existence of cointegration ($0 < r < k$) implies that the Π matrix has reduced rank, and therefore the appropriate specification is a Vector Error Correction Model (VECM). Accordingly, a VECM is estimated with two cointegration vectors[1], including a dummy variable capturing the presence or absence of the PPCDAm, in order to account for institutional changes over time.

To evaluate the contribution of each variable to the dynamics of deforestation in the Amazon biome, a variance decomposition analysis was conducted. This procedure allows for the identification of the proportion of forecast error variance attributable to shocks in each variable over different time horizons. The results are presented in Table 4.

Table 4 – Variance Decomposition of Deforestation in the Amazon Biome.

Horizon	*Def*	*IPE*	*Exchange Rate*	*GDPdef*
1	0.62	0.01	0.57	0.01
2	0.13	0.05	0.82	0.00
3	0.06	0.04	0.68	0.22
4	0.03	0.03	0.45	0.48

Horizon	Def	IPE	Exchange Rate	GDPdef
5	0.02	0.09	0.49	0.40
6	0.01	0.14	0.50	0.34
7	0.02	0.17	0.53	0.29
8	0.03	0.18	0.54	0.25
9	0.04	0.18	0.55	0.23
10	0.05	0.17	0.54	0.23

Source: Prepared by the authors based on the results of the estimated model.

The variance decomposition results indicate a predominant role of the real exchange rate in explaining deforestation dynamics over time, accounting for up to approximately 82% of the variation in deforestation. At longer horizons, price dynamics – captured by IPE (reaching approximately 18%) – and agricultural GDP (explaining up to 48%) also become increasingly relevant. These findings suggest that both price-related incentives and income dynamics contribute to changes in deforestation levels.

Overall, the results indicate that macroeconomic conditions that enhance external competitiveness and sectoral profitability may intensify pressures on deforestation. Consequently, conservation policies should be designed in alignment with macroeconomic dynamics, as the existence of a long-run relationship implies that such variables systematically influence deforestation outcomes over time.

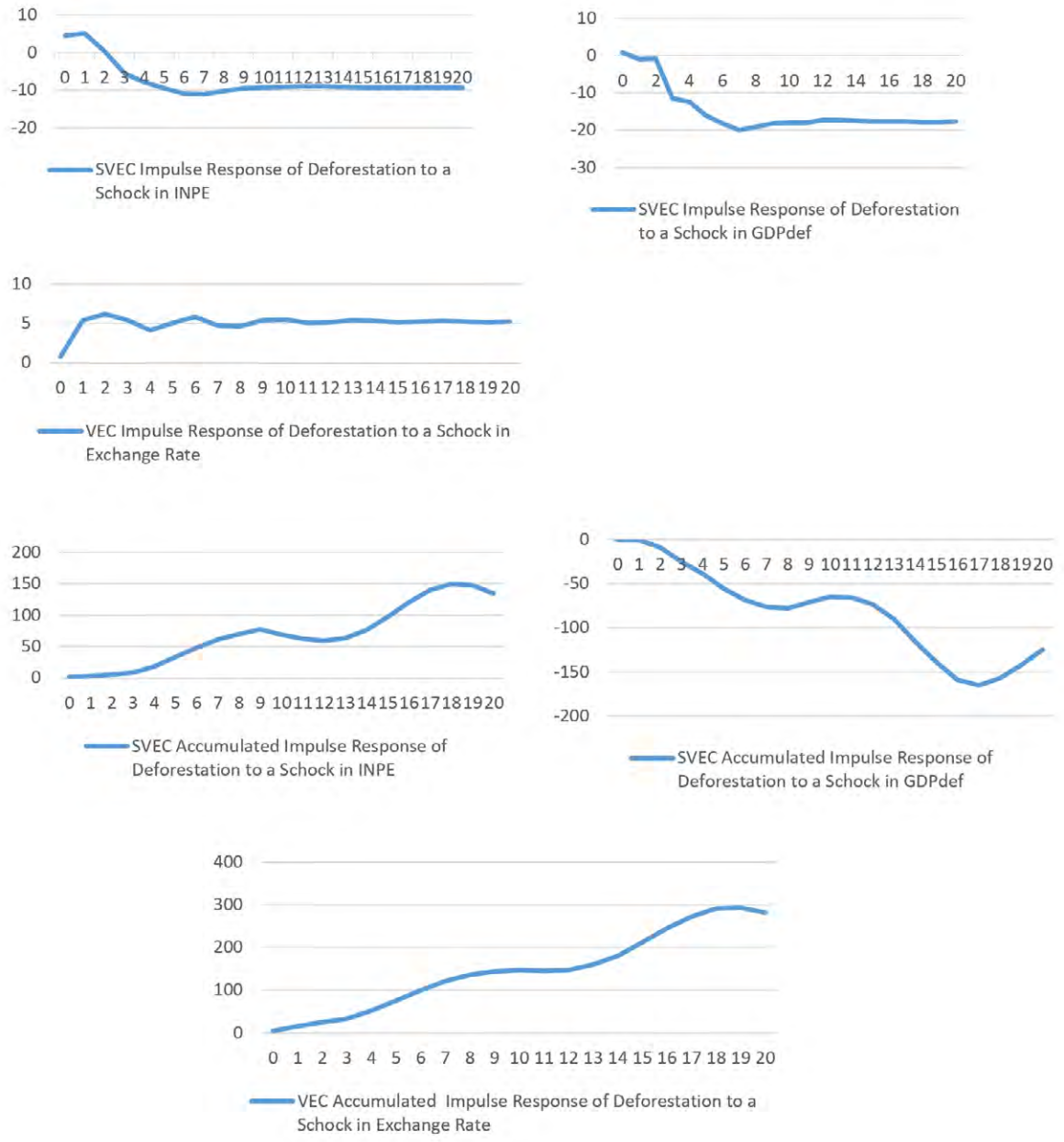
These findings are broadly consistent with the literature summarised in Table 1. For instance, Haddad *et al.* (2024) show that favourable market conditions and price dynamics tend to increase pressure on deforestation rates. Similarly, Silveira *et al.* (2025) argue that economic growth in the region introduces complexity into deforestation dynamics, generating both opportunities for environmental improvement and risks of expansion, depending on institutional conditions.

Across the reviewed studies – and as supported by the results presented here – a consistent conclusion emerges: while economic variables influence deforestation, their effects are strongly mediated by the design and effectiveness of conservation policies. When such policies are weak or poorly enforced, deforestation tends to accelerate. Therefore, it is essential to integrate conservation and sustainability policies with economic development strategies, particularly by creating incentives for sustainable production practices rather than promoting expansion through deforestation for grain cultivation or extensive cattle ranching.

Although the estimated model attempts to capture institutional effects through the inclusion of a binary variable associated with the PPCDAm, other relevant factors – such as rural credit availability, enforcement intensity, and broader institutional changes in environmental governance – could not be incorporated into the empirical specification.

Regarding the dynamic responses of deforestation to macroeconomic shocks, the results – illustrated in Figure 3 – indicate that positive shocks in both prices and the exchange rate generate positive effects on deforestation. This finding reinforces the importance of macroeconomic conditions in shaping the expansion of the agricultural frontier. In particular, exchange rate depreciation increases the profitability of agricultural exports, thereby stimulating investment and the expansion of cultivated areas.

Figure 3 – Accumulated Impulse Response of Deforestation in the Amazon Biome to a Shock in IPE, Real Exchange Rate, and Agriculture and Livestock Farming GDP.



Source: Prepared by the authors based on the results of the estimated model.

This result is consistent with the literature identifying exchange rate movements and commodity prices as key drivers of agricultural expansion in the Amazon, as highlighted by Ferreira Filho and Hanusch (2022), and Haddad *et al.* (2024).

Conversely, the cumulative negative effect of GDP on deforestation suggests a more complex process of structural transformation. This effect may be associated with institutional improvements, technological progress, or enhanced environmental governance accompanying economic growth. As discussed by Lima *et al.* (2025), higher income levels may strengthen institutional capacity for environmental monitoring and enforcement, as well as facilitate the adoption of more efficient production technologies. Similar findings are reported by Assunção, Gandour, and Rocha (2023), who show that monitoring systems such as Deter, combined with command-and-control policies, played a crucial role in reducing deforestation during certain periods, even in the presence of economic incentives favouring agricultural expansion.

These dynamics are also influenced by developments in supply chain governance, including increased monitoring of production processes, destination markets, and private-sector initiatives aimed at enhancing environmental standards. Examples include mechanisms such as the Soy Moratorium and traceability systems in the beef supply chain, which seek to expand market access while promoting compliance with zero-deforestation commitments.

In summary, the evidence suggests that Brazil has previously been able to combine economic growth with reductions in deforestation in the Amazon biome. Achieving this outcome required coordination among multiple actors within both the economic and institutional environment. Reestablishing such coordination is essential to ensure that the agricultural sector continues to generate income and access international markets while, through effective conservation policies, regulatory enforcement, and incentives for sustainable practices, significantly reducing deforestation rates.

5 CONCLUDING REMARKS

This study aimed to assess whether macroeconomic variables, particularly those related to income and international trade, affect deforestation in the Amazon biome. Specifically, the analysis examined the existence of a long-run relationship between deforestation in the Legal Amazon and selected economic variables, namely agricultural prices, the real exchange rate, and agricultural GDP. The results from the Johansen cointegration test indicate that these variables are cointegrated, confirming the presence of a long-term equilibrium relationship.

The descriptive analysis reveals a significant acceleration in deforestation in recent years. However, during the early 2000s through the early 2010s, agricultural income increased substantially while deforestation declined considerably in the Amazon biome. This finding suggests that economic growth in the agricultural sector can occur without necessarily increasing deforestation, particularly in the presence of effective conservation policies.

The variance decomposition results indicate that exchange rate shocks account for a substantial share of the fluctuations in deforestation, while agricultural GDP and prices play a secondary, yet still relevant, role. This suggests that macroeconomic conditions directly affect the economic incentives associated with the expansion of the agricultural frontier. The impulse–response functions further support this interpretation, showing that positive shocks in prices and in the exchange rate generate positive cumulative effects on deforestation. In contrast, the effect of income is more complex, potentially reflecting structural and institutional transformations over the development process.

These findings are consistent with studies such as Lima *et al.* (2025) and Silveira *et al.* (2025), which emphasise the role of structural dynamics and regional economic conditions in shaping environmental outcomes in the Amazon. In this context, the results indicate that macroeconomic variables exert a measurable influence on deforestation, with the real exchange rate emerging as a particularly relevant determinant. This suggests that pressures arising from international market conditions may contribute to the expansion of deforestation and, therefore, should be considered in the design of economic and trade policies.

The results also reinforce the interpretation found in the recent literature that deforestation in the Amazon is closely linked to the profitability of agricultural activities and the region's integration into national and global value chains, as discussed by Ferreira Filho and Hanusch (2022) and Haddad *et al.* (2024). Although the present study captures institutional effects only through the inclusion of a dummy variable, existing evidence shows that command-and-control policies, combined with satellite-based monitoring systems and effective enforcement mechanisms, have played a critical role in reducing deforestation during certain periods. This is highlighted in the work of Assunção, Gandour and Rocha (2023) and Nunes *et al.* (2024).

Overall, the results indicate that deforestation in the Amazon biome is strongly associated with macroeconomic conditions, particularly exchange rate movements, agricultural prices, and income dynamics. Exchange rate fluctuations, by affecting external competitiveness and sectoral profitability, appear to be a central mechanism influencing land-use decisions. At the same time, the empirical evidence suggests that the institutional environment mediates the impact of these economic drivers. Periods characterised by stronger monitoring systems, effective enforcement, and robust conservation policies tend to mitigate environmental pressures arising from favourable market conditions. Therefore, the interaction between macroeconomic incentives and institutional capacity emerges as a key factor in understanding deforestation dynamics in the Amazon.

Despite these contributions, the study presents several limitations. The analysis is based on annual data, which could be extended in future research using higher-frequency datasets, such as monthly observations, and more advanced econometric frameworks capable of handling larger datasets. This would allow the estimation of more complex macroeconomic models – similar to those employed by central banks – and enable the analysis of potential links between monetary policy and deforestation dynamics. In addition, the relatively small sample size limits the scope of the empirical analysis. The model also does not include variables that may be important in explaining deforestation dynamics, such as rural credit availability, enforcement intensity, and broader institutional mechanisms related to environmental governance. The incorporation of these factors represents an important avenue for future research.

NOTE

1 | The estimated VEC model followed the Schwarz Information Criterion (SIC) for lag selection. Normality tests—Doornik–Hansen, Lütkepohl, and Jarque–Bera—were conducted, indicating that the residuals do not deviate from normality. Regarding autocorrelation, the LM test indicates its presence, which may be associated with the small sample size or dynamics not fully captured by the specified lags.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (OpenAI) only for language editing and stylistic polishing. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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Determinants of innovation in aquaculture organisations of the Peruvian Amazon

Determinantes de inovação em organizações aquícolas da Amazônia Peruana

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ABSTRACT

Amazonian aquaculture is recognised as a strategic sector for food security, employment generation, and ecosystem conservation, particularly in a context where innovation is essential to addressing environmental and social challenges. This study aimed to analyse the main determinants of innovation in aquaculture organisations in the San Martín region of Peru. A cross-sectional quantitative design was employed, using face-to-face surveys administered to a random sample of 76 organisations benefiting from the National Programme for Innovation in Fisheries and Aquaculture. Data were analysed using partial least squares structural equation modelling (PLS-SEM) to assess the reliability and validity of the measurement model and the structural relationships between seven internal and external determinants and three types of innovation: process, organisational, and marketing. The results indicate that technological cooperation and fiscal incentives positively influence innovation, highlighting the importance of public policies and collaborative networks in supporting a competitive and resilient aquaculture sector.

Keywords: Aquaculture. Innovation determinants. Technological cooperation.

RESUMO

A aquicultura amazônica é reconhecida como um setor estratégico para a segurança alimentar, a geração de emprego e a conservação de ecossistemas, em um contexto no qual a inovação é fundamental para responder a desafios ambientais e sociais. O objetivo desta pesquisa foi analisar os principais determinantes da inovação em organizações aquícolas na região de San Martín, no Peru. Foi adotado um desenho quantitativo transversal, por meio de entrevistas presenciais aplicadas a uma amostra aleatória de 76 organizações beneficiárias do Programa Nacional de Inovação em Pesca e Aquicultura. A análise foi realizada com modelos de equações estruturais com mínimos

quadrados parciais, avaliando a confiabilidade, a validade e as relações estruturais entre sete determinantes internos e externos e três tipos de inovação (processos, organizacional e marketing). Os resultados evidenciam que a cooperação tecnológica e os incentivos fiscais influenciam positivamente a inovação, destacando a importância de políticas públicas e de redes colaborativas para um desenvolvimento aquícola competitivo e resiliente.

Palabras clave: *Acuicultura. Determinantes de innovación. Cooperación tecnológica.*

1 INTRODUCTION

Aquaculture has established itself over recent decades as the fastest-growing food production sector worldwide, playing a strategic role in contemporary agri-food systems, particularly in emerging economies, where it contributes to food security and job creation (Bohnes *et al.*, 2022; FAO, 2022). Since the early 2000s, while capture fisheries have remained stable, aquaculture has grown steadily, becoming a productive alternative to the stagnation of fishery resources and a factor that may help reduce pressure on wild populations (Naylor *et al.*, 2021).

Within this framework, aquaculture is directly linked to the Sustainable Development Goals (SDGs) of the 2030 Agenda. Its importance lies not only in the supply of nutritious food but also in its contribution to job creation, economic development, and the cultural preservation of numerous communities (FAO, 2022; Troell *et al.*, 2023). Aquatic products—both farmed and captured—are fundamental to food security: in 2020, global per capita consumption reached 20.2 kg, compared to 9 kg in 1961, providing about 17% of the world's animal protein intake and accounting for nearly 20% of the protein diet of 3.3 billion people (FAO, 2022).

Meeting the 2030 Agenda will require partnerships, innovation, and comprehensive strategies at multiple scales (Troell *et al.*, 2023). In this sense, aquaculture not only represents a source of animal protein with a lower environmental footprint than traditional livestock farming (Bennett *et al.*, 2021; Costello *et al.*, 2020; Springmann *et al.*, 2018) but also constitutes a sector capable of adapting to sustainability demands in food production (Bohnes *et al.*, 2022).

In Peru, aquaculture accounts for only 2.2% of national hydrobiological production, despite the favourable natural conditions offered by the coast, highlands, and Amazon region (FAO, 2022; Hidalgo, 2019). Nevertheless, since 2015, the activity has shown sustained growth, reflected in the increasing number of licences granted, the rise in gross production value, and its contribution to job creation (Produce, 2024). Looking ahead, it is projected that by 2030, fishery production will decrease by 23%, while aquaculture will grow by 32% compared to 2018. However, a significant gap in the supply of hydrobiological products will persist (FAO, 2022).

Given this potential, the Peruvian government has implemented regulatory frameworks and support instruments, such as the General Aquaculture Law (2016) and the National Programme for Innovation in Fisheries and Aquaculture – PNIPA (2017–2023), which co-financed more than 1,500 projects with an investment exceeding 427 million soles (PNIPA, 2023). However, structural limitations remain, particularly the weakness of the innovation services market, the lack of coordination between technological supply and demand, and low competitiveness relative to regional countries such as Chile and Brazil (Produce, 2023).

The Amazon is a particularly relevant case, as it harbours one of the world's greatest diversities of freshwater fish. However, only about 280 species are used for human consumption, many of which are under conservation threat (Albert *et al.*, 2011; Dagosta; Pinna, 2019; Pelicice *et al.*, 2021). In this context, Amazonian aquaculture—particularly the cultivation of native species—emerges as a sustainable alternative, with a carbon footprint up to ten times lower than livestock farming per tonne of protein produced, and without requiring further agricultural expansion (Pacheco *et al.*, 2025).

Nevertheless, the sustainability of aquaculture depends largely on the social and institutional dynamics that mediate innovation processes (Ferreiro; Sousa, 2019). These processes may originate from science, local knowledge, or the private sector, and develop in diverse economic and political environments (Alexander *et al.*, 2015; Jespersen *et al.*, 2014). Therefore, understanding the multifaceted nature of aquaculture, which integrates environmental, social, and economic dimensions, is essential to identify both the opportunities and challenges that will shape its future development (Troell *et al.*, 2023).

1.1 DETERMINANTS OF INNOVATION

In today's business environment, characterised by uncertainty and rapid technological change, innovation has become a central element of organisational competitiveness and sustainability (Teece, 2007). Various authors have identified internal determinants (strategy, absorptive capacity, organisational structure, and culture) and external determinants (government support, technological cooperation, and market factors) that influence innovative outcomes (Amabile *et al.*, 2004; Crossan; Apaydin, 2010; Keizer *et al.*, 2002).

1.1.1 INTERNAL DETERMINANTS OF INNOVATION

The internal environment is crucial to the capacity for innovation of aquaculture organisations, as it provides the strategic and cultural foundations needed to translate resources into sustainable outcomes. Strategic orientation, in particular, ensures that decisions align with the institutional mission and vision, serving as a framework that guides and strengthens innovation processes (Valladares, 2012; Yam *et al.*, 2011). The literature highlights that a strategy explicitly linked to innovation enhances idea generation and facilitates the integration of new technologies and processes (Crossan; Apaydin, 2010; O'regan; Ghobadian, 2005). In addition, absorptive capacity is a key mechanism for transforming external knowledge into competitive advantages, integrating the processes of knowledge acquisition, assimilation, transformation, and exploitation (Todorova; Durisin, 2007; Zahra; George, 2002). Organisational culture also acts as a catalyst for innovation, encouraging openness to learning, risk-taking, and recognition of employee-initiated initiatives (Becheikh *et al.*, 2006). Furthermore, intrapreneurship constitutes another internal determinant, referring to the ability of members of an organisation to generate and promote new ideas, initiatives, or projects from within established structures, thereby contributing to innovation capacity (Antoncic; Hisrich, 2003; Gawke *et al.*, 2019). Finally, organisational structure affects the speed and quality of innovation processes, as lower levels of centralisation and formalisation facilitate knowledge flows and greater adaptability to change (Liu *et al.*, 2018).

1.1.2 EXTERNAL DETERMINANTS OF INNOVATION

External environmental determinants are key factors shaping organisations' capacity for innovation, arising from regulatory, technological, and market environments that extend beyond organisational boundaries. Firstly, government support is a decisive factor in the development of innovation, particularly through public policies and fiscal incentives. Bell and Pavitt (1993) highlight that the availability of funding for basic research, alongside grants, awards, and loans, is an essential instrument for stimulating the generation and dissemination of innovations. Moreover, Becheikh *et al.* (2006) note that these measures, together with regulations and public-private partnerships, have been crucial to the competitiveness of the most dynamic economies when compared with those with lower innovative capacity.

Another critical component of the external environment is technological cooperation, which reflects the increasing reliance of innovative organisations on external sources of knowledge. The open

innovation literature argues that firms cannot rely exclusively on internal resources, but must interact with universities, research institutes, suppliers, customers, competitors, and consultants, forming networks that enhance their capacity for innovation (Chesbrough, 2006). Models such as the Triple Helix (Etzkowitz; Leydesdorff, 2000) and the democratisation of innovation (VON HIPPEL, 2005) emphasise that the quality of these collaborative relationships determines the speed and success of innovation processes (Ferguson, 2005).

Finally, market orientation is another key external determinant, reflecting organisations' ability to collect, disseminate, and respond effectively to market changes, integrating customer feedback into the development of innovative products and services (Jaworski; Kohli, 1993; Slater; Narver, 1994). Organisations that systematise market learning can strengthen their competitiveness by transforming customer knowledge into innovations that add value (Simpson *et al.*, 2006; Valladares, 2012).

This research aims to analyse the influence of the main determinants of innovation, both internal and external, on aquaculture organisations engaged in fish production in the San Martín region. The study seeks to provide evidence from a strategic Amazonian territory, where biodiversity, social challenges, and the need for sustainable production converge, thereby contributing to a better understanding of the factors that shape the competitiveness and development of the aquaculture sector.

2 METHODOLOGY

The research focused on the analysis of aquaculture organisations engaged in fish production at the first stage of the value chain—namely, cultivation and grow-out—while excluding processing units and other entities. The reference population comprised organisations in the San Martín region that benefitted from the National Programme for Innovation in Fisheries and Aquaculture (PNIPA) between 2018 and 2023, during which 182 aquaculture innovation projects were funded. From this database, a random sample of 76 organisations was selected, representing a substantial proportion of the population. Data collection was carried out through face-to-face surveys administered at production centres; when producers could not be reached in person, virtual surveys were conducted. The surveys targeted project coordinators or legal representatives, as they were the individuals most familiar with innovation-related activities. Prior to administration, all participants were fully informed of the study's aims, ensuring confidentiality and the exclusive use of data for research purposes.

The instrument used was designed based on specialised literature and subjected to a two-phase validation process. In the first phase, a panel of experts evaluated the relevance and clarity of the items; in the second, a pilot field test was conducted, which enabled the refinement of certain items and, in particular, justified the exclusion of the product innovation dimension, as the surveyed organisations did not develop this type of innovation. Thus, the dependent variable was defined as the degree of innovation in three dimensions: process innovation, organisational innovation, and marketing innovation. The independent variables corresponded to the determinants of innovation, classified as internal factors (strategy, absorptive capacity, organisational structure, and organisational culture) and external factors (government support, technological cooperation, and market factors), as shown in Figure 1.

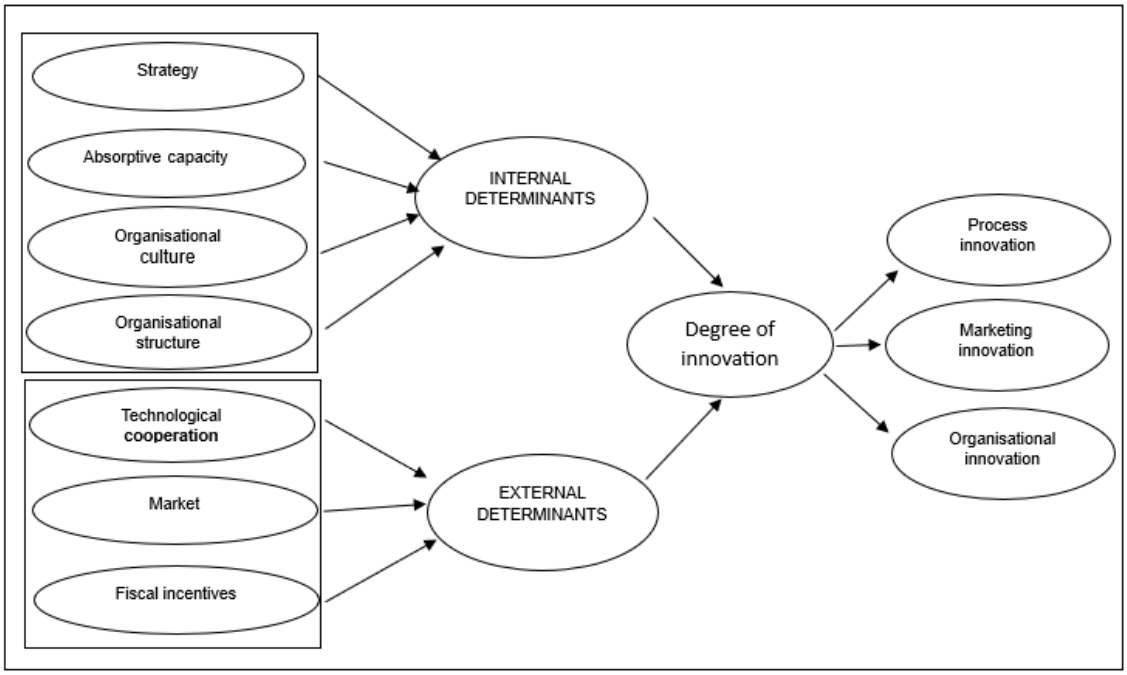


Figure 1 – Conceptual framework of the research.

Source: The authors.

Data analysis was conducted using partial least squares structural equation modelling (PLS-SEM), a technique suitable for moderate sample sizes and complex latent variable structures (Hair *et al.*, 2022; Henseler *et al.*, 2016). The procedure comprised estimating both the measurement and structural models, following standardised evaluation criteria. For the measurement model, internal consistency reliability was assessed using Cronbach's alpha and composite reliability (≥ 0.70), convergent validity using the average variance extracted (AVE ≥ 0.50), discriminant validity using the Fornell-Larcker criterion and the heterotrait-monotrait ratio (HTMT ≤ 0.85/0.90), and collinearity using the variance inflation factor (VIF < 3–5) (Fornell; Larcker, 1981; Hair *et al.*, 2022). For the structural model, path coefficients were assessed using bootstrapping with 5,000 resamples and percentile and BCa confidence intervals. The coefficients of determination (R^2), effect sizes (f^2 = 0.02/0.15/0.35), and predictive relevance ($Q^2 > 0$) were also evaluated. As a global diagnostic, the SRMR index (< 0.08/0.10) was reported (Hair *et al.*, 2022).

3 RESULTS AND DISCUSSION

This section presents the multivariate results, beginning with the evaluation of the measurement model, followed by the analysis of the structural model. The influence of internal factors (strategy, absorptive capacity, organisational culture, and organisational structure) and external factors (market, technological cooperation, and fiscal incentives) on the different types of innovation (process, marketing, and organisational innovation) is considered.

Table 1 displays the coefficients for the validity and reliability parameters of the proposed general model. Most constructs exhibited values consistent with those recommended in the literature: average variance extracted (AVE) above 0.50, Cronbach's alpha greater than 0.70, and composite reliability above 0.70 (Hair *et al.*, 2009; Ringle *et al.*, 2014). The only exception was the construct "fiscal incentives", which yielded a Cronbach's alpha of 0.295; however, both composite reliability (0.701) and AVE (0.564) were satisfactory, and it was therefore retained in the model.

Table 1 – Convergent Validity, Internal Consistency, and Composite Reliability

	Cronbach's alpha	*Composite reliability (rho_c)*	*Average variance extracted (AVE)*
Absorptive capacity	0.913	0.935	0.742
Technological cooperation	0.935	0.951	0.796
Organisational culture	0.928	0.946	0.777
Strategy	0.953	0.966	0.877
Organisational structure	0.753	0.843	0.590
Fiscal incentives	0.295	0.701	0.564
Process innovation	0.832	0.899	0.749
Marketing innovation	0.872	0.913	0.724
Organisational innovation	0.876	0.907	0.619
Market	0.843	0.894	0.680

Source: The authors.

Discriminant validity, assessed using the Fornell-Larcker criterion, is presented in Table 2. The results indicate that, in most cases, the square root of the AVE was greater than the correlations between constructs, thereby satisfying the criterion. An exception was observed in the correlation between absorptive capacity and organisational culture, which exceeded the reference value, suggesting possible conceptual redundancy between these constructs. This issue was further examined in conjunction with collinearity (VIF) in the structural model.

Table 2 – Discriminant Validity: Fornell-Larcker Criterion (1981)

	I	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*
I. Absorptive capacity	0.861									
II. Technological cooperation	0.796	0.892								
III. Organisational culture	0.880	0.733	0.881							
IV. Strategy	0.875	0.836	0.739	0.937						
V. Organisational structure	0.806	0.695	0.793	0.715	0.768					
VI.Fiscal incentives	0.711	0.702	0.594	0.762	0.603	0.751				
VII. Process innovation	0.746	0.819	0.679	0.801	0.609	0.747	0.866			
VIII. Marketing innovation	0.539	0.616	0.563	0.573	0.489	0.481	0.654	0.851		
IX. Organisational innovation	0.765	0.820	0.717	0.786	0.644	0.792	0.839	0.689	0.787	
X. Market	0.729	0.819	0.732	0.749	0.718	0.669	0.692	0.643	0.752	0.824

Source: The authors.

Table 3 presents the results of the structural model. Of the estimated paths, four were statistically significant: technological cooperation and process innovation ($\beta = 0.464$; $p < 0.01$), technological cooperation and organisational innovation ($\beta = 0.355$; $p < 0.01$), fiscal incentives and process innovation ($\beta = 0.279$; $p < 0.01$), and fiscal incentives and organisational innovation ($\beta = 0.384$; $p < 0.001$). The

remaining paths did not reach statistical significance, although some displayed moderately positive coefficients, such as the relationship between market and marketing innovation (β = 0.358; p = 0.059) (Figure 2).

Table 3 – Structural Model Results

	Coefficient	*Standard deviation*	*p-values*
Absorptive Capacity → Process Innovation	-0.066	0.208	0.750
Absorptive Capacity → Marketing Innovation	-0.224	0.276	0.417
Absorptive Capacity → Organisational Innovation	-0.004	0.186	0.983
Technological Cooperation → Process Innovation	0.464	0.145	0.001
Technological Cooperation → Marketing Innovation	0.190	0.228	0.403
Technological Cooperation → Organisational Innovation	0.355	0.128	0.006
Organisational Culture → Process Innovation	0.172	0.175	0.325
Organisational Culture → Marketing Innovation	0.280	0.209	0.181
Organisational Culture → Organisational Innovation	0.206	0.145	0.155
Strategy → Process Innovation	0.257	0.169	0.129
Strategy → Marketing Innovation	0.187	0.233	0.421
Strategy → Organisational Innovation	0.050	0.166	0.766
Organisational Structure → Process Innovation	-0.092	0.145	0.525
Organisational Structure → Marketing Innovation	-0.080	0.172	0.642
Organisational Structure → Organisational Innovation	-0.091	0.105	0.387
Fiscal Incentives → Process Innovation	0.279	0.107	0.009
Fiscal Incentives → Marketing Innovation	0.006	0.184	0.976
Fiscal Incentives → Organisational Innovation	0.384	0.110	0.000
Market → Process Innovation	-0.079	0.133	0.554
Market → Marketing Innovation	0.358	0.190	0.059
Market → Organisational Innovation	0.085	0.126	0.501

Source: The authors

In the supplementary analyses, the average VIF was 5.147, which is considered acceptable as it remains below the threshold of 10 (Gujarati; Porter, 2009). The analysis of effect sizes (f^2) indicated small (0.02) and medium (0.15) effects, according to Cohen's (1988) classification. Regarding the model's explanatory power, the adjusted coefficients of determination (R^2) were 0.725 for process innovation, 0.398 for marketing innovation, and 0.761 for organisational innovation. This demonstrates that the model had the greatest explanatory power for organisational innovation, followed by process innovation, with lower explanatory power for marketing innovation.

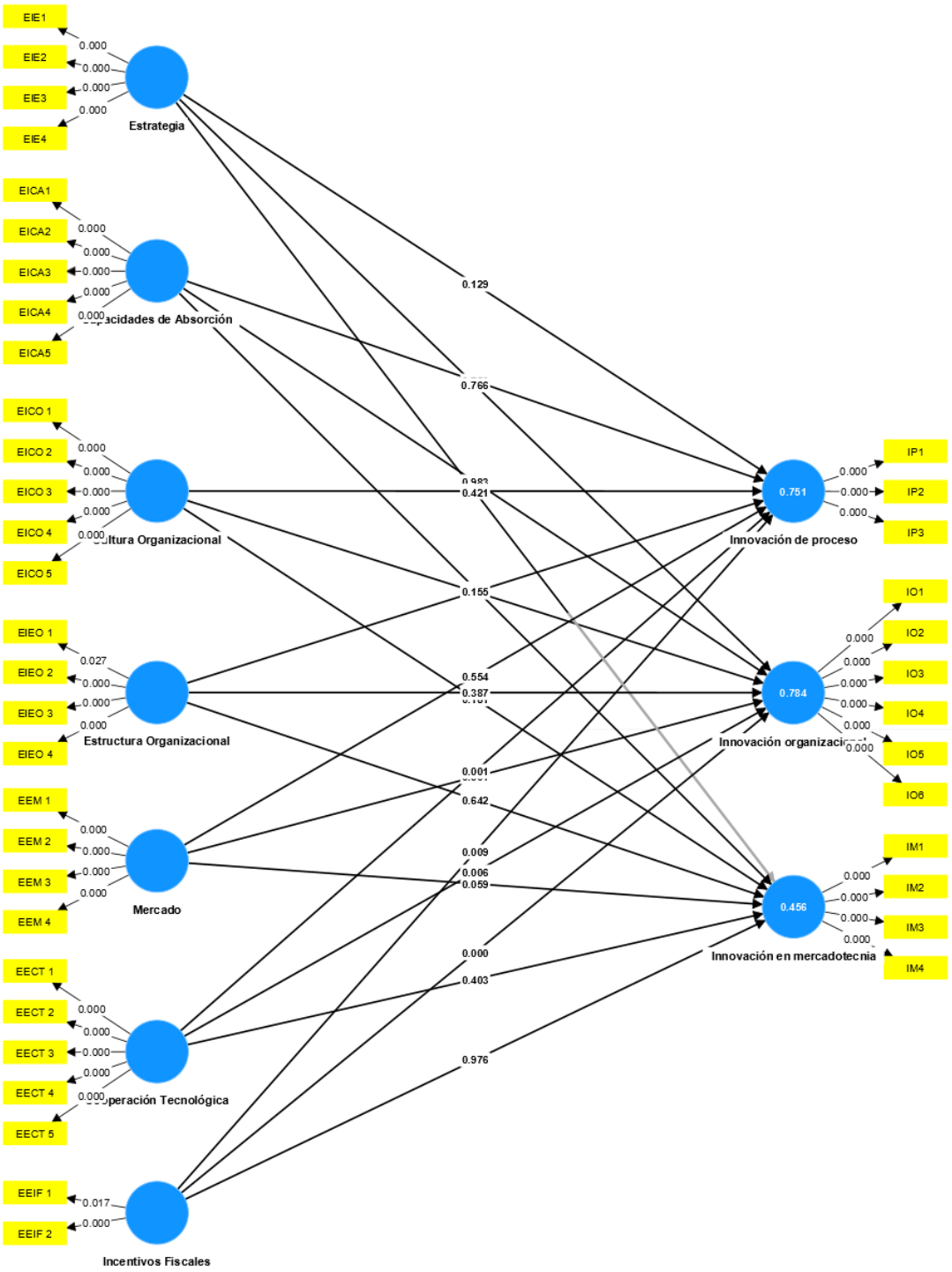


Figure 2 – PLS-SEM Structural Model of Internal and External Determinants of Innovation in Amazonian Aquaculture Organisations

Source: The authors

Aquaculture has grown rapidly and has become a strategic component of contemporary agri-food systems, contributing to food security and employment. At a global level, studies have shown that the economic, social, and environmental pillars can mutually reinforce one another within aquaculture systems, without systematic trade-offs between them (Garlock *et al.*, 2024). This evidence is closely linked to the international emphasis on partnerships and innovation to advance the objectives of the 2030 Agenda (Troell *et al.*, 2023), and to the idea that aquaculture represents a source of animal

protein with a lower environmental footprint than traditional livestock sectors, while also adapting to more demanding sustainability requirements (Bennett *et al.*, 2021; Bohnes *et al.*, 2022; Costello *et al.*, 2020; Springmann *et al.*, 2018).

In this context, the empirical findings indicate that external determinants—particularly technological cooperation and fiscal incentives—are positively and significantly associated with process innovation and organisational innovation. This pattern is consistent with the literature, which emphasises the centrality of collaboration and institutional arrangements in activating and sustaining change in productive sectors. It has been noted that the success of innovation is closely linked to the quality of collaborative relationships (Ferguson, 2005) and that innovative activities are often observed primarily among suppliers and service providers connected to aquaculture, reinforcing the importance of networks that extend beyond production units (Aarstad; Jakobsen, 2020; Aarstad *et al.*, 2023). Furthermore, in the face of environmental concerns and resource constraints, the need for cooperation and for combining technological solutions with improved management practices has also been highlighted, along with policies that promote innovative techniques aimed at more responsible production (Laktuka *et al.*, 2023; Ogello; Munguti, 2016).

On the other hand, the internal factors considered—strategy, culture, organisational structure, and absorptive capacity—did not show significant effects on the innovations analysed. The literature offers useful insights for understanding this result. The adoption of innovations in aquaculture may be limited by capital requirements, funding barriers, and difficulties in accessing equipment, inputs, and training, especially in smaller-scale organisations (Rosgren, 2022; Vecchio *et al.*, 2024). Added to this are cultural influences and routines that affect the acceptance of new practices (Stanfield, 1999), as well as the role of local institutions in creating enabling conditions and embedding innovation within the territory (Kumar, 2018). It has also been noted that without the involvement of the productive sector, research funded by public resources tends to be less relevant and impactful, making openness and effective engagement among actors essential if R&D is to translate into concrete change (Iversen; Hydle, 2023). The effect of the market environment on marketing innovation approached statistical significance, suggesting signs of commercial adjustment that could be further strengthened through differentiation strategies tailored to the regional context (Cojocaru *et al.*, 2020).

The Amazon is a region of high biological diversity and a need for productive alternatives that strengthen livelihoods and reduce pressure on ecosystems. Evidence indicates that innovation processes in aquaculture depend on the social and institutional dynamics that mediate their adoption (Ferreiro; Sousa, 2019). In this sense, it has been suggested that innovation can help make the cultivation of native species viable and strengthen weaker links in the value chain (Vecchio *et al.*, 2024), while the heterogeneity of performance observed globally opens up opportunities for policies and investments capable of improving economic, social, and environmental outcomes where these remain incipient (Garlock *et al.*, 2024). This aligns with the idea that, in the region, there are possible development pathways with a lower carbon footprint per unit of protein and without further agricultural expansion, provided that decisions are guided by evidence and cooperation (Pacheco *et al.*, 2025). At the same time, various studies on sustainability transitions have analysed how innovations can generate multiple impacts on development objectives. These studies offer frameworks for anticipating both synergies and potential trade-offs between economic, social, and environmental goals (Dorninger *et al.*, 2020; Gaitán-Cremaschi *et al.*, 2019).

From a governance perspective, the effectiveness of policy networks is associated with the inclusion of relevant actors, the openness of processes, and participants' perception of outcomes (Krause, 2015). When these conditions are not met, a gap may emerge between stakeholders and policies, resulting in regulations that are poorly targeted or even detrimental to the sector (Green, 2023; Vecchio *et al.*, 2024). At the same time, innovation may also be understood as a vector of institutional development, insofar as governments strengthen the instruments used to promote science, technology, and innovation within the business sector. Overall, the results from San Martín—where technological cooperation and

fiscal incentives were positively associated with process and organisational innovation—are consistent with this trend. Thus, innovative capacity is effectively consolidated when collaborative networks and institutional support enable learning and technical assistance to be translated into lasting organisational and operational changes. This, in turn, strengthens the sector's resilience and its prospects for more balanced development in a complex Amazonian environment.

4 CONCLUSIONS

The analysis of the determinants of innovation in aquaculture organisations in San Martín showed that technological cooperation and fiscal incentives were the factors significantly associated with process and organisational innovation. These results indicate that, in Amazonian contexts, innovation capacity is strongly shaped by external support and institutional coordination, whereas internal organisational factors—such as strategy, structure, culture, and absorptive capacity—have not yet emerged as decisive drivers of change.

This finding highlights the importance of consolidating mechanisms for collaboration and support policies that assist producers in adopting new practices. Technological cooperation contributes to improving the efficiency and quality of production. At the same time, fiscal incentives facilitate the channelling of resources towards changes that strengthen organisational stability and generate benefits beyond the economic sphere, including enhancements to community quality of life and the protection of aquatic environments. In this sense, non-repayable funding programmes act as catalysts, promoting not only producers' competitiveness but also a more balanced relationship between productive activities and the Amazonian environment.

The study has limitations that should be taken into account, such as its exclusive focus on beneficiaries of a national programme and its cross-sectional design, both of which restrict the possibility of generalising the results and establishing causal relationships. Nevertheless, the findings provide valuable evidence for understanding how specific factors influence the development of innovative capacities in Amazonian aquaculture.

Future research could broaden the analysis to other regions of the country, include organisations that are not beneficiaries of support programmes, and incorporate longitudinal studies to observe how innovation capacities evolve over time. It would also be relevant to further examine internal organisational aspects such as intrapreneurship—understood as the capacity to generate and promote innovative initiatives from within organisations—and the role of microcredit as a complementary factor linked to access to resources for the adoption of improvements and innovations. Over time, these may become decisive elements in consolidating a more resilient aquaculture sector capable of addressing environmental challenges.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used Grammarly Pro, Grammarly Inc. for language editing and stylistic polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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Determinantes de Innovación en Organizaciones Acuícolas de la Amazonía Peruana

Determinants of innovation in aquaculture organisations of the Peruvian Amazon

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RESUMEN

La acuicultura amazónica es reconocida como un sector estratégico para la seguridad alimentaria, la generación de empleo y conservación de ecosistemas, en un contexto donde la innovación resulta clave para responder a desafíos ambientales y sociales. El objetivo de esta investigación fue analizar los principales determinantes de innovación en organizaciones acuícolas en la región San Martín, en Perú. Se aplicó un diseño cuantitativo transversal mediante encuestas presenciales a una muestra aleatoria de 76 organizaciones beneficiarias del Programa Nacional de Innovación en Pesca y Acuicultura. El análisis se efectuó con modelos de ecuaciones estructurales con mínimos parciales, evaluando fiabilidad, validez y relaciones estructurales entre siete determinantes internos y externos y tres tipos de innovación (procesos, organizacional y marketing). Los resultados evidencian que la cooperación tecnológica y los incentivos fiscales influyen positivamente en la innovación, resaltando la importancia de políticas públicas y redes colaborativas para un desarrollo acuícola competitivo y resiliente.

Palabras clave: Acuicultura. Determinantes de innovación. Cooperación tecnológica.

ABSTRACT

Amazonian aquaculture is recognised as a strategic sector for food security, employment generation, and ecosystem conservation, particularly in a context where innovation is essential to addressing environmental and social challenges. This study aimed to analyse the main determinants of innovation in aquaculture organisations in the San Martín region of Peru. A cross-sectional quantitative design was employed, using face-to-face surveys administered to a random sample of 76 organisations benefiting from the National Programme for Innovation in Fisheries and Aquaculture. Data were analysed using partial least squares structural equation modelling (PLS-SEM) to assess the reliability

and validity of the measurement model and the structural relationships between seven internal and external determinants and three types of innovation: process, organisational, and marketing. The results indicate that technological cooperation and fiscal incentives positively influence innovation, highlighting the importance of public policies and collaborative networks in supporting a competitive and resilient aquaculture sector.

Keywords: *Aquaculture. Innovation determinants. Technological cooperation.*

1 INTRODUCCIÓN

La acuicultura se ha consolidado en las últimas décadas como el sector de producción alimentaria con mayor crecimiento a nivel global, desempeñando un rol estratégico en los sistemas agroalimentarios contemporáneos, particularmente en economías emergentes, donde contribuye a la seguridad alimentaria y a la generación de empleo (Bohnes *et al.*, 2022; FAO, 2022). Desde inicios de la década del 2000, mientras la pesca de captura se mantenía estable, la acuicultura prosperó, consolidándose como una alternativa productiva frente al estancamiento de los recursos pesqueros y como un factor que podía contribuir a evitar la disminución de poblaciones silvestres (Naylor *et al.*, 2021).

En este marco, la actividad acuícola se vincula de forma directa con los Objetivos de Desarrollo Sostenible (ODS) de la Agenda 2030. Su importancia radica no solo en el suministro de alimentos nutritivos, sino también en su contribución a la generación de empleo, el desarrollo económico y la preservación cultural de múltiples comunidades (FAO, 2022; Troell *et al.*, 2023). Los productos acuáticos —tanto cultivados como capturados— son fundamentales para la seguridad alimentaria: en 2020 el consumo mundial per cápita alcanzó 20,2 kg, frente a 9 kg en 1961, proporcionando alrededor del 17% de la ingesta mundial de proteínas animales y constituyendo casi el 20% de la dieta proteica de 3 300 millones de personas (FAO, 2022).

Cumplir con la Agenda 2030 exigirá alianzas, innovación y estrategias integrales a múltiples escalas (Troell *et al.*, 2023). En este sentido, la acuicultura no solo representa una fuente de proteína animal con menor huella ambiental que la ganadería tradicional (Bennett *et al.*, 2021; Costello *et al.*, 2020; Springmann *et al.*, 2018), sino que además constituye un sector capaz de adaptarse a las demandas de sostenibilidad en la producción de alimentos (Bohnes *et al.*, 2022).

En el Perú, la acuicultura representa apenas el 2,2% de la producción hidrobiológica nacional, a pesar de las condiciones naturales favorables que ofrecen la costa, la sierra y la selva (FAO, 2022; Hidalgo, 2019). No obstante, desde 2015 la actividad ha mostrado un crecimiento sostenido, reflejado en el incremento del número de derechos otorgados, en el aumento del valor bruto de producción y en su aporte al empleo (Produce, 2024). De cara al futuro, se proyecta que para 2030 la producción pesquera se reduzca en 23%, mientras que la acuícola crecería en 32% respecto a 2018, aunque persistirá una amplia brecha en la oferta de productos hidrobiológicos (FAO, 2022).

Ante este potencial, el Estado peruano implementó marcos normativos e instrumentos de fomento, como la Ley General de Acuicultura (2016) y el Programa Nacional de Innovación en Pesca y Acuicultura – Pnipa (2017–2023), que cofinanció más de 1 500 proyectos con una inversión superior a 427 millones de soles (Pnipa, 2023). Sin embargo, persisten limitaciones estructurales vinculadas a la debilidad del mercado de servicios de innovación, la falta de articulación entre oferta y demanda tecnológica y la escasa competitividad frente a países de la región como Chile y Brasil (Produce, 2023).

La Amazonía constituye un caso especialmente relevante, pues concentra una de las mayores diversidades de peces de agua dulce a nivel mundial. Sin embargo, solo cerca de 280 especies son utilizadas para el consumo humano, muchas de ellas bajo riesgo de conservación (Albert *et al.*, 2011;

Dagosta; Pinna, 2019; Pelicice *et al.*, 2021). En este contexto, la acuicultura amazónica —particularmente el cultivo de especies nativas— se configura como una alternativa sostenible, al presentar una huella de carbono hasta diez veces menor que la ganadería por tonelada de proteína producida y sin requerir la expansión de la frontera agrícola (Pacheco *et al.*, 2025).

No obstante, la sostenibilidad de la acuicultura depende en gran medida de las dinámicas sociales e institucionales que median los procesos de innovación (Ferreiro; Sousa, 2019). Estos procesos pueden tener su origen en la ciencia, en el conocimiento local o en el sector privado, y se desarrollan en entornos económicos y políticos diversos (Alexander *et al.*, 2015; Jespersen *et al.*, 2014). Por ello, comprender la naturaleza multifacética de la acuicultura, que integra aspectos ambientales, sociales y económicos, resulta esencial para identificar tanto las oportunidades como los desafíos que determinarán su desarrollo futuro (Troell *et al.*, 2023).

1.1 DETERMINANTES DE INNOVACIÓN

En el contexto empresarial actual, caracterizado por la incertidumbre y el acelerado cambio tecnológico, la innovación emerge como un elemento central para la competitividad y sostenibilidad de las organizaciones (Teece, 2007). Diversos autores han identificado determinantes internos (estrategia, capacidad de absorción, estructura y cultura organizacional) y externos (apoyo gubernamental, cooperación tecnológica y mercado) que influyen en los resultados innovadores (Amabile *et al.*, 2004; Crossan; Apaydin, 2010; Keizer *et al.*, 2002)

1.1.1 DETERMINANTES INTERNOS DE INNOVACIÓN

El ambiente interno es determinante para la capacidad innovadora de las organizaciones acuícolas, al proveer las bases estratégicas y culturales necesarias para transformar recursos en resultados sostenibles. La orientación estratégica, en particular, asegura que las decisiones se alineen con la misión y visión institucional, constituyéndose en un marco que guía y fortalece los procesos de innovación (Yam *et al.*, 2011; Valladares, 2012). La literatura subraya que una estrategia explícitamente vinculada a la innovación potencia la generación de ideas y facilita la incorporación de nuevas tecnologías y procesos (Crossan; Apaydin, 2010; O'regan; Ghobadian, 2005). Por otro lado, la capacidad de absorción constituye un mecanismo clave para transformar conocimiento externo en ventajas competitivas, al integrar procesos de adquisición, asimilación, transformación y explotación de conocimiento (Todorova; Durisin, 2007; Zahra; George, 2002). Así mismo, la cultura organizacional actúa como catalizador de la innovación en la medida que fomenta la apertura al aprendizaje, la toma de riesgos y el reconocimiento de iniciativas generadas por los empleados (Becheikh *et al.*, 2006). Además, el intraemprendimiento constituye también un determinante interno, en tanto se refiere a la capacidad de los miembros de una organización para generar e impulsar nuevas ideas, iniciativas o proyectos desde el interior de estructuras ya establecidas, contribuyendo al fortalecimiento de la innovación (Antoncic; Hisrich, 2003; Gawke *et al.*, 2019). Finalmente, la estructura organizativa condiciona la velocidad y calidad de los procesos innovadores, ya que niveles menores de centralización y formalización facilitan la circulación del conocimiento y una mayor adaptabilidad al cambio (Liu *et al.*, 2018).

1.1.2 DETERMINANTES EXTERNOS DE INNOVACIÓN

Los determinantes del ambiente externo constituyen factores clave que condicionan la capacidad de innovación de las organizaciones, al provenir de entornos regulatorios, tecnológicos y de mercado que trascienden sus propios límites internos. En primer lugar, el apoyo gubernamental constituye un factor decisivo para el desarrollo de la innovación, particularmente a través de políticas públicas e incentivos fiscales. Bell y Pavitt (1993) destacan que la disponibilidad de financiamiento para investigación básica,

junto con subvenciones, premios y préstamos, representa un instrumento esencial para dinamizar la generación y difusión de innovaciones. Por otra parte, Becheikh *et al.* (2006) señalan que estas medidas, sumadas a normas y a las alianzas público-privadas, han sido determinantes en la competitividad de las economías más dinámicas frente a aquellas con menor capacidad innovadora.

Otro componente crítico del entorno externo es la cooperación tecnológica, que responde a la creciente dependencia de fuentes externas de conocimiento en las organizaciones innovadoras. La literatura sobre innovación abierta sostiene que las empresas no pueden basarse exclusivamente en sus recursos internos, sino que deben interactuar con universidades, institutos de investigación, proveedores, clientes, competidores y consultores, conformando redes que potencian su capacidad de innovación (Chesbrough, 2006). Modelos como la Triple Hélice (Etzkowitz; Leydesdorff, 2000) y la democratización de la innovación (Von Hippel, 2005) enfatizan que la calidad de estas relaciones colaborativas determina la velocidad y éxito de los procesos innovadores (Ferguson, 2005).

Finalmente, la orientación al mercado constituye otro determinante externo clave, en tanto refleja la capacidad de las organizaciones para recopilar, difundir y responder de manera efectiva a las variaciones del mercado, integrando la retroalimentación de clientes en la generación de productos y servicios innovadores (Jaworski; Kohli, 1993; Slater; Narver, 1994). Aquellas organizaciones que sistematizan el aprendizaje del mercado logran fortalecer su competitividad, transformando el conocimiento de los clientes en innovaciones que agregan valor (Simpson *et al.*, 2006; Valladares, 2012).

Esta investigación tiene como objetivo analizar la influencia de los principales determinantes de innovación —internos y externos— en organizaciones acuícolas productoras de pescado de la región San Martín. El estudio busca aportar evidencia en un territorio amazónico estratégico, donde confluyen biodiversidad, desafíos sociales y necesidades de producción sostenible, contribuyendo así a fortalecer la comprensión de los factores que condicionan la competitividad y el desarrollo del sector acuícola.

2 METODOLOGÍA

La investigación se orientó al análisis de organizaciones acuícolas productoras de pescado del primer eslabón de la cadena, cultivo y engorde, excluyendo unidades de procesamiento y otras entidades. La población de referencia estuvo conformada por las organizaciones beneficiarias del Pnipa en la región San Martín entre 2018 y 2023, donde se financiaron 182 proyectos de innovación acuícola. A partir de esta base de datos se seleccionó aleatoriamente una muestra de 76 organizaciones, lo que representa un porcentaje significativo de la población. El levantamiento de información se realizó mediante encuestas presenciales aplicadas en los centros de producción y, en los casos en que los productores no pudieron ser ubicados, se recurrió a la modalidad virtual. Las encuestas estuvieron dirigidas a los coordinadores de los proyectos o a los representantes legales, dado que estos son los que están más familiarizados con las actividades de innovación. Previo a la aplicación, todos los participantes fueron debidamente informados sobre los objetivos del estudio, asegurando la confidencialidad y el uso exclusivo de los datos con fines de investigación.

El instrumento utilizado fue diseñado con base en la literatura especializada y sometido a un proceso de validación en dos fases. En la primera, un panel de expertos evaluó la pertinencia y claridad de los ítems; en la segunda, se ejecutó una prueba piloto en campo que permitió ajustar la redacción de algunos ítems, y en particular, justificar la exclusión de la dimensión de innovación de producto, al constatarse que las organizaciones encuestadas no desarrollan este tipo de innovación. De esta forma, la variable dependiente quedó definida como el grado de innovación en tres dimensiones: innovación de procesos, innovación organizacional e innovación en marketing. Las variables independientes correspondieron a los determinantes de la innovación, clasificados en factores internos (estrategia, capacidad de absorción, estructura organizacional y cultura organizacional) y externos (apoyo gubernamental, cooperación tecnológica y mercado) como se muestra en la Figura 1.

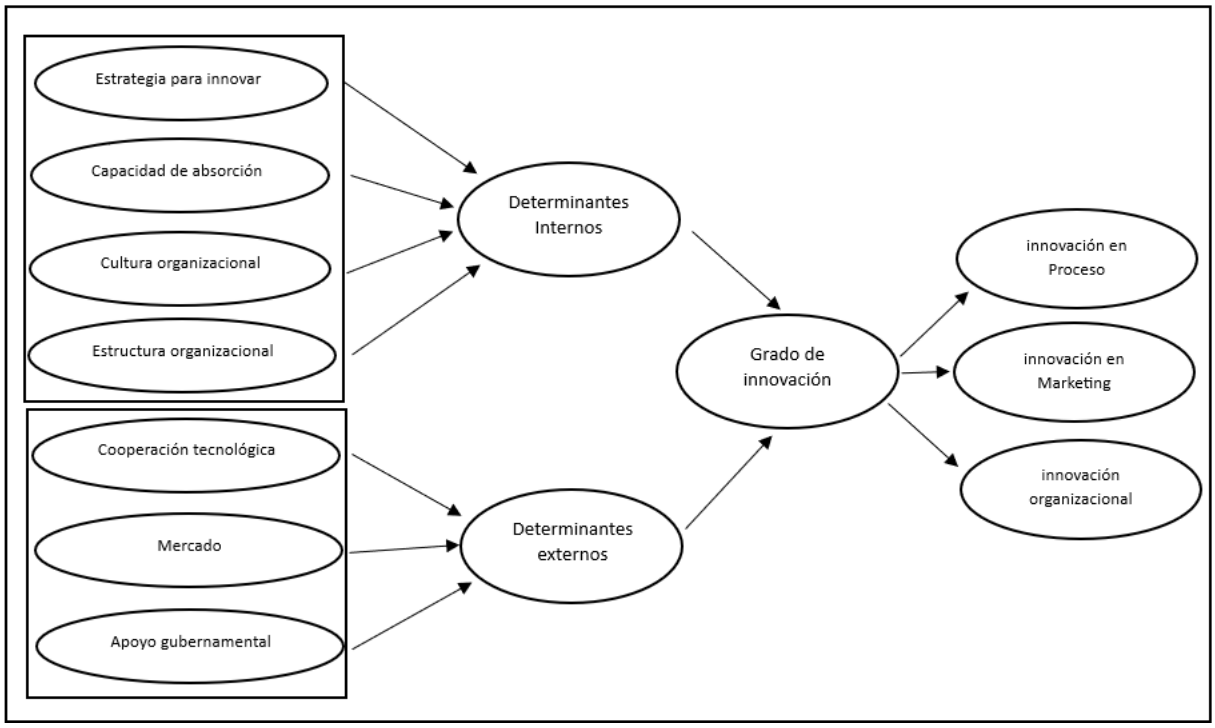


Figura 1 – Marco conceptual de la investigación.

Fuente: Los autores.

El análisis de datos se abordó mediante modelos de ecuaciones estructurales con mínimos cuadrados parciales (PLS-SEM), técnica adecuada para muestras moderadas y estructuras complejas de variables latentes (Hair *et al.*, 2022; Henseler *et al.*, 2016). El procedimiento contempló la estimación del modelo de medida y del modelo estructural, siguiendo criterios aestandarizados de evaluación. En el modelo de medida se verificaron los valores de fiabilidad y validez interna a través del alfa de Cronbach y la confiabilidad compuesta (≥0.70), la varianza media extraída (AVE ≥0.50), la validez discriminante mediante el criterio de Fornell-Larcker y la razón de heterotrait-monotrait (HTMT ≤0.85/0.90), así como la ausencia de colinealidad (VIF <3–5) (Fornell; Larcker, 1981; Hair *et al.*, 2022). Para el modelo estructural se examinaron los coeficientes de trayectoria a partir de bootstrapping con 5,000 remuestreos y cálculo de intervalos de confianza percentil y BCa, la magnitud y significancia de los coeficientes de determinación (R^2), los tamaños de efecto (f^2 = 0.02/0.15/0.35) y la validez predictiva (Q^2 >0). Como diagnóstico global se reportó el índice SRMR (<0.08/0.10) (Hair *et al.*, 2022).

2 RESULTADOS Y DISCUSIÓN

En esta sección se presentan los resultados multivariados, iniciando con la evaluación del modelo de medida y posteriormente con el análisis del modelo estructural, considerando la influencia de los factores internos (estrategia, capacidades de absorción, cultura y estructura organizacionales) y externos (mercado, cooperación tecnológica e incentivos fiscales) sobre los diferentes tipos de innovación (proceso, marketing y organizacional).

La tabla 1 muestra los coeficientes de los parámetros de validez y confiabilidad del modelo general propuesto. La mayoría de los constructos presentaron valores que cumplen con lo recomendado en la literatura: varianza media extraída (AVE) superiores a 0,50, alfa de Cronbach mayores a 0,70 y fiabilidad compuesta por encima de 0,70 (Hair *et al.*, 2009; Ringle *et al.*, 2014). La única excepción fue el constructo “incentivos fiscales”, que alcanzó un alfa de Cronbach de 0,295; sin embargo, tanto la fiabilidad compuesta (0,701) como la AVE (0,564) resultaron satisfactorias, por lo que se mantuvo en el modelo.

Tabla 1 – Validez Convergente, Consistencia Interna y Confiabilidad Compuesta.

	Alfa de Cronbach	*Fiabilidad compuesta (rho_c)*	*Varianza media extraída (AVE)*
Capacidades de absorción	0.913	0.935	0.742
Cooperación Tecnológica	0.935	0.951	0.796
Cultura de la organización	0.928	0.946	0.777
Estrategia	0.953	0.966	0.877
Estructura organizativa	0.753	0.843	0.590
Incentivos fiscales	0.295	0.701	0.564
Proceso de innovación	0.832	0.899	0.749
Innovación en marketing	0.872	0.913	0.724
innovación organizacional	0.876	0.907	0.619
Mercado	0.843	0.894	0.680

Fuente: Los autores.

La validez discriminante, evaluada mediante el criterio de Fornell y Larcker (1981), se presenta en la tabla 2. Los resultados indican que en la mayoría de los casos la raíz cuadrada del AVE fue superior a las correlaciones entre constructos, cumpliendo con el criterio establecido. La excepción se observó en la correlación entre capacidades de absorción y cultura organizacional, que excedió el valor de referencia, lo que sugiere una posible redundancia conceptual entre ambos constructos. Este aspecto se analizó conjuntamente con la colinealidad (VIF) en el modelo estructural.

Tabla 2 – Validez discriminante: Criterio Fornell y Larcker (1981).

	I	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*
I. Capacidades de absorción	0.861									
II. Cooperación Tecnológica	0.796	0.892								
III Cultura de la organización	0.880	0.733	0.881							
IV. Estrategia	0.875	0.836	0.739	0.937						
V. Estructura Organizativa	0.806	0.695	0.793	0.715	0.768					
VI Incentivos fiscales	0.711	0.702	0.594	0.762	0.603	0.751				
VII. Proceso de innovación	0.746	0.819	0.679	0.801	0.609	0.747	0.866			
VIII. Innovación en marketing	0.539	0.616	0.563	0.573	0.489	0.481	0.654	0.851		
IX. innovación organizacional	0.765	0.820	0.717	0.786	0.644	0.792	0.839	0.689	0.787	
X Mercado	0.729	0.819	0.732	0.749	0.718	0.669	0.692	0.643	0.752	0.824

Fuente: Los autores

Los resultados del modelo estructural se presentan en la tabla 3, de las relaciones estimadas, cuatro fueron estadísticamente significativas: cooperación tecnológica - innovación de procesos (β = 0,464; p < 0,01), cooperación tecnológica - innovación organizacional (β = 0,355; p < 0,01), incentivos fiscales - innovación de procesos (β = 0,279; p < 0,01) e incentivos fiscales - innovación organizacional (β = 0,384; p < 0,001). Las demás trayectorias no alcanzaron significancia estadística, aunque algunas mostraron coeficientes positivos moderados, como la relación entre mercado - innovación en marketing (β = 0,358; p = 0,059) (Figura 2).

Tabla 3 – Modelo estructural

	Coeficiente	*Desviación estándar*	*valores p*
Capacidades de Absorción -> Innovación de procesos	-0.066	0.208	0.750
Capacidades de Absorción -> Innovación en marketing	-0.224	0.276	0.417
Capacidades de Absorción -> Innovación Organizacional	-0.004	0.186	0.983
Cooperación Tecnológica -> Innovación de procesos	0.464	0.145	0.001
Cooperación Tecnológica -> Innovación en marketing	0.190	0.228	0.403
Cooperación Tecnológica -> Innovación organizacional	0.355	0.128	0.006
Cultura Organizacional -> Innovación de procesos	0.172	0.175	0.325
Cultura Organizacional -> Innovación en marketing	0.280	0.209	0.181
Cultura Organizacional -> Innovación Organizacional	0.206	0.145	0.155
Estrategia -> Innovación de procesos	0.257	0.169	0.129
Estrategia -> Innovación en marketing	0.187	0.233	0.421
Estrategia -> Innovación organizacional	0.050	0.166	0.766
Estructura Organizativa -> Innovación de procesos	-0.092	0.145	0.525
Estructura Organizativa -> Innovación en marketing	-0.080	0.172	0.642
Estructura Organizativa -> Innovación organizacional	-0.091	0.105	0.387
Incentivos Fiscales -> Innovación de procesos	0.279	0.107	0.009
Incentivos Fiscales -> Innovación en marketing	0.006	0.184	0.976
Incentivos Fiscales -> Innovación organizacional	0.384	0.110	0.000
Mercado -> Innovación de procesos	-0.079	0.133	0.554
Mercado -> Innovación en marketing	0.358	0.190	0.059
Mercado -> Innovación organizacional	0.085	0.126	0.501

Fuente: Los autores

En los análisis complementarios, los valores VIF promediaron 5,147, lo que se considera aceptable al estar por debajo del umbral de 10 (Gujarati; Porter, 2009). El análisis de tamaños de efecto (f^2) mostró valores pequeños (0,02) y medianos (0,15), según la clasificación de Cohen (1988). En cuanto al poder explicativo del modelo, los coeficientes de determinación ajustados (R^2) alcanzaron valores de 0,725 para innovación en procesos, 0,398 para innovación en marketing y 0,761 para innovación organizacional, lo que evidencia que el modelo presentó un mayor poder explicativo sobre la innovación organizacional, seguido de la innovación en procesos y, en menor medida, de la innovación en marketing.

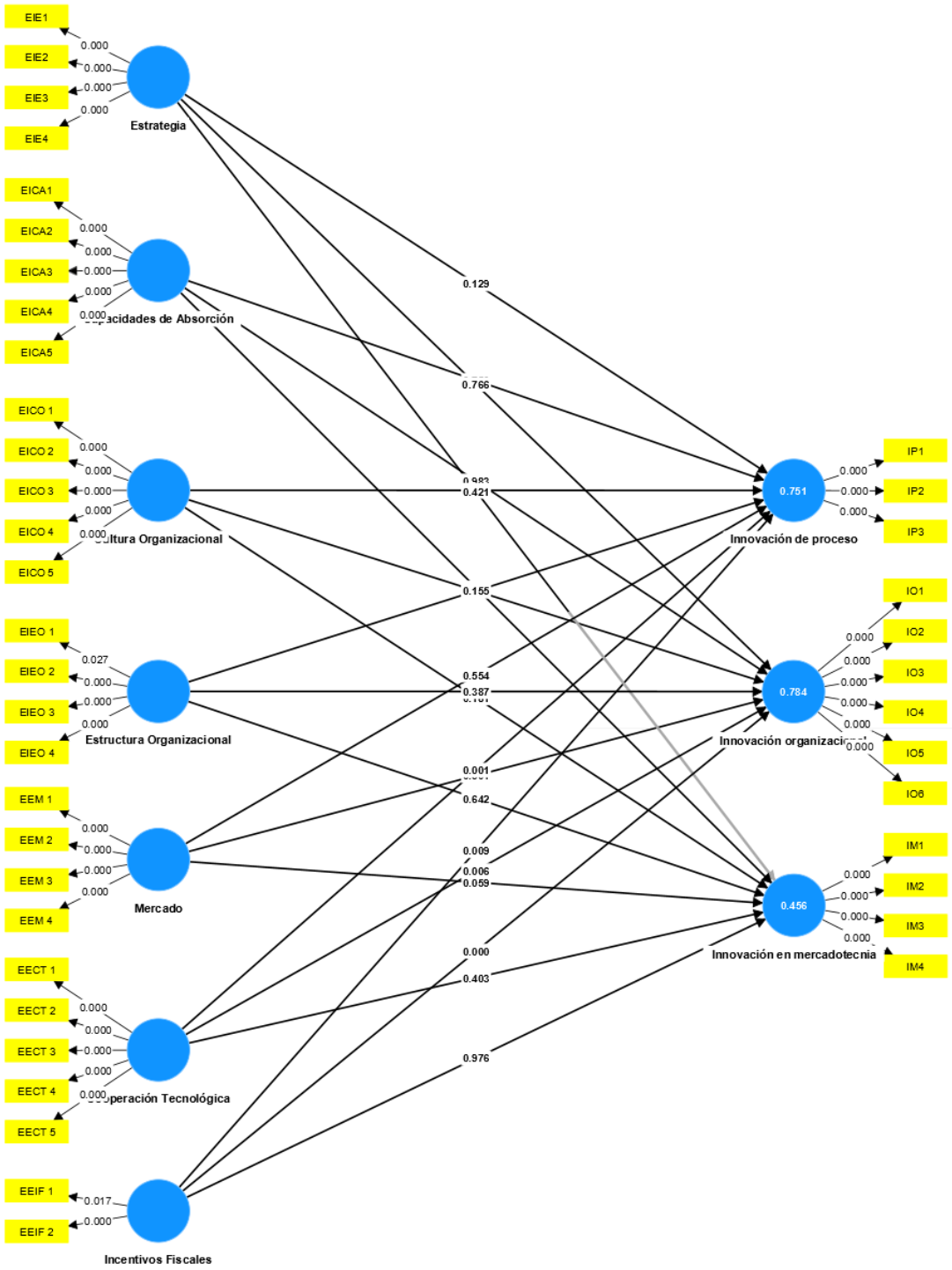


Figura 2 – Modelo estructural PLS SEM de los determinantes internos y externos sobre la innovación en organizaciones acuícolas amazónicas

Fuente: Los autores

La acuicultura ha crecido con rapidez y ha sido ubicada como un componente estratégico de los sistemas agroalimentarios contemporáneos, aportando a la seguridad alimentaria y al empleo. A escala global, se ha mostrado que los pilares económico, social y ambiental pueden reforzarse de manera mutua en los sistemas acuícolas, sin que existan compensaciones sistemáticas entre ellos (Garlock *et al.*, 2024). Esta evidencia se vincula con el interés internacional en alianzas e innovación para avanzar en el logro de los objetivos de la Agenda 2030 (Troell *et al.*, 2023) y con el planteamiento de que la acuicultura

representa una fuente de proteína animal con menor huella que rubros ganaderos tradicionales, a la vez que se adapta a exigencias de desempeño más responsables (Bennett *et al.*, 2021; Bohnes *et al.*, 2022; Costello *et al.*, 2020; Springmann *et al.*, 2018).

En ese marco, los hallazgos empíricos indican que los determinantes externos —en particular la cooperación tecnológica y los incentivos fiscales— se asocian de manera positiva y significativa con la innovación de procesos y con la innovación organizacional. Este patrón es coherente con la literatura que subraya la centralidad de la colaboración y de los arreglos institucionales para activar y sostener cambios en sectores productivos. Se ha señalado que el éxito de la innovación está estrechamente ligado a la calidad de las relaciones colaborativas (Ferguson, 2005) y que las actividades innovadoras suelen manifestarse principalmente entre proveedores y prestadores de servicios vinculados a la acuicultura, lo que refuerza la importancia de redes que trascienden a las unidades productivas (Aarstad; Jakobsen, 2020; Aarstad *et al.*, 2023). Asimismo, ante preocupaciones ambientales y restricciones de recursos, se destaca la necesidad de cooperación y de combinar soluciones tecnológicas con mejores prácticas de gestión (Laktuka *et al.*, 2023), junto con políticas que promuevan técnicas innovadoras orientadas a la producción responsable (Ogello; Munguti, 2016).

Por otro lado, los factores internos considerados —estrategia, cultura, estructura organizacional y capacidad de absorción— no mostraron efectos significativos en las innovaciones analizadas. La literatura ofrece elementos para comprender este resultado; la adopción de innovaciones en la acuicultura puede verse limitada por requerimientos de capital, barreras de financiamiento y dificultades de acceso a equipamiento, insumos y formación, especialmente en organizaciones de menor escala (Rosgren, 2022; Vecchio *et al.*, 2024). A ello se suman influencias culturales y rutinas que condicionan la aceptación de nuevas prácticas (Stanfield, 1999), así como el papel de las instituciones locales para crear condiciones propicias y anclar la innovación en el territorio (Kumar, 2018). También se ha advertido que, sin la participación del sector productivo, la investigación financiada con recursos públicos tiende a tener menor relevancia e impacto, lo que vuelve clave la apertura y la vinculación efectiva entre actores para que la I+D se traduzca en cambios concretos (Iversen; Hydle, 2023). El efecto del entorno de mercado sobre la innovación en marketing mostró una tendencia cercana a la significancia estadística, lo que sugiere señales de ajuste comercial que podrían potenciarse mediante estrategias de diferenciación adecuadas al contexto regional (Cojocaru *et al.*, 2020).

La Amazonia es un territorio con alta diversidad biológica y con necesidades de alternativas productivas que fortalezcan medios de vida y reduzcan presiones sobre los ecosistemas. La evidencia indica que los procesos de innovación en acuicultura dependen de dinámicas sociales e institucionales que median su adopción (Ferreiro; Sousa, 2019). En este sentido, se ha planteado que la innovación puede contribuir a hacer viable el cultivo de especies nativas y a fortalecer eslabones más débiles de la cadena (Vecchio *et al.*, 2024), mientras que la heterogeneidad de desempeños observada a escala global abre espacios para medidas de política e inversión capaces de elevar resultados económicos, sociales y ambientales donde aún son incipientes (Garlock *et al.*, 2024). Ello es convergente con la idea de que, en la región, existen trayectorias posibles de desarrollo productivo con menor huella de carbono por unidad de proteína y sin expansión de frontera agropecuaria, siempre que las decisiones se orienten con base en evidencia y cooperación (Pacheco *et al.*, 2025). Al mismo tiempo, diversos estudios sobre transiciones hacia la sostenibilidad han analizado cómo las innovaciones pueden generar impactos múltiples en los objetivos de desarrollo. Estos trabajos ofrecen marcos para anticipar tanto las sinergias como las posibles compensaciones entre metas económicas, sociales y ambientales (Dorninger *et al.*, 2020; Gaitán-Cremaschi *et al.*, 2019).

Desde la perspectiva de la gobernanza, la efectividad de las redes de política se asocia con la inclusión de actores relevantes, la apertura de los procesos y la percepción de resultados por parte de quienes participan (Krause, 2015). Cuando estas condiciones no se cumplen, puede emerger una brecha entre actores y políticas que derive en regulaciones poco pertinentes o incluso perjudiciales para el sector (Green, 2023; Vecchio *et al.*, 2024). A la vez, se ha remarcado que la innovación es también un vector

de desarrollo político, en la medida en que los gobiernos fortalecen herramientas para impulsar la ciencia, la tecnología y la innovación desde las empresas. En conjunto, los resultados obtenidos en San Martín, donde la cooperación tecnológica y los incentivos económicos mostraron asociaciones positivas con la innovación de procesos y organizacional. son coherentes con esta tendencia. Así, las capacidades innovadoras se consolidan efectivamente cuando existen redes de colaboración y apoyos institucionales que permiten traducir el aprendizaje y la asistencia técnica en cambios organizativos y operativos duraderos. Ello favorece la resiliencia del sector y su proyección hacia un desarrollo más equilibrado en un entorno amazónico complejo.

4 CONCLUSIONES

El análisis de los determinantes de la innovación en organizaciones acuícolas de San Martín mostró que la cooperación tecnológica y los incentivos fiscales fueron los factores que incidieron de manera significativa en la innovación de procesos y en la innovación organizacional. Estos resultados evidencian que, en contextos amazónicos, la capacidad de innovar se encuentra fuertemente condicionada por los apoyos externos y la articulación institucional, mientras que los factores internos de las organizaciones, como la estrategia, la estructura, la cultura o la capacidad de absorción, aún no logran consolidarse como motores determinantes de cambio.

Este hallazgo resalta la importancia de consolidar mecanismos de colaboración y políticas de apoyo que acompañen a los productores en la adopción de nuevas prácticas. La cooperación tecnológica contribuye a mejorar la eficiencia y la calidad de la producción, mientras que los incentivos fiscales permiten canalizar recursos hacia transformaciones que fortalecen la estabilidad de las organizaciones y generan beneficios más allá de lo económico, en ámbitos relacionados con la calidad de vida de las comunidades y el cuidado de los entornos acuáticos. En este sentido, programas de financiamiento no reembolsable se configuran como catalizadores que favorecen no solo la competitividad de los productores, sino también el equilibrio en la relación entre actividad productiva y territorio amazónico.

El estudio presenta limitaciones que deben ser consideradas, como el hecho de haber trabajado únicamente con beneficiarios de un programa nacional y con un diseño transversal, lo que restringe la posibilidad de generalizar los resultados y establecer relaciones causales. Aun así, los hallazgos aportan evidencia valiosa para comprender cómo algunos factores influyen en el desarrollo de capacidades innovadoras en la acuicultura amazónica.

Futuras investigaciones podrían extender el análisis hacia otras regiones del país, incluir organizaciones no beneficiarias de programas de apoyo e incorporar estudios de seguimiento que permitan observar cómo evolucionan en el tiempo las capacidades de innovación. También sería pertinente profundizar en la medición de aspectos organizacionales internos como el intra emprendimiento, entendido como la capacidad de generar y promover iniciativas innovadoras desde el interior de las organizaciones, y en el papel del microcrédito como un factor complementario relacionado con el acceso a recursos para la adopción de mejoras e innovaciones, que, con el tiempo, podrían convertirse en elementos decisivos para la consolidación de un sector acuícola más resiliente y capaz de enfrentar los desafíos de su entorno.

DECLARACIÓN SOBRE EL USO DE LA INTELIGENCIA ARTIFICIAL

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Application of participatory research techniques in the socio-environmental study conducted in the Jacaré-Curituba settlement in Brazil

Aplicação de técnicas de pesquisa participativa no estudo socioambiental realizado no assentamento Jacaré-Curituba do Brasil

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ABSTRACT

This article initially presents reflections on existing qualitative methods and techniques within the social sciences, and subsequently analyses how some of them can be effectively applied in socio-environmental research. The use of these techniques in case studies allows for greater representativeness of the results, considering the descriptive and narrative nature of the data, which contributes to enriching the research processes. The objective of this work is to present some methodological techniques applied in a case study as an example of successful application. For this study, participant observation and data analysis from semi-structured interviews were applied, conducted in the Jacaré Curituba Settlement, located between the municipalities of Poço Redondo and Canindé de São Francisco, in the high hinterland of Sergipe. The study enabled the identification, based on the population's perceptions, of different socio-environmental problems in the area. The results indicate that prioritising qualitative evaluation methods favours the consolidation of denser, more meticulous analyses. It has been observed that, in many cases, quantitative approaches in the field of environmental sciences face limitations in measuring subjective dimensions, which is a critical factor in identifying problems and estimating their impacts.

Keywords: Qualitative research. Socio-environmental studies. Climate change. Nexus+ approach. Brazilian Northeast.

RESUMO

Este artigo apresenta inicialmente reflexões sobre os métodos e técnicas qualitativas existentes no âmbito das ciências sociais para posteriormente analisar como algumas delas podem ser aplicadas de forma eficaz em pesquisas socioambientais. O uso dessas técnicas em estudos de caso permite ampliar a representatividade dos resultados, considerando o caráter descritivo e narrativo dos dados, o que contribui para o enriquecimento dos processos de pesquisa. O objetivo do trabalho é apresentar algumas técnicas metodológicas aplicadas em estudo de caso como exemplo de aplicação bem-sucedida. Para este estudo, aplicaram-se a observação participante e a análise de dados de entrevistas semiestruturadas, realizadas no Assentamento Jacaré Curituba, localizado entre os municípios de Poço Redondo e Canindé de São Francisco, no alto sertão sergipano. O estudo permitiu identificar, a partir da

percepção da população, diferentes problemáticas socioambientais existentes no local. Os resultados obtidos indicam que a adoção prioritária de métodos de avaliação sob uma perspectiva qualitativa favorece a consolidação de análises mais densas e minuciosas. Verifica-se que, em diversos casos, abordagens quantitativas no âmbito das ciências ambientais enfrentam limitações na mensuração de dimensões subjetivas, o que constitui um fator crítico na identificação de problemáticas e na estimativa de seus impactos.

Palavras-chave: *Pesquisa qualitativa. Estudos socioambientais. Mudanças climáticas. Abordagem Nexus+. Nordeste brasileiro.*

1 INTRODUCTION

The use of different types of qualitative methodological research techniques, whether ethnographic or biographical, has gained ground in social science research. Their characteristics make these techniques appropriate for addressing sociocultural and environmental processes, in which social interactions with the environment constitute the predominant object of study, positioning subjects as agents possessing knowledge. In this sense, this work aims to present data collection and analysis techniques used in the social sciences, in order to include them in the environmental sciences, since the interaction between humans and nature has become increasingly intense and complex.

Among the characteristics of this social methodology, the fact that it allows for greater interaction between the researcher and the object stands out, since its construction and understanding presuppose the sharing of experiences and meanings between researcher and subject. In this context, the researcher can immerse themselves in the subjects' universe of action (Bernal, 2024; Costa, 1987; Dalfovo, 2008; Delari, 2015), obtaining a more concrete vision (Woods, 1987) and constituting themselves as the main instrument of the investigation (Bogdan; Biklen, 1994), since the nature of the data collected depends on their stance, the orientations they adopted, and their methodological skills.

In this context, knowledge is constructed collectively, considering the conceptions of social actors and the meanings they attribute to their practices. Therefore, participants are considered sources of knowledge and partners in the process of constructing reality. According to Goetz and Lecompte (1988), human action is explained in terms of the cultural context in which actors construct the meaning of their interactions and their interpretation of reality. The researcher, therefore, needs to be embedded in the context, as it is not possible to adequately investigate a culture through interpreters. The construction of the object implies close, prolonged, and contextualised interaction between the researcher and the subjects, allowing for a more consensual view of the social, environmental, and cultural (Conjo, 2022; Erlandson, 1993; Paranhos, 2016).

Both quantitative and qualitative methodologies have always influenced the social sciences. These fields have witnessed an unprecedented and rapid diffusion of data collection and analysis techniques, especially in the qualitative field. The numerous publications of this nature have contributed to redefining the course of social and human research. Qualitative research encompasses diverse fields of knowledge, including anthropology, sociology, economics, psychology, administration, biology, and education, among others. Data collection techniques include field studies, participant observation, qualitative interviews, case studies, and participatory research.

However, the choice of technique to be implemented in a specific study depends on the nature of the research, its focus, its objectives, and the object of study.

2 THE INCORPORATION OF QUALITATIVE AND MIXED-METHODS APPROACHES WITHIN ENVIRONMENTAL SCIENCES

Environmental education, in addition to promoting behavioural changes in environmental care, seeks to establish critical perspectives and actions aimed at promoting transformations in society and the environment, using empirical studies (Bôlla; Milioli, 2011). However, to date, this area of knowledge still needs to demonstrate, in a more consistent way, empirical evidence regarding socio-environmental aspects. In the field of environmental impact analysis of projects, for example, studies with a socio-environmental focus frequently face limitations in determining concrete impacts, as well as in evaluating the effectiveness of projects in mitigating these impacts (Guanabara *et al.*, 2009).

In this context, new evaluation strategies capable of capturing the complexity of the environmental issue as it articulates with social aspects are necessary. The exclusive use of quantitative criteria has proven insufficient in the evaluation of environmental projects, since it does not adequately consider subjectivity, a central variable in understanding the causes and dynamics of the environmental crisis. Thus, the incorporation of qualitative approaches presents itself as a relevant alternative, as it allows for the investigation of dimensions that escape quantitative methods, incorporating aspects related to perception, experiences, and the meanings attributed by the subjects (Silverman, 2001).

Given the contemporary challenges in the social and environmental dimensions, it is essential to investigate, evaluate, and apply various research models within the scope of environmental management. To this end, it is necessary to incorporate multiple theoretical and methodological approaches into the analysis to overcome predominantly strictly economic views, which are limited in understanding socio-environmental complexity. In many cases, such approaches have contributed to the aggravation of environmental degradation problems and the intensification of social exclusion, as observed in populations affected by dams (Bernal, 2021).

In this sense, the present study aims to understand, explain, and describe, with greater precision, environmental problems in a specific territorial context, through the application of qualitative methodology and data collection and analysis techniques in a concrete Brazilian case. It seeks to demonstrate how this approach allows for a deeper understanding of aspects of reality that are not quantifiable, contributing to the comprehension of the universe of meanings, motivations, aspirations, beliefs, values, and attitudes (Minayo, 2014).

2.1 QUALITATIVE RESEARCH: FOUNDATIONS, INTERVENTION, METHOD AND TECHNIQUES

The genesis of qualitative methodology is associated with critiques of positivism and is often referred to as qualitative research. This approach encompasses various types of investigation, supported by theoretical and methodological frameworks such as ethnography, historical materialism, and phenomenology (Godoy, 1995). According to Minayo (2001), qualitative research was initially applied in anthropological and sociological studies as a counterpoint to the predominance of the quantitative approach. Subsequently, it expanded to areas such as psychology and education. Although criticised for its empiricism, subjectivity, and the involvement of the researcher, qualitative research offers relevant contributions to science by enabling the analysis of historically underexplored problems.

According to Godoy (1995), the qualitative approach presents the following characteristics: conducting the study in the natural environment, where social facts must be observed, analyzed, and interpreted in their context; the central role of the researcher in the observation, selection, and analysis of data; the valuing of descriptive data derived from empirical reality; the use of techniques such as interviews, visual records, and testimonies; consideration of the perspective of the subjects investigated; commitment to the reliability of the data; and adherence to ethical principles.

On the other hand, Knechtel (2014) highlights that qualitative research is characterised by understanding reality as socially constructed, by the relationship between researcher and object of study, by the emphasis on processes and meanings, and by the use of interpretive methods, such as interviews and detailed observation. It also includes case studies, an emphasis on in-depth descriptions, and the use of historical narratives and biographical and autobiographical materials.

Gerhardt and Silveira (2009) emphasise that the qualitative approach involves understanding the phenomenon in its totality, articulating the global and the local, respecting the specificities of the social world in relation to the natural world, and valuing the interaction between research objectives, theoretical frameworks, and empirical data. Furthermore, it opposes the idea of a single research model applicable to all areas of knowledge.

In this sense, qualitative methodology presents itself as a suitable alternative for understanding, explaining, and describing environmental problems more precisely in specific contexts, offering a consistent set of theoretical and methodological guidelines.

According to Neves (1996), qualitative research assumes different meanings in the field of social sciences, encompassing a set of interpretive techniques—such as unstructured and semi-structured interviews, participant observation, structured observation, and focus groups—that aim to describe and interpret complex systems of meaning. Complementarily, Alencar (1999) emphasises that the researcher begins fieldwork with theoretical assumptions that guide the investigation.

Qualitative research seeks to understand the complexity of social phenomena, which cannot be measured on a numerical scale (Rosental, 2001). Unlike the quantitative approach, it is not based on statistical instruments and prioritises the interpretation and understanding of phenomena (Dalfovo *et al.*, 2008).

Qualitative data includes information not expressed exclusively in words, such as paintings, photographs, drawings, films, videos, and even soundtracks (Dalfovo *et al.*, 2008). In this context, phenomenology constitutes an important theoretical foundation for qualitative research, seeking to understand the meanings individuals attribute to their experiences in specific contexts and emphasising the relevance of symbolic interaction and culture.

According to Trato (2005), qualitative research works with values, beliefs, representations, habits, attitudes, and opinions, being especially useful for understanding the context in which certain phenomena occur. Instead of measuring variables, its objective is to achieve a deep—and, when necessary, subjective—understanding of the object of study. In this way, it is directed at groups delimited in territorial and social terms, allowing for an intensive analysis of their dynamics.

As noted, qualitative research is not guided by numerical representativeness, but by a deeper understanding of social groups and their relationships with the context in which they are embedded. Researchers who adopt this approach reject the idea of a single model of scientific investigation, recognising the specificity of the social sciences and the need for their own methods. In this sense, the environment constitutes the main source of data, and the researcher can become directly involved in the investigative process.

Finally, qualitative data analysis enables the researcher to interpret the participants' discourses and understand, in depth, complex social phenomena, based on the relevance of the subjective aspect of social action in the face of the configuration of social structures (Haguette, 1997).

2.2 MAIN TECHNIQUES FOR COLLECTING QUALITATIVE DATA USED IN SCIENCE

As indicated, qualitative research does not have a single standardised method. In many cases, it can be characterised by a spectrum of methods and techniques adapted to specific cases, according to the needs and possibilities of the researcher and their object of study. However, the techniques most commonly employed in social research include: case studies, ethnography, interviews (structured, semi-structured, open, and projective), social cartography, observation (simple and participant), life histories and focus groups, content analysis, action research, phenomenology, and the Delphi method, among others.

Once the data is collected, these techniques allow for the analysis of the phenomenon and the organisation of the steps of description, understanding, and explanation, as well as the more precise identification of the relationships between the global and the local. Additionally, they make it possible to observe the differences between the social world and the natural world and to achieve more reliable results.

3 METHODOLOGY

3.1 AREA OF STUDY

This study was conducted in the Jacaré Curituba Settlement (AJC), located between the municipalities of Poço Redondo and Canindé de São Francisco, in the Alto Sertão region of Sergipe. This area is part of the INCT – Odisseia research project, Catinga site. Specifically, the project's study area comprised the agricultural villages of Braço Erguido, Nossa Senhora da Conceição, São José, and Samariva Daniel. The latter two were considered a single unit due to the absence of clear boundary delimitation, as shown in Figure 1.

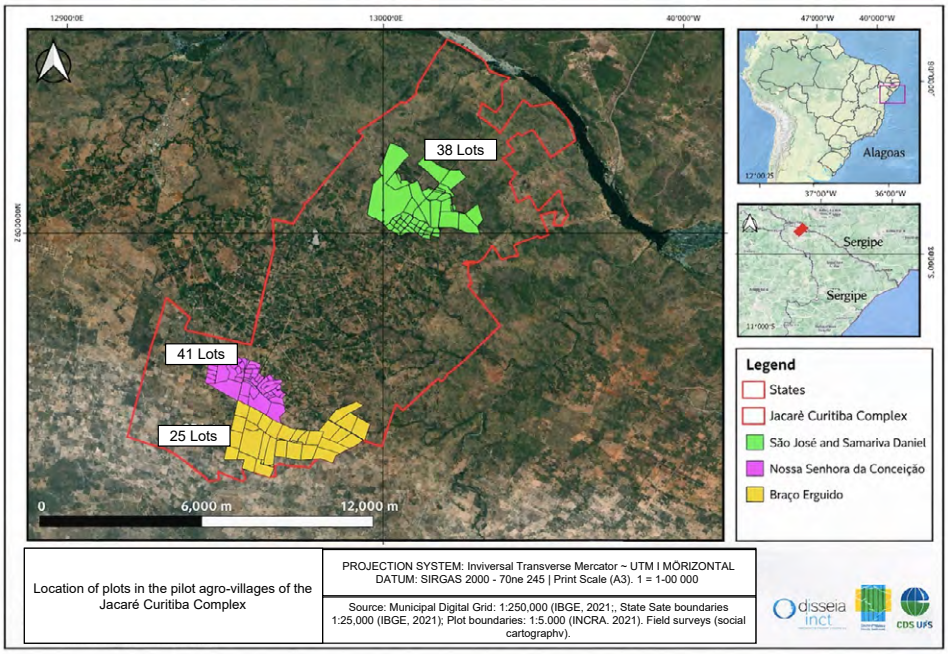


Figure 1 – Location and division of the Jacaré Curituba Settlement in the State of Sergipe and Brazil

Source: Authors' own work.

3.1 QUALITATIVE METHODOLOGICAL TECHNIQUES APPLIED AND DATA ANALYSIS

In this study, interview and participant observation techniques were applied within the scope of the INCT – Odisseia project, described in the following section. These techniques allowed for an understanding of the study area and its most relevant problems. Both methodological techniques were applied. The interview, in turn, allowed for the establishment of a "process of social interaction between two or more people, in which one of them, the interviewer, aims to obtain information from the other, the interviewee" (Haguette, 1997, p. 86.). Observation, in turn, enabled the collection of information about certain aspects of reality, helping researchers identify and understand aspects of which individuals are not aware but that guide their behaviour (Lakatos, 1996).

A semi-structured interview script was prepared, considering the interviewee's thought process, aiming to maintain the flow of conversation and conduct the interview logically. This instrument contained 18 central questions. In many cases, other questions arose based on statements or themes mentioned by the interviewees. Table 1 below presents a summary of the themes addressed during the interviews.

In total, 10 interviews were conducted. Among those interviewed were representatives and employees of the São Francisco and Parnaíba Valleys Development Company (Codevasf), the National Institute for Colonisation and Agrarian Reform (Incra), the Rural Technical Assistance and Extension Company (Emater), the municipalities of Poço Redondo and Canindé de São Francisco, local cooperatives, as well as residents of the settlement. It should be noted that the interviews were conducted between 2022 and 2023.

Table 1 – List of topics covered in the interviews

Interviewer identification	
Interview location	
Characterisation of the dwelling	
Characterisation of the interviewee	Guys
	Personal mobility
	Activities
Family characterisation	General
	Mobility for children
Family Social Capital	Associativism
Income characterisation	Non-agricultural
	Agriculture
Agricultural Activity	Lot characterisation
	Agriculture
	Livestock farming
	Extractive Activities and Conservation
	Agricultural practices
	Pesticides
	Agroecology
	Water system
	Marketing
Support for producing	Information
	assistance policies
	Credit

Characterisation of the dwelling	
Land Tenure Situation	Regularisation
	Use of other areas
	Own area / third parties (present/past)
	Acquisition of new lands
	Land sale
	Use of the Floodplain
Observed Changes	Abandonment
	Impact of monoculture and large-scale production
	Change
	Impacts of new products: Soybean tickets, among others.
Water, Food and Energy System	Situation and problems
Perceptions	Future
	Climate (precipitation and temperature) / Rainfall and droughts
	Phenology
	Flowmetry
	Climate impacts
	Traditional knowledge
Popular epistemologies	Weather forecast

Source: own

Regarding the observation carried out, the researcher sought to collect and record facts from reality without the use of special technical means, recording facts, elements or situations in field notebooks relating to several of the structural themes mentioned in Table 1. These notebooks were updated daily after the visits to the families carried out in the field.

3.3 REGARDING THE SYSTEMATISATION AND ANALYSIS OF DATA

All interviews were transcribed and compiled into a 105-page document. Data processing was performed using two software programs: NVivo and IRaMuTeQ. The use of these software programs allowed for a more in-depth analysis based on determinant variables, as well as the application of factor analysis, descending hierarchical classification, and similarity analysis.

Factor analysis allows us to observe the characteristics of the text through word frequency and the distribution of forms on a proximity plane, where those located at the centre are the most recurrent and relevant, and are related to other themes identified in the quadrants.

Hierarchical classification allows for the identification of vocabulary present in the text through classes. From the analysis of the words, different themes can be established in each class, facilitating the identification of the main concerns of the population mentioned in the interviews, as well as the relationships between them.

Similarity analysis, in turn, allows the identification of proximity relationships between words organised into communities. At the centre of a word map, the most relevant terms are observed, connected to

other themes discussed throughout the interviews. For coding purposes in the software, numbers and codes were assigned to each interviewee (see Table 2).

Table 2 – Coding of respondents for analysis in the Iramuteq software.

Node	Code	Person
1	**** *Interview_1	xxxx
2	**** *Interview_2	xxxx
3	**** *Interview_3	xxxx
4	**** *Interview_4	xxxx
5	**** *Interview_5	xxxx
6	**** *Interview_6	xxxx
7	**** *Interview_7	xxxx
8	**** *Interview_8	xxxx
9	**** *Interview_9	xxxx
10	**** *Interview_10	xxxx

Source: own

Finally, it is worth mentioning that this research was submitted to the evaluation of the Research Ethics Committee in Human and Social Sciences of the University of Brasilia, under protocol number 01037218.5.0000.5540 and opinion number 3.440.596.

4 RESULTS AND DISCUSSION

The systematic incorporation of qualitative methods in socio-environmental studies is a central strategy for optimising analytical and evaluative outcomes. Delving into the symbolic and contextual allows the researcher to value local knowledge and interpret the symbolic, cultural, and subjective dimensions of the society-nature relationship. Such approaches broaden the explanatory capacity of research and overcome the limitations inherent in exclusively quantitative measurement.

Thus, the application of methods such as ethnography, in-depth interviews, participant observation, and case studies favours more accurate diagnoses, as well as the development of more consistent assessments of socio-environmental impacts, possessing greater legitimacy in their results, since they integrate the meanings, perceptions, and practices of social actors. Consequently, studies that adopt qualitative frameworks tend to produce more integrated, contextualised, and effective analyses for environmental management and for the formulation of transformative interventions.

To validate these assertions, below are some of the results of the applied study, observing the population's appreciation for the economic and productive activities they carry out, the social and environmental problems identified, the marketing of products, and the important role that some state institutions have or represent for the local population.

According to some local residents, a large part of the settlement's territory is dedicated to agriculture and livestock farming in extensive pastures. Regarding agriculture, it is stated that it is predominantly practised using an irrigated farming system and, to a minimal extent, rainfed farming. The population's agricultural production is diversified, with a predominance of vegetables, legumes, greens, and fruits. It is stated that the main crops are okra, cassava, corn, beans, sunflower, guava, passion fruit, lettuce, watermelon, and pumpkin.

It is observed that rural families, in addition to the various agricultural crops they cultivate, also, in parallel and to a lesser extent, engage in beef and dairy cattle farming. This activity contributes to local families' income. On the other hand, it is stated that a large part of the settlement's production is marketed through intermediaries, who transport and sell their products in different parts of the country.

These were some of the most important general elements identified in the interviews. However, once the interviews were entered into the aforementioned software and a factor analysis was applied, a large number of themes were identified that are clearly of concern to the population, including: *land title, access to water/irrigation and consumption, water charges, production and marketing/cooperatives*, as well as general problems (See Figure 2).

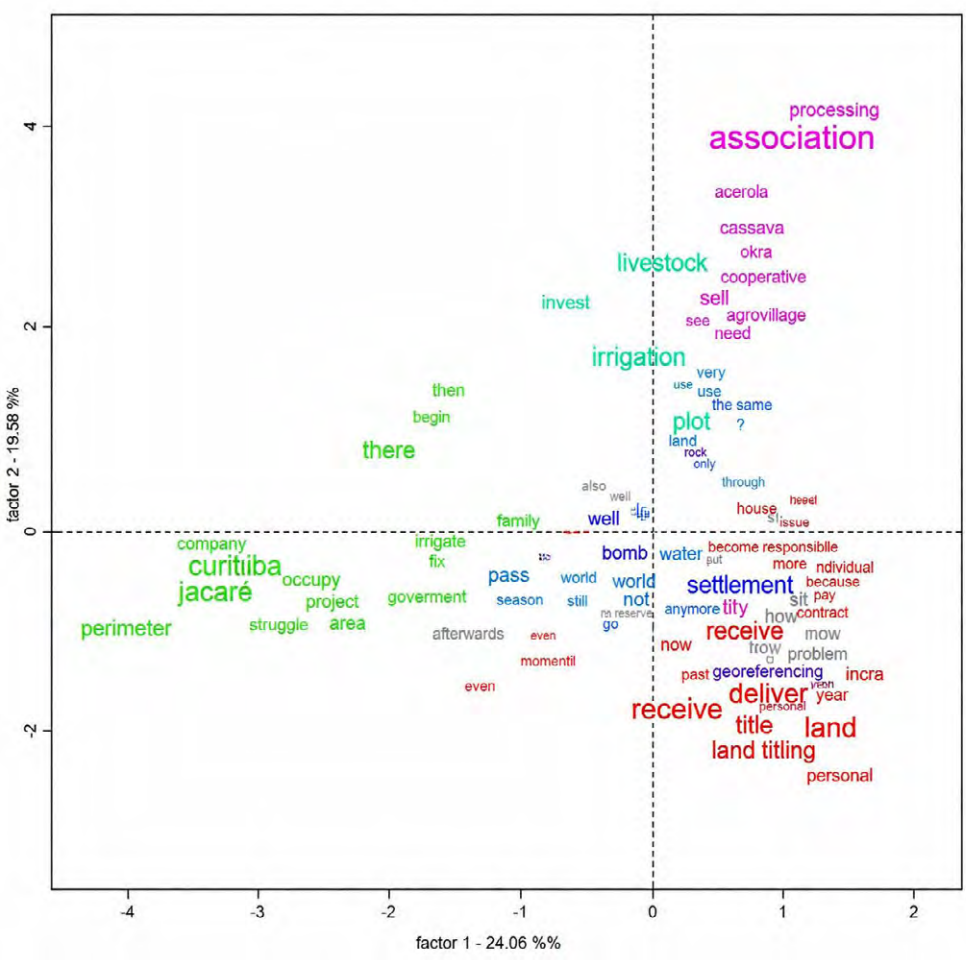


Figure 2 – Identifying the most frequently discussed themes in the interviews.

Source. The authors

These themes were verified through the implementation of descending hierarchical classification, which allowed for the identification of vocabulary within the text through classifications. It is observed that different themes emerged within each classification, facilitating the identification and validation of the population's themes and concerns.

Regarding the topic of land, for example, it can be observed through people's statements that this element is treated in terms of conquering territory for production, as well as being a determining factor in internal difficulties and disparities related to access to land, water, production, and environmental pollution.

> "Those who chose to keep the irrigated plot would stay here because it has irrigation, and those who chose the dryland plot would go to another area or camp so they could acquire those lands. [...] Many people talk about the issue of land titles, but the decree that exists is for those who have eighty tarefas (a local unit of land measurement), it's for those who can afford all the investments. And here, nobody can afford to make investments."
>
> Testimonials from residents of the Settlement

Analysing the interviews, it is observed that the settlement faces greater difficulties in areas categorised as rainfed, a factor mainly due to the quantity of production and commercialisation. This area largely depends on rain or artisanal irrigation, limiting production for family consumption and, in part, for commercialisation. The area's population, as well as other interviewees, reports that large-scale production is compromising soil quality and accelerating salinisation due to excessive irrigation and fertiliser use. These data validate the results of soil analysis carried out by the INCT-Odisseia project (Oliveira, 2024). In this study, of the 104 plots analysed in the study area (22 intended for irrigation, 47 for livestock, and 35 for rainfed activities), 64 exhibited problems due to soil salinity, with 63 plots classified as saline and 1 as saline-sodic. Of these, 41 plots were identified in the Braço Erguido agricultural village, while the remaining 23 were in the Nossa Senhora da Conceição agricultural village.

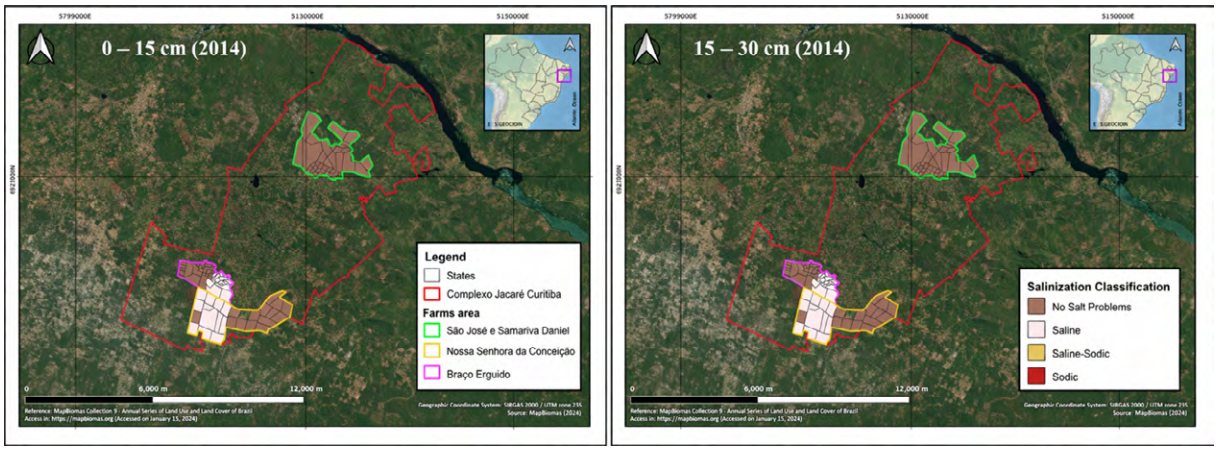


Figure 3 – Classification according to the level of salinity in the plots of the studied areas.

Source: Oliveira (2024)

On this point, it is noteworthy that the population indicates that, in addition to compromising environmental health, this practice also affects the health of various residents, causing a range of illnesses and, in some cases, death.

> "All of this happens in the settlement: silting, salinisation of the land, land that no longer produces, but there is still no awareness that the land is not producing because too much fertiliser and chemicals were used, so there is no knowledge about this. Our biggest concern is with the environment, which has suffered, but mainly with life [...]. We have many people who have died here in the settlement because of pesticides. Unfortunately, medicine doesn't tell us about pesticides; when we look at the history, it reports deaths from leukaemia, cancer, blood problems, and we know that the person used a lot of pesticides, was continuously in contact with this type of substance."
>
> Testimonials from residents of the Settlement

At the same time, it is observed that many families in the agricultural villages indicate a commitment and effort towards agroecological production. However, although the practice is growing, residents indicate that the benefits and accelerated production are much more attractive to some families, hindering the transition to this type of production.

Regarding access to water in the settlement, this is mainly addressed from two perspectives: the quality of water for consumption and water for irrigation. On the first point, it was observed that only three of the 36 existing agricultural villages in the Jacaré-Curituba settlement have potable water, with the others being supplied by water intended for irrigation. To lessen the health impacts of consuming this water, the population opts to add chemical products such as "*sodium hypochlorite and pills distributed at health centres*" before consuming the resource. However, it is reported that these methods are not always effective, affecting the health of the most vulnerable, including the elderly and children.

> "Now, drinking water is a problem because the same water being used for irrigation is also being used for consumption. The agencies that assess water quality are reporting it as okay, but that's not the case. And we don't have any projects that attempt to improve the water distribution situation [...] we've raised the issue of drinking water and the intervention of the Sergipe Sanitation Company (DESO). People treat water at home with chlorine and hypochlorite, but they don't have water from DESO because all the pipes are connected. Some people say they have water from DESO, but they already know that all the rural villages have connected pipes. There was a court order to remove the pipes and have DESO put them back, but it's been two years and nothing has happened."
>
> Testimonials from residents of the Settlement

Regarding irrigation water, the population indicates that there are not many problems, apart from some cuts in the resource. They state that the biggest difficulty lies in the established irrigation period, which is not respected by some families, affecting the irrigation of others. The greatest concern is the power cut that supplies the irrigation pumps, which to this day is paid for by the São Francisco and Parnaíba Valleys Development Company (Codevasf). According to the population, there is already an association that is responsible for the gradual collection of charges for water and energy consumption in the irrigated perimeter of the settlement, since these represent an expense of approximately R$ 60,000.00 per month for the institution.

> "They had to reduce irrigation, they had to stop irrigating one day. On Wednesdays we couldn't turn on the water; they went two years without being able to irrigate on Wednesdays. Now, because of the reduced irrigation, Jacaré Curituba Settlement doesn't suffer as much, but if the pump breaks, then there's a problem, they lose a lot of money."
>
> Testimonials from residents of the Settlement

On the other hand, socially, it is evident that from the moment irrigation arrived in the studied area, individualism began to prevail among people, leading each family to produce on their own plot, consolidating a distancing in internal relations. This fact, it is stated, was not evident in the cohesive groups of the initial MST, compromising production, associativism and cooperativism, and with that, innovation, growth and commercialisation.

Regarding the production, marketing, and presence of cooperatives, it is observed that the products predominantly produced in the Jacaré Curituba Settlement are: cassava, okra, cowpeas, acerola, guava, onion, and garlic, among others. And on a smaller scale, more backyard production includes cilantro, chives, and tomatoes, among others.

> "Right now, we are working with cassava, okra, cowpeas, acerola, and guava. Many of the proposals from the settlement focus on fruit growing for acerola and guava production, milk production, and the installation of a dairy cow [...]. In the backyard, we grow cilantro, chives, and tomatoes for consumption."
>
> Testimonials from residents of the Settlement

The population expresses that the production and profit of families is an achievement of the people, a result of struggle, prevalence, and effort, bringing a feeling of gratitude and belonging in relation to the territory and the Landless Rural Workers Movement (MST). It is noted that families recognise the change in the perspective of work, distinguishing that today they are owners of their territory and their production, but not from commercialisation, regarding their products. On this last point, it is considered a serious problem by the population, since a large part of the production is frequently delivered to so-called "middlemen": people who collect the products from the production areas at prices low compared to the market.

It is also observed that the problem of marketing through intermediaries occurs for three reasons: first, the lack of options for selling their products, such as fairs, local commerce, sales centres, etc. Second, due to a lack of internal cooperation, the organisation of marketing procedures is limited not only at the local level but also at the municipal and state levels. This factor encourages the population to hand over the product to intermediaries, without knowing where their product is destined or what the final market value is (See Figure 4). In some cases, the population indicates that the amount received does not reach 10% of the value sold in other states.



Figure 4 – Okra harvesting within the AJC by middlemen

Source: Authors (2024)

Third, the population highlights the lack of transportation for producers, limiting the movement of products for sale. It is indicated that there were efforts to commercialise the products; however, these were limited to the sale of only a few products, such as cassava (or manioc).

> "Most of the settlement sells through middlemen, a few sell directly at the market, there are also cooperatives, some farmers are members and take their produce to the cooperative so that it can market it [...] we don't have transportation for the settlers to go and sell their own produce. Since they don't have credit to invest in farming and don't have transportation to take it, what they produce is taken by the middleman."
>
> Testimonials from residents of the Settlement (2022)

On this point, the population indicates that some residents prefer to deliver their produce to middlemen because it facilitates marketing, even if the producer receives a much lower price than the final market value. Here, it is observed that the producer thus avoids the work of selling at fairs and the expenses of transporting the product. Although this practice is more common within the settlement, it is one of the least profitable.

Moving on from the analysis of the interviews to that of similarity, it is observed that the population is concerned about the role played by some governmental institutions within the settlement, both in the development process and in the support provided within the area. In Figure 5, it can be seen how some names or words such as: Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba (Codevasf), Instituto Nacional de Colonização e Reforma Agrária (Incra), Companhia de Saneamento de Sergipe (DESO), the energy company Energisa, Família, or cooperatives, such as the União das Associações de Cooperação Agrícola do Perímetro Irrigado Jacaré Curituba (Unituba) and Cooperativa de Produção Agroindustrial e Comercialização do Estado de Sergipe Ltda (Coopac), are positioned as central in the word communities, constituting these as the key institutions to resolve the existing deficiencies in the region. Each of these is linked to other themes discussed throughout the interview, establishing an important relationship. The relationship between these aspects is verified.

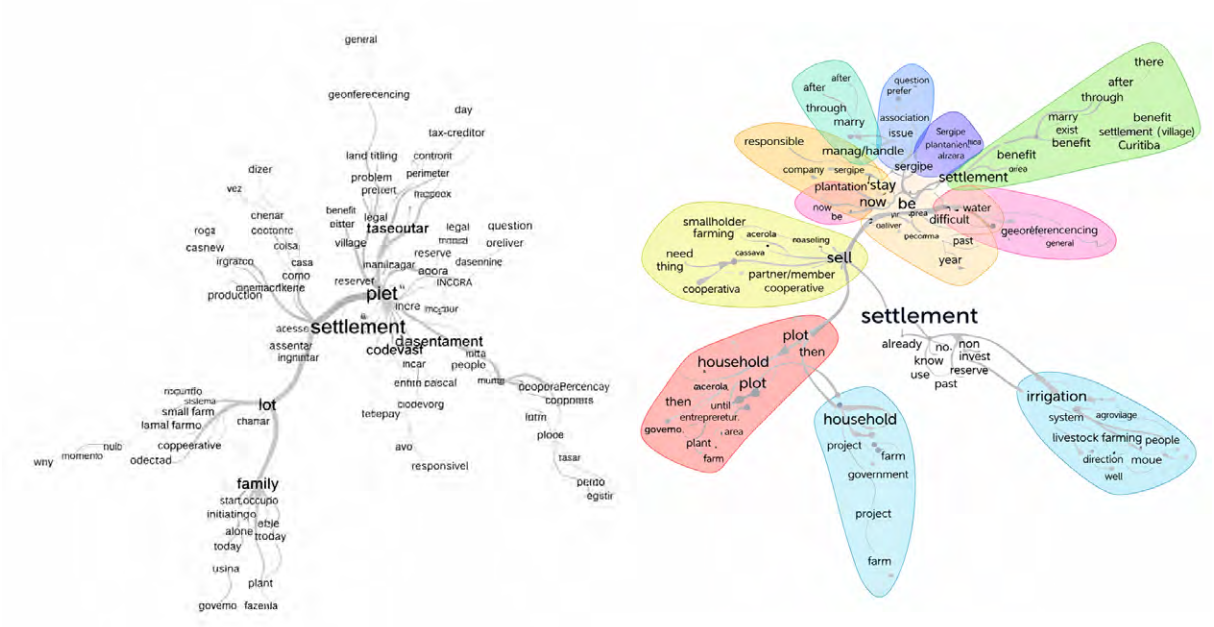


Figure 5 – Interview analysis by similarity

Source: Authors (2024)

Regarding the population's perception of Codevasf, this is linked to three aspects: its importance as a determining institution for securing land and production within the AJC (Area of Irrigation of the São Francisco River); the support provided to the irrigated perimeter in relation to the maintenance of irrigation pumps, technical assistance with Incra (National Institute for Colonisation and Agrarian Reform) and other partner institutions; and, finally, the supply of water for irrigation and consumption, in addition to payment for the energy consumed for irrigation. It is observed that, for the population, the institution is fundamental, since its presence and actions enable local productive growth. Furthermore, a great sense of gratitude towards the institution is observed, as it acts as a decision-maker for internal actions or a determiner of structural issues.

The Incra institution finds itself in a similar position, since, for the population, this institution acts as an internal articulator in relation to production and cooperativism, a mediator for families to obtain land titles, a facilitator of technical assistance, and a bridge for financing regional productive projects. On the other hand, it is also observed that the institution acts at a social level in relation to the promotion and revaluation of women, a noteworthy fact due to the role they assume within the settlement in the numerous crops they cultivate daily.

> "That's why each agro-village has an association, because Incra only released funds through them, so every agro-village had to form one. It was to receive those projects for chickens, corrals, equipment, for the construction of houses [...] it comes individually and through a contract, the

> Incra technician goes to the settler's house to deliver the contract and release the benefit [...] Incra has always worked on this, including in the application of the 'Fomenta Mulher' credit program, we held numerous meetings with groups of women, talking about its importance, and we discussed this with the Incra technicians, and that's when we really started working on the issue of gender, on empowering women to be active in the development process of their plot."
>
> Testimonials from residents of the Settlement (2022)

Indeed, the actions of Incra and Codevasf have become quite important in terms of women's empowerment. Over the years, many women have reported feeling freer to speak and act in their daily work, a situation that was not possible in previous generations. This transformation has enabled women to position themselves at the centre of decision-making and action. It is observed that their role has become fundamental in relation to structural issues within families, such as: water consumption and quality, production and marketing, management of cooperatives and associations, children's education, food provision and preparation, productive economy, family health and well-being, environmental care, among others.

The theme of cooperatives emerges as a structural element in the analysis by similarity, since it constitutes the primary means of food production and commercialisation. It is evident that currently there are several associations and cooperatives within the settlement, the most representative being Unituba and Coopac, which make it possible to add value to certain products.

> "There are several associations and cooperatives here, but the most important are Unituba and Coopac. Unituba coordinates the factory, processes the cassava, makes cassava cakes and sells them in the markets, while Coopac is more involved in the production side, for the..." The Food Acquisition Program (PAA) and the National School Feeding Program (Pnae). Currently, it's at a standstill; everything is reduced. What they used to do, today you see fifteen, twenty, which is already a lot.
>
> Testimonials from residents of the Settlement (2022)

It should be noted that the role of cooperatives was once much more important, but today they are forgotten and abandoned. This fact demonstrates a limited internal organisation and cohesion, making it impossible to balance social justice with economic prosperity and internal sustainability. As a result, the achievement of tangible financial results is restricted, the emergence of collective interests is inhibited, and the possibility of individual aspirations prevailing is opened.

Regarding DESO, the institution is identified as crucial to regional development and as a generator of local well-being due to its role as a distributor of potable water. However, the institution is considered deficient in terms of water supply, as it only covers 20% of the settlement. This fact causes a series of impacts on the population, such as water insecurity and an increase in human health problems. To date, several local actions involving municipal authorities have been undertaken to address this situation, but they have not yielded concrete results and have left the population reliant on water consumption for irrigation.

> "80% of the settlement doesn't have treated water; it's irrigation water from Codevasf, and Codevasf isn't obligated to treat water for everyone. The company that treats the settlers' water is called DESO; it's responsible for the settlers' water, but that water never arrived. Then, when the Codevasf pipeline arrived, the population improvised, and now everyone uses non-potable water because the potable water is the responsibility of another company."
>
> Testimonials from residents of the Settlement (2022)

Regarding the family as a basic and initial social institution, it is responsible for the so-called socialisation or primary interaction of the individual in society through language teaching, the transmission of values, and the teaching of basic norms of social interaction (Bauman, 1998; Stewart; Glynn, 1978; Vaitsman, 1994). In the settlement, it is observed that this is the basis of agroecological production. According to members of the agro-villages, some families are increasingly concerned with agroecological and sustainable production and, in turn, are promoting the articulation of local bases to advance aspects such as organisation, sustainable peasant production, and reducing the impact of climate change on production and the population, among others. Likewise, there is a concern to propose public policies that help improve the local situation in relation to the various themes presented so far.

Another important element regarding this aspect is observed in the families' concern to establish productive family units. In this sense, many of them have been carrying out productive activities in the same backyards as their homes, taking advantage of family labour, space, and the agricultural knowledge of each member. Among these, we can mention the efforts of entrepreneurial women who, based on local needs, began producing cakes, ice cream and popsicles from local fruits, dairy products, jams, liqueurs, pulps, among others. Products that today already form part of the basis of local production and family income.

As observed so far, the qualitative analysis of the data has made important contributions to the project's research, allowing us to delve meticulously into certain facts from the perspective of the population. Themes such as water security (in terms of resource quality), production processes, and marketing were those that attracted the most attention. The importance of the first... One reason is the high degree of vulnerability of the residents in relation to health, and the second is the lack of investment for the adequate sale of local products, an aspect that, in turn, is exploited by external marketers.

The detailed analysis of the facts was achieved through the use of qualitative techniques and methodologies, developed from records of perceptions, beliefs, representations, habits, attitudes, and opinions. As some authors previously noted, this data was useful for understanding the context of the phenomena; in this case, several factors became evident, including production, soil salinisation, and commercialisation through intermediaries.

In summary, the analysis of qualitative data, as well as participant observation, through the tools and software used, allowed for a deep understanding of some latent themes and problems within the settlement.

In this sense, it is argued that the use of this methodology within environmental sciences can be quite useful, as it allows one to delve into the subjectivity of phenomena. Environmental problems need to be increasingly evaluated from a social perspective, analysing issues arising from production, population, gender issues, generational issues, health, discrimination, social and environmental injustice, among others.

Many of these topics were not addressed in this work due to the scope of the research, but they are considered of paramount importance. Therefore, it is believed that addressing them in future studies may bring relevant analyses and debates to society and science.

5 CONCLUSIONS

The results demonstrate that prioritising qualitative data evaluation methods tends to yield deeper, more detailed analyses. In many cases, quantitative studies in the field of environmental sciences have limitations in measuring subjective aspects, a factor that restricts the understanding of phenomena and can introduce biases into the results.

It is observed that qualitative research allows for the analysis of subjective aspects and broadens its representativeness, especially due to the proximity between researcher and participants, as well as the descriptive and narrative nature of the data collected. The critical perspective adopted in this study regarding the application of quantitative techniques in environmental sciences is directed towards questioning the interpretations used to infer effects of diverse nature on the social characteristics of certain populations. In this sense, more in-depth analyses, which incorporate the participation of social actors, become fundamental for understanding such aspects.

Thus, the need to expand spaces for dialogue, interaction, and the collection of qualitative data—such as interviews and observations—becomes evident, which can contribute to a more accurate understanding of the real impacts of large-scale projects on local populations.

Therefore, it becomes essential to expand impact assessment strategies, as well as diversify the methodological techniques adopted, advancing the implementation of more robust and consistent approaches. The findings of this study indicate that qualitative research promotes a significant appreciation of social phenomena and processes, by considering motivations, beliefs, values, and representations present in social relations.

The results discussed throughout this study demonstrate that the adoption of qualitative methods in socio-environmental research significantly expands analytical and interpretative capacity, especially given the complexity of the society-nature interface. By incorporating symbolic, cultural, and subjective dimensions—often rendered invisible by exclusively quantitative approaches—qualitative methodology allows for a deeper understanding of the social processes that condition environmental dynamics.

The researcher's contextual immersion, the valuing of local knowledge, and direct interaction with the subjects being investigated strengthen the production of more consistent diagnoses and more reliable assessments of socio-environmental impacts. Furthermore, such approaches contribute to the formulation of environmental management strategies that are more sensitive to territorial realities and the socio-cultural specificities of the groups involved.

It can be concluded, therefore, that the systematic integration of qualitative techniques in socio-environmental studies not only improves the quality of the results obtained but also promotes more integrated, contextualised, and socially legitimised analyses, thereby constituting a relevant methodological approach for addressing contemporary sustainability challenges.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT for language editing. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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Aplicação de técnicas de pesquisa participativa no estudo socioambiental realizado no assentamento Jacaré-Curituba do Brasil

Application of participatory research techniques in a socio-environmental study conducted in the Jacaré-Curituba settlement in Brazil

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ARTICLE- VARIA

RESUMO

Este artigo apresenta inicialmente reflexões sobre os métodos e técnicas qualitativas existentes no âmbito das ciências sociais para posteriormente analisar como algumas delas podem ser aplicadas de forma eficaz em pesquisas socioambientais. O uso dessas técnicas em estudos de caso permite ampliar a representatividade dos resultados, considerando o caráter descritivo e narrativo dos dados, o que contribui para o enriquecimento dos processos de pesquisa. O objetivo do trabalho é apresentar algumas técnicas metodológicas aplicadas em estudo de caso como exemplo de aplicação bem-sucedida. Para este estudo, aplicaram-se a observação participante e a análise de dados de entrevistas semiestruturadas, realizadas no Assentamento Jacaré Curituba, localizado entre os municípios de Poço Redondo e Canindé de São Francisco, no alto sertão sergipano. O estudo permitiu identificar, a partir da percepção da população, diferentes problemáticas socioambientais existentes no local. Os resultados obtidos indicam que a adoção prioritária de métodos de avaliação sob uma perspectiva qualitativa favorece a consolidação de análises mais densas e minuciosas. Verifica-se que, em diversos casos, abordagens quantitativas no âmbito das ciências ambientais enfrentam limitações na mensuração de dimensões subjetivas, o que constitui um fator crítico na identificação de problemáticas e na estimativa de seus impactos.

Palavras-chave: Pesquisa qualitativa. Estudos socioambientais. Mudanças climáticas. Abordagem Nexus+. Nordeste brasileiro.

ABSTRACT

This article initially presents reflections on existing qualitative methods and techniques within the social sciences, and subsequently analyzes how some of them can be effectively applied in socio-environmental research. The use of these techniques in case studies allows for greater representativeness of the results, considering the descriptive and narrative nature of the data, which contributes to enriching the research processes. The objective of this work is to present some methodological techniques applied in a case study as an example of successful application. For this study, participant observation and data analysis from semi-structured interviews were applied, conducted in the Jacaré Curituba Settlement, located between the municipalities of Poço Redondo and Canindé de São Francisco, in the high hinterland of Sergipe. The study allowed for the identification, from the population's perception, of different socio-environmental problems existing in the area. The results obtained indicate that the priority adoption of evaluation methods from a qualitative perspective favors the consolidation of denser and more meticulous analyses. It has been observed that, in many cases, quantitative approaches in the field of

environmental sciences face limitations in measuring subjective dimensions, which is a critical factor in identifying problems and estimating their impacts.

Keywords: *Qualitative research. Socio-environmental studies. Climate change. Nexus+ approach. Brazilian Northeast.*

1 INTRODUÇÃO

O uso de diferentes tipos de técnicas metodológicas qualitativas de investigação, sejam etnográficas ou biográficas, tem ganhado terreno na pesquisa em ciências sociais. Suas características tornam essas técnicas apropriadas para a abordagem de processos socioculturais e ambientais, nos quais as interações sociais com o ambiente constituem o objeto predominante, posicionando os sujeitos como agentes detentores de saberes. Nesse sentido, este trabalho tem como objetivo apresentar técnicas de coleta e análise de dados utilizadas nas ciências sociais, a fim de incluí-las nas ciências ambientais, uma vez que a interação homem-natureza tem se tornado cada vez mais intensa e complexa.

Entre as características dessa metodologia social, destaca-se o fato de que ela possibilita maior interação do investigador com o objeto, já que sua construção e compreensão pressupõem a partilha de experiências e significações entre investigador e sujeito. Nesse contexto, o pesquisador consegue mergulhar no universo de ação dos sujeitos (Bernal, 2024; Costa, 1987; Dalfovo, 2008; Delari, 2015), obtendo uma visão mais concreta (Woods, 1987) e constituindo-se como o principal instrumento da investigação (Bogdan; Biklen, 1994), uma vez que a natureza dos dados recolhidos depende de sua postura, das orientações que adotou e de suas competências metodológicas.

Nesse contexto, a construção do saber é feita coletivamente, considerando as concepções dos atores sociais e os significados que atribuem às suas práxis. Por isso, os participantes são considerados fontes de conhecimento e parceiros no processo de construção da realidade. Segundo Goetz e Lecompte (1988), a ação humana é explicada em função do contexto cultural no qual os atores constroem o significado de suas interações e sua interpretação da realidade. O investigador, portanto, precisa estar inserido no contexto, pois não é possível investigar adequadamente uma cultura por meio de intérpretes. A construção do objeto implica interação estreita, prolongada e contextualizada entre investigador e sujeitos, permitindo alcançar uma visão mais consensual sobre o social, o ambiental e o cultural (Conjo, 2022; Erlandson, 1993; Paranhos, 2016).

As ciências sociais sempre foram influenciadas por metodologias quantitativas e qualitativas. Essas áreas presenciaram uma difusão inédita e veloz de técnicas de coleta e análise de dados, especialmente no campo qualitativo. As inúmeras publicações dessa natureza têm contribuído para redefinir os rumos das pesquisas sociais e humanas. A pesquisa qualitativa abrange diversos campos do saber, incluindo antropologia, sociologia, economia, psicologia, administração, biologia, educação, entre outros. Entre as técnicas de coleta de dados destacam-se o estudo de campo, a observação participante, a entrevista qualitativa, o estudo de caso e a pesquisa participante.

No entanto, a definição do tipo de técnica a ser implementado em um estudo específico depende da natureza da pesquisa, de seu enfoque, de seus objetivos e do objeto de estudo.

2 A INCORPORAÇÃO DAS METODOLOGIAS QUALI-QUALITATIVAS DENTRO DAS CIÊNCIAS AMBIENTAIS

A educação ambiental, além de promover mudanças comportamentais no cuidado com o meio ambiente, busca estabelecer perspectivas e ações críticas voltadas à promoção de transformações na sociedade e no ambiente, recorrendo a estudos empíricos (Bôlla; Milioli, 2011). No entanto, até o

momento, essa área do conhecimento ainda precisa demonstrar, de forma mais consistente, evidências empíricas acerca dos aspectos socioambientais. No campo da análise de impacto ambiental de projetos, por exemplo, estudos com enfoque socioambiental frequentemente enfrentam limitações na determinação de impactos concretos, bem como na avaliação da efetividade dos projetos na mitigação desses impactos (Guanabara *et al.*, 2009).

Nesse contexto, tornam-se necessárias novas estratégias de avaliação capazes de apreender a complexidade da questão ambiental em sua articulação com os aspectos sociais. O uso exclusivo de critérios quantitativos tem se mostrado insuficiente na avaliação de projetos ambientais, uma vez que não contempla adequadamente a subjetividade, variável central na compreensão das causas e dinâmicas da crise ambiental. Assim, a incorporação de abordagens qualitativas apresenta-se como uma alternativa relevante, pois permite investigar dimensões que escapam aos métodos quantitativos, incorporando aspectos relacionados à percepção, às experiências e aos significados atribuídos pelos sujeitos (Silverman, 2001).

Diante dos desafios contemporâneos nas dimensões social e ambiental, torna-se fundamental investigar, avaliar e aplicar diferentes modelos de pesquisa no âmbito da gestão ambiental. Para tanto, é necessário incorporar múltiplos enfoques teóricos e metodológicos à análise, de modo a superar as visões estritamente econômicas predominantes, que se mostram limitadas na compreensão da complexidade socioambiental. Em muitos casos, tais abordagens contribuíram para o agravamento de problemas de degradação ambiental e para a intensificação da exclusão social, como observado em populações atingidas por barragens (Bernal, 2021).

Nesse sentido, o presente estudo tem como objetivo compreender, explicar e descrever, com maior precisão, os problemas ambientais em um determinado contexto territorial, por meio da aplicação da metodologia qualitativa e de técnicas de coleta e análise de dados em um caso concreto brasileiro. Busca-se demonstrar como essa abordagem possibilita o aprofundamento de aspectos da realidade que não são passíveis de quantificação, contribuindo para a compreensão do universo de significados, motivações, aspirações, crenças, valores e atitudes (Minayo, 2014).

2.1 A PESQUISA DE NATUREZA QUALITATIVA: BASES, INTERVENÇÃO, MÉTODO E TÉCNICAS

A gênese da metodologia qualitativa está associada às críticas ao positivismo e, muitas vezes, encontra-se sob a denominação de pesquisa qualitativa. Essa abordagem abrange diferentes tipos de investigação, apoiados em variados referenciais teóricos e metodológicos, tais como a etnografia, o materialismo histórico e a fenomenologia (Godoy, 1995). Segundo Minayo (2001), a pesquisa qualitativa foi inicialmente aplicada em estudos de antropologia e sociologia como contraponto à predominância da abordagem quantitativa. Posteriormente, expandiu-se para áreas como a psicologia e a educação. Embora seja criticada por seu empirismo, pela subjetividade e pelo envolvimento do pesquisador, a pesquisa qualitativa oferece contribuições relevantes à ciência ao possibilitar a análise de problemáticas historicamente pouco exploradas.

De acordo com Godoy (1995), a abordagem qualitativa apresenta as seguintes características: a realização do estudo no ambiente natural, onde os fatos sociais devem ser observados, analisados e interpretados em seu contexto; o papel central do pesquisador na observação, seleção e análise dos dados; a valorização de dados descritivos provenientes da realidade empírica; o uso de técnicas como entrevistas, registros visuais e depoimentos; a consideração da perspectiva dos sujeitos investigados; o compromisso com a fidedignidade dos dados; e a observância de princípios éticos.

Por outro lado, Knechtel (2014) destaca que a pesquisa qualitativa se caracteriza pela compreensão da realidade como socialmente construída, pela relação entre pesquisador e objeto de estudo, pela ênfase

nos processos e significados e pelo uso de métodos interpretativos, como entrevistas e observação detalhada. Incluem-se ainda os estudos de caso, a valorização de descrições aprofundadas e o uso de narrativas históricas, materiais biográficos e autobiográficos.

Gerhardt e Silveira (2009) ressaltam que a abordagem qualitativa envolve a compreensão do fenômeno em sua totalidade, a articulação entre o global e o local, o respeito às especificidades do mundo social em relação ao natural e a valorização da interação entre objetivos de pesquisa, referenciais teóricos e dados empíricos. Além disso, opõe-se à ideia de um modelo único de investigação aplicável a todas as áreas do conhecimento.

Nesse sentido, a metodologia qualitativa apresenta-se como uma alternativa adequada para compreender, explicar e descrever com maior precisão os problemas ambientais em contextos específicos, oferecendo um conjunto consistente de orientações teórico-metodológicas.

Segundo Neves (1996), a pesquisa qualitativa assume diferentes significados no campo das ciências sociais, englobando um conjunto de técnicas interpretativas — como entrevistas não estruturadas e semiestruturadas, observação participante, observação estruturada e grupos focais — que visam descrever e interpretar sistemas complexos de significados. Complementarmente, Alencar (1999) ressalta que o pesquisador inicia o trabalho de campo com pressupostos teóricos que orientam a investigação.

A pesquisa qualitativa busca compreender a complexidade dos fenômenos sociais, não sendo passível de mensuração em escala numérica (Rosental, 2001). Diferentemente da abordagem quantitativa, não se baseia em instrumentos estatísticos, priorizando a interpretação e a compreensão dos fenômenos (Dalfovo *et al.*, 2008).

Os dados qualitativos incluem informações não expressas exclusivamente em palavras, tais como pinturas, fotografias, desenhos, filmes, vídeos e até trilhas sonoras (Dalfovo *et al.*, 2008). Nesse contexto, a fenomenologia constitui um importante fundamento teórico da pesquisa qualitativa, ao buscar compreender os significados atribuídos pelos indivíduos às suas experiências em contextos específicos, enfatizando a relevância da interação simbólica e da cultura.

De acordo com Trato (2005), pesquisas qualitativas trabalham com valores, crenças, representações, hábitos, atitudes e opiniões, sendo especialmente úteis para compreender o contexto em que determinados fenômenos ocorrem. Em vez de mensurar variáveis, seu objetivo é alcançar uma compreensão aprofundada — e, quando necessário, subjetiva — do objeto de estudo. Dessa forma, direciona-se a grupos delimitados em termos territoriais e sociais, permitindo uma análise intensiva de suas dinâmicas.

Como observado, a pesquisa qualitativa não se orienta pela representatividade numérica, mas pelo aprofundamento da compreensão de grupos sociais e de suas relações com o contexto em que estão inseridos. Os pesquisadores que adotam essa abordagem rejeitam a ideia de um modelo único de investigação científica, reconhecendo a especificidade das ciências sociais e a necessidade de métodos próprios. Nesse sentido, o ambiente constitui a principal fonte de dados, e o pesquisador pode envolver-se diretamente no processo investigativo.

Por fim, a análise de dados qualitativos possibilita ao pesquisador interpretar os discursos dos participantes e compreender, de forma aprofundada, fenômenos sociais complexos, com base na relevância do aspecto subjetivo da ação social diante da configuração das estruturas sociais (Haguette, 1997).

2.2 PRINCIPAIS TÉCNICAS DE COLETA DE DADOS QUALITATIVOS UTILIZADOS NA CIÊNCIA

Como indicado, a pesquisa qualitativa não possui um método único padronizado. Em muitos casos, ela pode ser caracterizada por um espectro de métodos e técnicas adaptados a casos específicos de acordo com as necessidades e possibilidades do pesquisador e de seu objeto de estudo. No entanto, as técnicas mais comumente empregadas em pesquisas sociais incluem: estudos de caso, etnografia, entrevistas (estruturadas, semiestruturadas, abertas e projetivas), cartografia social, observação (simples e participante), histórias de vida e grupos focais, análise de conteúdo, pesquisa-ação, fenomenologia, método Delphi, entre outras.

Uma vez coletados os dados, essas técnicas permitem analisar o fenômeno e organizar as etapas de descrição, compreensão e explicação, além de identificar, com maior precisão, as relações entre o global e o local. Adicionalmente, possibilitam observar as diferenças entre o mundo social e o mundo natural, e alcançar resultados mais fidedignos.

3 METODOLOGIA

3.1 ÁREA DO ESTUDO

O presente estudo foi realizado no Assentamento Jacaré Curituba (AJC), localizado entre os municípios de Poço Redondo e Canindé de São Francisco, no Alto Sertão Sergipano. Essa área faz parte do projeto de pesquisa INCT – Odisseia, sítio Caatinga. Especificamente, a área de estudo do projeto foi composta pelas agrovilas Braço Erguido, Nossa Senhora da Conceição, São José e Samariva Daniel. Essas duas últimas foram consideradas uma única unidade, devido à ausência de uma delimitação clara de limites, conforme apresentado na Figura 1.

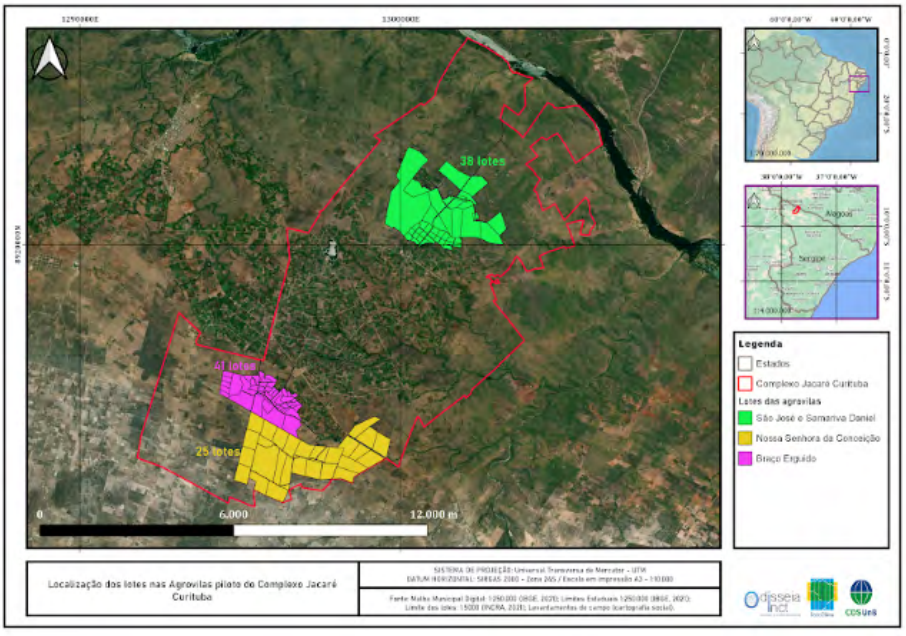


Figura 1 – Localização e divisão do Assentamento Jacaré Curituba no estado de Sergipe e Brasil

Fonte: Elaboração dos autores.

3.2 TÉCNICAS METODOLÓGICAS QUALITATIVAS APLICADAS E ANÁLISE DOS DADOS

Neste estudo, aplicaram-se as técnicas de entrevista e observação participante no âmbito do projeto INCT – Odisseia, descrito na seção seguinte. A partir dessas técnicas, foi possível compreender a área de estudo e suas problemáticas mais relevantes. Ambas as técnicas metodológicas foram aplicadas. A entrevista, por sua vez, permitiu estabelecer um "processo de interação social entre duas ou mais pessoas, nas quais uma delas, o entrevistador, tem por objetivo a obtenção de informações por parte do outro, o entrevistado" (Haguette, 1997, p. 86.). A observação, por sua vez, permitiu obter informações sobre determinados aspectos da realidade, auxiliando os pesquisadores a identificar e compreender aspectos sobre os quais os indivíduos não têm consciência, mas que orientam seu comportamento (Lakatos, 1996).

Preparou-se um roteiro de entrevista semiestruturada, considerando a sequência do pensamento do entrevistado, buscando dar continuidade à conversação e conduzir a entrevista com sentido lógico. Esse instrumento continha 18 perguntas centrais. Em muitos casos, outras perguntas surgiam em função de falas ou temas mencionados pelos entrevistados. A Tabela 1 a seguir apresenta um resumo dos temas abordados durante as entrevistas.

Ao todo, foram realizadas 10 entrevistas. Entre os entrevistados, há representantes e funcionários da Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba (Codevasf), do Instituto Nacional de Colonização e Reforma Agrária (Incra), da Empresa de Assistência Técnica e Extensão Rural (Emater), das prefeituras dos municípios de Poço Redondo e Canindé de São Francisco, de cooperativas locais, bem como moradores do assentamento. Cabe ressaltar que as entrevistas foram realizadas entre 2022 e 2023.

Tabela 1 – Lista de temas abordados nas entrevistas

Identificação do entrevistador	
Localização da entrevista	
Caracterização do domicílio	
Caracterização do entrevistado	Pessoal
	Mobilidade pessoal
	Atividades
Caracterização da família	Geral
	Mobilidade filhos
Capital Social da família	Associativismo
Caracterização da renda	Não agrícola
	Agropecuária
Atividade Agropecuária	Caracterização do lote
	Agricultura
	Pecuária
	Extrativismo e Conservação
	Práticas agrícolas
	Agrotóxicos
	Agroecologia
	Sistema hídrico
	Comercialização
Apoio para produzir	Informação
	Acesso a políticas públicas de auxílio
	Crédito

Caracterização do domicílio	
Situação Fundiária	Regularização
	Uso de outras áreas
	Própria área/terceiros (presente/passado)
	Aquisição de novas terras
	Venda de terras
	Uso da várzea
Mudanças Observadas	Abandono
	Impacto da monocultura e produção em grande escala
	Alteração
	Impactos de novos produtos: ingressos da soja, entre outros
Sistema hídrico, alimentar e energético	Situação e problemáticas
Percepções	Futuro
	Clima (precipitação e temperatura) / chuvas e estiagens
	Fenologia
	Fluviométrica
	Impactos do clima
	Conhecimentos tradicionais
Epistemologias populares	Previsão do tempo

Fonte: elaboração própria

No que concerne à observação realizada, o pesquisador buscou recolher e registrar os fatos da realidade sem a utilização de meios técnicos especiais, registrando fatos, elementos ou situações em cadernos de campo relativos a vários dos temas estruturais citados na Tabela 1. Esses cadernos foram atualizados diariamente após as visitas das famílias realizadas em campo.

3.3 SOBRE A SISTEMATIZAÇÃO E ANÁLISE DE DADOS

Todas as entrevistas foram transcritas e reunidas em um documento de 105 páginas. O tratamento dos dados foi realizado em dois softwares: o NVivo e o IRaMuTeQ. O uso desses softwares permitiu a realização de uma análise mais aprofundada, com base em variáveis determinantes, bem como a aplicação de análise fatorial, classificação hierárquica descendente e análise de similitude.

A análise fatorial permite observar as características do texto por meio da frequência das palavras, bem como a distribuição das formas em um plano de proximidade, no qual aquelas situadas no centro são as mais recorrentes e relevantes, relacionadas a outros temas identificados nos quadrantes.

A classificação hierárquica permite a identificação dos vocábulos presentes no texto por meio de classes. A partir da análise das palavras, podem ser estabelecidos diferentes temas em cada classe, facilitando a identificação das principais preocupações da população mencionadas nas entrevistas, bem como das relações existentes entre elas.

A análise de similitude, por sua vez, permite identificar relações de proximidade entre palavras organizadas em comunidades. No centro de um mapa de palavras, observam-se os termos mais

relevantes, conectados a outros temas discutidos ao longo das entrevistas. Para fins de codificação no software, aplicou-se a atribuição de números e códigos a cada entrevistado (ver Tabela 2).

Tabela 2 – Codificação de entrevistados para análise no software Iramuteq

Nº	*Código*	*Pessoa*
1	**** *Entrevista_1	xxxx
2	**** *Entrevista_2	xxxx
3	**** *Entrevista_3	xxxx
4	**** *Entrevista_4	xxxx
5	**** *Entrevista_5	xxxx
6	**** *Entrevista_6	xxxx
7	**** *Entrevista_7	xxxx
8	**** *Entrevista_8	xxxx
9	**** *Entrevista_9	xxxx
10	**** *Entrevista_10	xxxx

Fonte: elaboração própria

Por fim, cabe mencionar que esta pesquisa foi submetida à avaliação do Comitê de Ética em Pesquisa em Ciências Humanas e Sociais da Universidade de Brasília, sob o protocolo nº 01037218.5.0000.5540 e parecer nº 3.440.596.

4 RESULTADOS E DISCUSSÃO

A incorporação sistemática de técnicas metodológicas qualitativas em estudos socioambientais se constitui como uma estratégia central para a otimização de resultados analíticos e avaliativos. Mergulhar no simbólico e contextual permite ao pesquisador a valorização dos saberes locais e a interpretação das dimensões simbólicas, culturais e subjetivas da relação sociedade-natureza. Tais abordagens ampliam a capacidade explicativa das pesquisas e superam as limitações inerentes à mensuração exclusivamente quantitativa.

Dessa forma, a aplicação de métodos como etnografia, entrevistas em profundidade, observação participante e estudos de caso favorece a realização de diagnósticos mais precisos, bem como a elaboração de avaliações mais consistentes de impactos socioambientais, possuidores de maior legitimidade dos resultados, uma vez que integra significados, percepções e práticas dos atores sociais. Consequentemente, estudos que adotam referenciais qualitativos tendem a produzir análises mais integradas, contextualizadas e efetivas para a gestão ambiental e para a formulação de intervenções transformadoras.

Para validar tais asseverações, a seguir alguns dos resultados do estudo aplicado, observando a valorização da população em relação às atividades econômicas e produtivas que realizam, as problemáticas sociais e ambientais identificadas, a comercialização dos produtos e o papel importante que algumas instituições do estado possuem ou significam para a população local.

Segundo alguns moradores locais, grande parte do território do assentamento está destinada à agricultura e à pecuária em pastagens extensivas. Sobre a agricultura, afirma-se que esta é praticada predominantemente por um sistema de agricultura irrigada e, em uma mínima parte, por sequeiro. A produção agrícola da população é diversificada, com o predomínio de verduras, legumes, hortaliças e frutas. Afirma-se que as principais plantações são de quiabo, mandioca, milho, feijão, girassol, goiaba, maracujá, alface, melancia e abóbora.

Observa-se que as famílias rurais, além das diferentes culturas agrícolas que realizam, dedicam-se, de maneira paralela e em menor proporção, à bovinocultura de corte e de leite, atividade que aporta à renda das famílias locais. Por outro lado, afirma-se que grande parte da produção do assentamento é comercializada mediante atravessadores, que transportam e vendem seus produtos em diferentes partes do país.

Esses foram alguns dos elementos gerais mais importantes identificados nas entrevistas. No entanto, uma vez lançadas as entrevistas nos softwares mencionados e aplicando uma análise fatorial destes, identificou-se um grande número de temas que claramente são de preocupação da população, entre eles: *título de terra, acesso à água/irrigação e consumo, cobrança pela água, produção e comercialização/cooperativa*, além de *problemas* em geral (Figura 2).

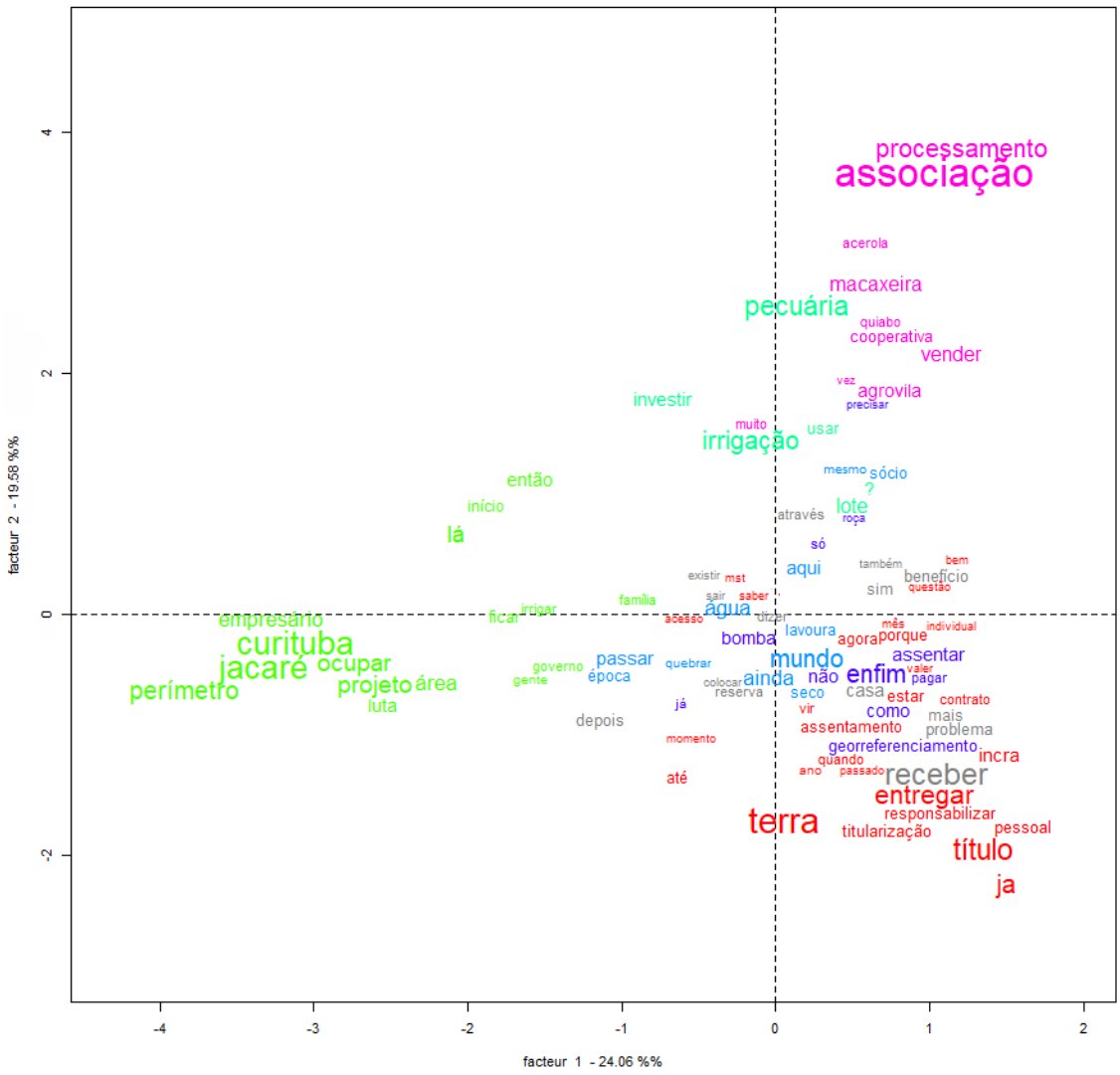


Figura 2 – Identificação de temas maiormente discutidos nas entrevistas

Fonte: elaboração própria

Esses temas foram verificados através da realização da classificação hierárquica descendente, que permitiu a identificação de vocabulários no texto mediante classes. Observa-se que em cada classe surgiram diferentes temas, facilitando a identificação e a validação dos temas e inquietudes da população.

Sobre o tema terra, por exemplo, observa-se através das falas das pessoas que esse elemento é tratado em função da conquista do território para produção, bem como um fator determinante de dificuldades e disparidades internas em relação a acesso à terra, água, produção e poluição do meio ambiente.

> "Quem escolheu ficar com o lote irrigado, ficaria aqui, pois tem irrigação, e quem escolheu o lote sequeiro, aí iam para outra área ou acampamento para que pudessem pegar essas terras. [...] Muita gente fala da questão do título da terra, mas o decreto que tem é para quem tem oitenta tarefas, é para quem tem condições de pagar todos os investimentos. E aqui ninguém tem condições de fazer investimento."
>
> Depoimentos de moradores do Assentamento

Analisando as entrevistas, observa-se que no assentamento existem maiores dificuldades em áreas categorizadas como de sequeiro, fator que se deve principalmente à quantidade de produção e comercialização. Essa área, em grande parte, depende da chuva ou da irrigação artesanal para a produção, que é limitada para consumo familiar e, em parte, para a comercialização. A população da área, assim como outras entrevistadas, observa que a produção em grande escala vem comprometendo a qualidade do solo, acelerando o processo de salinização por excesso de irrigação e uso de fertilizantes. Esses dados validam os resultados de análise de solo realizado pelo projeto INCT-Odisseia (Oliveira, 2024). Neste estudo, observa-se que dos 104 lotes analisados na área de estudo (22 destinados à irrigação, 47 à pecuária e 35 para atividades de sequeiro), 64 apresentaram problemas devido à presença de sais no solo, sendo 63 lotes classificados como salinos e 1 como salino-sódico. Destes, 41 lotes foram identificados na agrovila Braço Erguido, enquanto os demais 23 estavam na agrovila Nossa Senhora da Conceição.

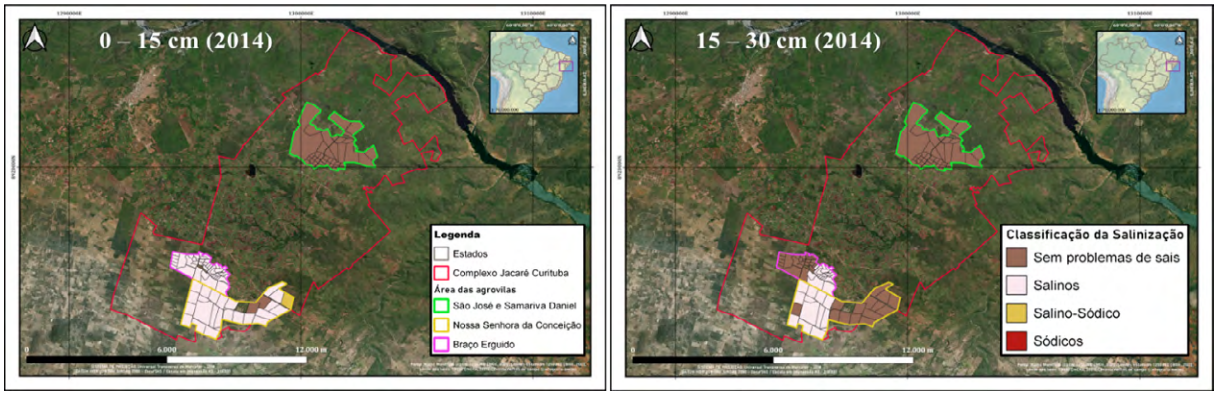


Figura 3 – Classificação quanto ao nível de salinização nos lotes das áreas estudadas

Fonte: Oliveira (2024)

Sobre esse ponto, destaca-se que a população indica que além dessa prática comprometer a saúde ambiental, ela vem afetando a saúde de diferentes moradores, causando uma série de doenças e, em alguns casos, a morte.

> "Tudo isso acontece no assentamento, assoreamento, salinização da terra, a terra que não produz mais, mas ainda não há uma consciência de que aquela terra não está produzindo, pois se usou muito adubo e produto químico, então não se tem conhecimento sobre isso. Nossa preocupação maior é com o meio ambiente, que tem sofrido, mas principalmente a vida [...]. Nós temos muitas pessoas que aqui no assentamento já morreram por causa do agrotóxico. Infelizmente a medicina não diz sobre agrotóxico, quando a gente vai ver o histórico onde relatam mortes por leucemia, câncer, problema no sangue, e a gente sabe que a pessoa usava muito agrotóxico, estava continuamente em contato com esse tipo de substância".
>
> Depoimentos de moradores do Assentamento

Ao mesmo tempo, observa-se que muitas famílias das agrovilas indicam um compromisso e esforço pela produção agroecológica. No entanto, ainda que a prática venha crescendo, os moradores indicam que os benefícios e a produção acelerada são muito mais atrativos para algumas famílias, dificultando a transição para esse tipo de produção.

Em relação ao acesso à água no assentamento, ele é tratado principalmente sob dois aspectos: a qualidade da água para o consumo e a água para irrigação. Sobre o primeiro ponto, observou-se que só três agrovilas, das 36 existentes no assentamento Jacaré-Curituba, dispõem de água potável, sendo as outras abastecidas por água destinada para irrigação. Para diminuir os impactos do consumo dessa água sobre a saúde, a população opta por colocar produtos químicos como "hipoclorito de sódio e pílulas distribuídas nos postos de saúde" antes do consumo do recurso. Entretanto, relata-se que os métodos nem sempre são eficientes, afetando a saúde dos mais vulneráveis, entre os quais estão idosos e crianças.

> "Agora a água para o consumo é um problema, porque a mesma água que está sendo usada para a irrigação está sendo usada para o consumo. Agora os órgãos que avaliam a qualidade da água, eles sinalizam como ok, mas não é assim. E não temos nenhum projeto que tente melhorar a situação da distribuição de água [...] colocamos em pauta a questão da água potável, e a intervenção da Companhia de Saneamento de Sergipe (Deso). O povo trata a água em casa, com cloro e hipoclorito, mas não tem água da Deso, pois todos os canos estão emendados. Tem algumas pessoas que dizem que tem água da Deso, mas já sabem que todas as agrovilas têm os canos emendados. Teve uma ordem judicial para tirarem e a Deso colocar de volta, mas já faz dois anos e não deu em nada"
>
> Depoimentos de moradores do Assentamento

Sobre a água para irrigação, a população indica que não existem muitos problemas, além de alguns cortes no recurso. Manifestam que a grande dificuldade está no período de irrigação estabelecido que não é respeitado por algumas famílias, afetando a irrigação das outras. A maior preocupação está no corte de energia que abastece as bombas de irrigação, até hoje pagas pela Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba (Codevasf). Segundo a população, já existe uma associação que se encarrega da cobrança paulatina sobre o consumo de água e de energia no perímetro irrigado do assentamento, já que estes representam um gasto de aproximadamente R$ 60.000,00 mensais à instituição.

> "Eles tiveram que reduzir a irrigação, tiveram que não irrigar um dia. Na quarta-feira não podíamos ligar a água, passaram dois anos sem poder irrigar na quarta. Agora o Assentamento Jacaré Curituba por isso da irrigação não sofre tanto, mas se quebrar a bomba, aí dá problema, perde muito dinheiro."
>
> Depoimentos de moradores do Assentamento

Por outro lado, socialmente, manifesta-se que a partir do momento em que chegou a irrigação na área estudada, passou a prevalecer o individualismo nas pessoas, levando cada família a produzir no seu lote, consolidando um distanciamento nas relações internas. Afirma-se que esse fato não se evidenciava nos grupos coesos do MST iniciais, comprometendo a produção, o associativismo e o cooperativismo, e, com isso, a inovação, o crescimento e a comercialização.

No que diz respeito à produção, comercialização e presença das cooperativas, observa-se que os produtos majoritariamente produzidos no Assentamento Jacaré Curituba são: macaxeira, quiabo, feijão-de-corda, acerola, goiaba, cebola, alho, entre outros. E numa menor escala, sendo uma produção mais de fundo de quintal, encontram-se: coentro, cebolinha, tomate, entre outros.

> "Aqui agora, a gente está trabalhando com macaxeira, quiabo, feijão-de-corda, acerola e goiaba. Então muitas das propostas que vieram do assentamento estão voltadas à fruticultura, para produção de acerola e goiaba, produção de leite também chegou e instalação de matriz leiteira [...]. No fundo do quintal, coentro, cebolinha e tomate para consumo mesmo."
>
> Depoimentos de moradores do Assentamento

A população manifesta que a produção e o lucro das famílias é uma conquista do povo, resultado da luta, prevalência e esforço, trazendo um sentimento de gratidão e pertencimento em relação ao território e ao Movimento dos Trabalhadores Rurais Sem Terra (MST). Nota-se que as famílias reconhecem a mudança na perspectiva de trabalho, distinguindo que hoje são donos do seu território e da sua produção, mas não da comercialização dos seus produtos. Sobre esse último ponto, ele é considerado pela população como um problema grave, já que frequentemente entrega-se grande parte da produção aos chamados "atravessadores": pessoas que coletam os produtos das áreas de produção a um preço baixo em relação ao mercado.

Verifica-se também que o problema da comercialização mediante os atravessadores se dá por três motivos: primeiro, a falta de opções para vender seus produtos, como feiras, comércio local, centros de venda, etc. Segundo, devido à falta de cooperativismo interno, que limita a organização dos procedimentos de comercialização não só na escala local, mas também nas escalas municipal e estadual. Este fator estimula a população a entregar o produto nas mãos dos atravessadores, desconhecendo para onde seu produto é destinado e qual o valor final comercializado (Figura 4). Em alguns casos, a população indica que o valor recebido não chega a 10% do valor vendido em outros estados.



Figura 4 – Coleta de quiabo dentro do AJC por atravessadores

Fonte: Autores (2024)

Terceiro, a população ressalta a falta de transporte dos produtores, limitando o deslocamento dos produtos para venda. Indica-se que existiram esforços para a comercialização, porém, limitou-se à comercialização de apenas alguns produtos, como a mandioca (ou macaxeira).

> "A maioria do assentamento comercializa com o atravessador, um ou outro comercializa diretamente na feira, tem também as cooperativas. Alguns agricultores são associados e levam para a cooperativa para que ela possa comercializar [...] não temos transportes para os assentados irem vender sua própria produção. Como não tem crédito para investir na roça e não tem transporte para levar, o que eles produzem é o atravessador que leva."
>
> Depoimentos de moradores do Assentamento (2022)

Sobre esse ponto, a população indica que parte dos moradores prefere entregar sua produção para os atravessadores porque facilita a comercialização, mesmo que o produtor receba um valor bem menor do que o valor final de mercado. Aqui se observa que o produtor evita assim o trabalho de venda em feiras e os gastos com o deslocamento do produto. Ainda que esse fato se trate de uma prática mais comum dentro do assentamento, ela se torna uma das menos lucrativas.

Passando a análise das entrevistas à de similitude, observa-se que existe preocupação da população com o papel que cumprem algumas instituições governamentais dentro do assentamento, tanto no processo de desenvolvimento quanto no apoio prestado dentro da área. Na Figura 5 pode-se observar como alguns nomes ou palavras, como Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba (Codevasf), Instituto Nacional de Colonização e Reforma Agrária (Incra), Companhia de Saneamento de Sergipe (Deso), a empresa de energia Energisa, família ou cooperativas, como a União das Associações de Cooperação Agrícola do Perímetro Irrigado Jacaré Curituba (Unituba) e Cooperativa de Produção Agroindustrial e Comercialização do Estado de Sergipe Ltda. (Coopac), se posicionam como centrais nas comunidades de palavras, constituindo-se como instituições-chave para resolver as deficiências existentes na região. Cada uma destas encontra-se ligada a outros temas discutidos ao longo da entrevista, estabelecendo uma importante relação. Verifica-se a relação entre esses aspectos.

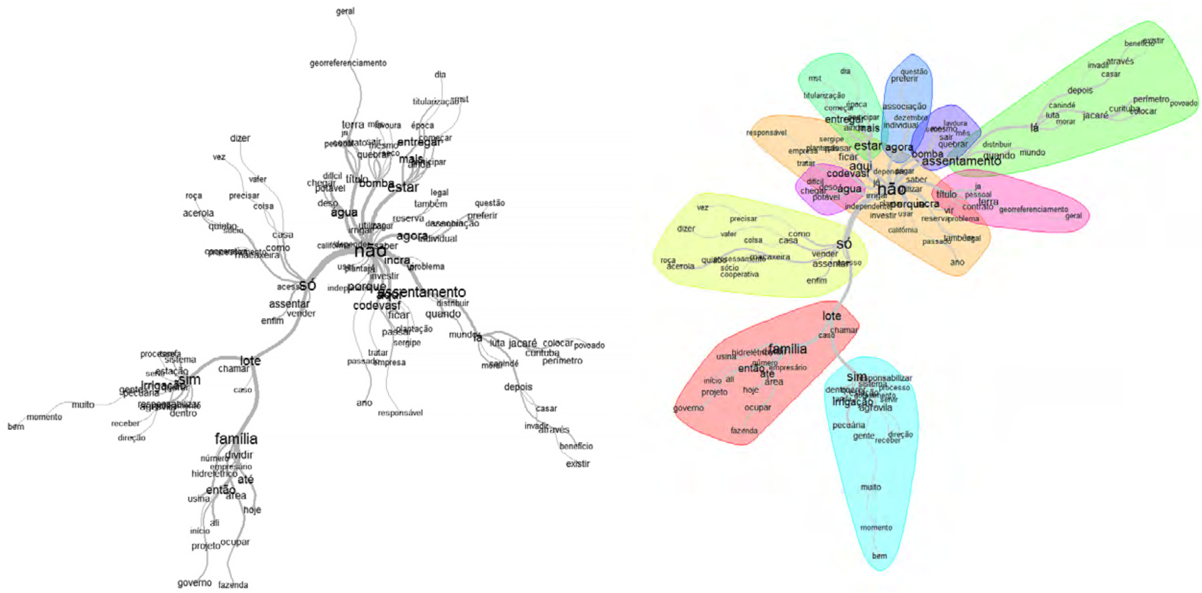


Figura 5 – Análises de entrevista por similitude

Fonte: Autores (2024)

Sobre a percepção da Codevasf pela população, ela está vinculada a três aspectos: sua importância enquanto instituição determinante para conseguir a terra e produção dentro do AJC; o apoio prestado ao perímetro irrigado em relação à manutenção das bombas de irrigação, assessoramento técnico do Incra e de outras instituições parceiras; e, finalmente, abastecimento de água para irrigação e consumo, além do pagamento pela energia consumida para irrigação. Observa-se que, para a população, a instituição é fundamental, já que sua presença e atuação possibilitam o crescimento produtivo local. Ainda, observa-se um grande sentimento de gratidão em relação à instituição, já que ela atua como decisor de ações internas ou determinador de temas estruturais.

A instituição Incra se encontra em posição semelhante, já que, para a população, ela se constitui como articulador interno em relação à produção e ao cooperativismo, mediador para que as famílias obtenham a titularidade dos lotes, facilitador de assistência técnica e ponte para o financiamento de projetos produtivos regionais. Por outro lado, observa-se também que a instituição atua no nível social em relação à promoção e revalorização da mulher, fato de destaque devido ao papel que ela assume dentro do assentamento nas inúmeras lavouras que desenvolve cotidianamente.

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> "Por isso que cada agrovila tem uma associação, pois o Incra só liberava através delas, então toda agrovila tinha que fazer. Era para receber aqueles projetos de galinha, curral, de equipamentos, para a construção das casas [...] vem de forma individual e através de contrato, o técnico do Incra vai até a casa do assentado para levar o contrato e liberar o benefício [...] O Incra sempre trabalhou sim, inclusive lá na aplicação do crédito fomenta mulher, nós fizemos inúmeras reuniões com grupo de mulheres, falando da importância, e nós tratamos isso tanto com os técnicos do Incra, aí começamos a trabalhar realmente a questão de gênero, do empoderamento das mulheres para serem ativas no processo de desenvolvimento do seu lote."

Depoimentos de moradores do Assentamento (2022)

De fato, a atuação do Incra e da Codevasf tornou-se bastante importante no aspecto do empoderamento da mulher. Com o passar dos anos, muitas mulheres relatam que sentem-se mais livres para falar e atuar em seus trabalhos cotidianos, situação que não era possível nas gerações anteriores. Essa transformação possibilitou que a mulher se posicionasse no centro das decisões e ações. Observa-se que seu papel se tornou fundamental em relação a temas estruturais dentro das famílias, como: consumo e qualidade da água, produção e comercialização, direção das cooperativas e associações, educação dos filhos, provisão e preparação de alimentos, economia produtiva, saúde e bem-estar das famílias, cuidado do meio ambiente, entre outros.

O tema das cooperativas aparece como estrutural dentro da análise por similitude, já que se constitui no principal meio para a produção de alimentos e sua comercialização. Manifesta-se que atualmente existem diversas associações e cooperativas dentro do assentamento, sendo as mais representativas a Unituba e a Coopac, que possibilitam adicionar um valor agregado a determinados produtos.

> "Associação e cooperativas aqui são várias, porém, as mais importantes são a Unituba e a Coopac. A Unituba faz a parte de coordenar a fábrica de processamento da macaxeira, processa bolinho e vende nos mercados, e a Coopac mexe mais com a parte de produção para o Programa de Aquisição de Alimentos (PAA) e Programa Nacional de Alimentação Escolar (Pnae). Atualmente está parada, é tudo reduzido, o que fazia antes, hoje você vê quinze, vinte, já é muita coisa".

Depoimentos de moradores do Assentamento (2022)

Ressalta-se que o papel das cooperativas antigamente era muito mais importante, ficando hoje esquecidas e abandonadas. Esse fato demonstra uma limitada organização interna, bem como de coesão, impossibilitando equilibrar a justiça social com a prosperidade econômica e a sustentabilidade interna. Com isso, fica restrita a obtenção de resultados financeiros palpáveis, inibe-se o surgimento de interesses coletivos e abre-se a possibilidade de prevalecimento de aspirações individuais.

Em relação à Deso, a instituição é identificada como determinante no desenvolvimento regional e como gerador de bem-estar local, devido ao seu papel de distribuidor de água potável. No entanto, a instituição é considerada deficiente em relação ao abastecimento de água, uma vez que cobre apenas 20% do assentamento. Esse fato provoca uma série de impactos sobre a população, como a insegurança hídrica e o incremento de problemas sobre a saúde humana. Até o momento, diversas ações locais envolveram autoridades municipais para enfrentar essa situação, que, porém, não tiveram resultados concretos e deixaram a população à mercê do consumo de água para irrigação.

> "80% do assentamento não tem água tratada, é água de irrigação da Codevasf, e a Codevasf não tem obrigação de tratar a água para todo mundo. A empresa que trata a água dos assentados se chama Deso, ela é responsável pela água dos assentados, só que essa água nunca chegou. Aí quando chegou a encanação da Codevasf, a população fez um improviso, e aí todos utilizam a água não potável, porque a água potável a responsável é outra empresa".

Depoimentos de moradores do Assentamento (2022)

No que concerne à família enquanto instituição social básica e inicial, esta é responsável pela chamada socialização ou interação primária do indivíduo em sociedade através do ensino da língua, da transmissão de valores e do ensinamento das normas básicas de convívio social (Bauman, 1998; Stewart; Glynn, 1978; Vaitsman, 1994). No assentamento, observa-se que essa é a base da produção agroecológica. Segundo membros das agrovilas, algumas famílias vêm se preocupando cada vez mais com a produção agroecológica e sustentável, e, por sua vez, promovendo a articulação das bases locais com a finalidade de fomentar aspectos como a organização, produção camponesa sustentável, diminuir o impacto das mudanças climáticas sobre a produção e a população, entre outros. Assim também, observa-se inquietude para propor políticas públicas que ajudem a melhorar o panorama local em relação aos diversos temas apresentados até aqui.

Outro elemento importante sobre esse aspecto se observa pela preocupação das famílias para constituir unidades familiares produtivas. Nesse sentido, muitas delas vêm realizando atividades produtivas derivadas nos mesmos quintais das moradias, aproveitando o trabalho familiar, o espaço e os conhecimentos em agricultura de cada membro. Entre elas, podemos citar o esforço de mulheres empreendedoras que a partir das necessidades locais passaram a produzir bolos, sorvetes e picolés de frutas locais, derivados de leite, geleias, licores, polpas, entre outros. Produtos que hoje já formam parte da base da produção local e do ingresso familiar.

Como observou-se até aqui, a análise qualitativa dos dados trouxe importantes contribuições à pesquisa do projeto, nos permitindo mergulhar minuciosamente em alguns fatos a partir da percepção da população. Temas como a segurança hídrica (em função da qualidade do recurso) e processos de produção e de comercialização foram os que mais chamaram atenção. A importância do primeiro se dá pelo alto grau de vulnerabilidade dos moradores em relação à saúde, e o segundo, pelo déficit de investimentos para uma adequada venda dos produtos locais, aspecto que, por sua vez, é aproveitado pelos comercializadores externos.

O detalhamento dos fatos foi alcançado mediante o uso das técnicas e metodologias qualitativas, trabalhadas a partir de registros de percepções, crenças, representações, hábitos, atitudes e opiniões. Como mencionado por alguns autores anteriormente, esses dados foram úteis para entender o contexto dos fenômenos, nesse caso, alguns fatores tornaram-se evidentes, como a produção, a salinização do solo e a comercialização por atravessadores.

Em suma, a análise dos dados qualitativos, bem como a observação participante, por meio das ferramentas e softwares usados, permitiu compreender profundamente alguns temas e problemas latentes dentro do assentamento.

Nesse sentido, advoga-se que o uso dessa metodologia dentro das ciências ambientais pode ser de bastante utilidade, pois possibilita adentrar na subjetividade dos fenômenos. Problemáticas ambientais precisam ser avaliadas cada vez mais a partir de um olhar social, analisando questões decorrentes sobre a produção, população, questões de gênero, questões geracionais, saúde, discriminação, injustiça social e ambiental, entre outras.

Muitos desses temas não foram tocados neste trabalho devido ao escopo da pesquisa, mas consideram-se de suma importância. Portanto, acredita-se que abordá-los em estudos futuros pode trazer análises e debates relevantes para a sociedade e a ciência.

5 CONCLUSÕES

Os resultados alcançados demonstram que o uso prioritário de métodos de avaliação de dados com base em uma abordagem qualitativa tende a consolidar análises mais profundas e detalhadas. Em muitos casos, estudos quantitativos no âmbito das ciências ambientais apresentam limitações

na mensuração de aspectos subjetivos, fator que restringe a compreensão dos fenômenos e pode introduzir vieses nos resultados.

Observa-se que a pesquisa qualitativa possibilita a análise de aspectos subjetivos e amplia sua representatividade, especialmente em função da proximidade entre pesquisador e participantes, bem como do caráter descritivo e narrativo dos dados coletados. A perspectiva crítica adotada neste estudo em relação à aplicação de técnicas quantitativas nas ciências ambientais direciona-se ao questionamento das interpretações utilizadas para inferir efeitos de natureza diversa sobre as características sociais de determinadas populações. Nesse sentido, análises mais aprofundadas, que incorporem a participação de atores sociais, tornam-se fundamentais para a compreensão de tais aspectos.

Dessa forma, evidencia-se a necessidade de ampliar os espaços de diálogo, interação e coleta de dados qualitativos — como entrevistas e observações —, o que pode contribuir para a compreensão mais precisa dos impactos reais de projetos de grande porte sobre as populações locais.

Portanto, torna-se fundamental expandir as estratégias de avaliação de impactos, bem como diversificar as técnicas metodológicas adotadas, avançando na implementação de abordagens mais robustas e consistentes. Os achados deste estudo indicam que a pesquisa qualitativa promove uma valorização significativa dos fenômenos e processos sociais, ao considerar motivações, crenças, valores e representações presentes nas relações sociais.

Os resultados discutidos ao longo deste estudo evidenciam que a adoção de técnicas metodológicas qualitativas em pesquisas socioambientais amplia significativamente a capacidade analítica e interpretativa, sobretudo diante da complexidade que caracteriza a interface sociedade-natureza. Ao incorporar dimensões simbólicas, culturais e subjetivas — frequentemente invisibilizadas por abordagens exclusivamente quantitativas —, a metodologia qualitativa permite compreender, com maior profundidade, os processos sociais que condicionam a dinâmica ambiental.

A imersão contextual do pesquisador, a valorização dos saberes locais e a interação direta com os sujeitos investigados fortalecem a produção de diagnósticos mais consistentes e avaliações mais fidedignas de impactos socioambientais. Ademais, tais abordagens contribuem para a formulação de estratégias de gestão ambiental mais sensíveis às realidades territoriais e às especificidades socioculturais dos grupos envolvidos.

Conclui-se, portanto, que a integração sistemática de técnicas qualitativas nos estudos socioambientais não apenas qualifica os resultados obtidos, mas também favorece análises mais integradas, contextualizadas e socialmente legitimadas, configurando-se como um caminho metodológico pertinente para enfrentar os desafios contemporâneos da sustentabilidade.

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Reviving the use of plant dyes for sisal (*Agave sisalana*) fibres in a Brazilian artisan community

*Revitalizando o uso tradicional de plantas corantes de fibras de sisal (*Agave sisalana*) em uma comunidade artesã brasileira*

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ABSTRACT

Sisal fibre handicrafts, common in tropical regions, traditionally relied on plant-based dyes. However, these have largely been replaced by synthetic dyes, contributing to the loss of traditional knowledge. This study aimed to document plant species historically used to dye sisal and assess the potential for reintroducing natural dyes in a Brazilian artisan community. An ethnobotanical study was conducted through interviews and participatory dyeing workshops with 154 artisans selected via the snowball sampling method. Although artisans relied exclusively on synthetic dyes, they recalled 33 plant species that had formerly been used for dyeing. The trials expanded the range of natural dye options for sisal and renewed artisan interest in producing market-aligned colours. The adoption of eco-friendly, non-toxic, low-cost natural dyes that add value to their crafts also strengthened community engagement. Efforts like this, especially in regions rich in plant and cultural diversity, help preserve traditional practices and support more sustainable artisanal production.

Keywords: Traditional knowledge. Natural dyes. Ethnobotany. Dyeing plants. Eco-friendly products.

RESUMO

O artesanato com fibras de sisal, comum em regiões tropicais, tradicionalmente envolve o uso de plantas corantes. Porém, elas foram substituídas pelo uso de corantes sintéticos, levando ao declínio de conhecimentos tradicionais. Este estudo objetivou documentar plantas historicamente usadas para corar sisal e verificar o potencial de reintroduzir essa prática em uma comunidade artesã brasileira. Estudos etnobotânicos, utilizando entrevistas e oficinas participativas de tingimento, com 154 artesãos, por meio de seleção por bola de neve, foram conduzidos. Apesar de utilizarem somente

corantes sintéticos, foram mencionadas 33 espécies tintoriais. Os resultados das oficinas de tingimento expandiram o repertório de cores e criaram tonalidades alinhadas às demandas do mercado. A adoção de corantes naturais, por serem de baixo custo, livres de substâncias tóxicas e capazes de agregar valor aos produtos, também aumentou o interesse da comunidade. Estudos dessa natureza, especialmente em regiões com rica biodiversidade vegetal e cultural, ajudam na conservação de práticas tradicionais e promovem a produção artesanal sustentável.

Palavras-chave: *Conhecimento tradicional. Corantes naturais. Etnobotânica. Plantas tintoriais. Produtos ecossustentáveis.*

1 INTRODUCTION

The textile industry is widespread worldwide, with cotton being the most widely used textile fibre (Kant, 2012). Other natural plant-based fibres used in clothing fabrics include linen and hemp, while sisal, pita, jute, and ramie are employed in the geotextile, rope, sack, and artefact industries (Nayak *et al.*, 2011; Simpson; Ogorzali, 2001).

The processing of these fibres, especially the chemical dyeing process, generates waste that can lead to environmental contamination and often contains heavy metals and other substances toxic to humans and the environment (Kant, 2012). In addition to dyes, mordants used in the dyeing process to fix colours can also be similarly toxic. Consequently, the synthetic chemicals used in fibre dyeing have caused significant environmental impacts (Kant, 2012). Thus, treating effluents from these industries in compliance with environmental regulations constitutes a significant challenge in the textile industry (Costa *et al.*, 2020; Kant, 2012).

Natural dyes can also ensure adequate colour fixation and may reduce production costs by using locally available plant resources (Costa *et al.*, 2020). In this context, natural dyes, such as those derived from plants, can constitute a sustainable alternative for this processing (Costa *et al.*, 2020). Alongside the use of natural dyes, the use of mordants, which are responsible for the quality and fixation of the colour, must also be managed with care to achieve the goal of eco-sustainable fibre production (Prabhu; Bhute, 2012).

Since ancient times, humans have used dyes extracted from plants, minerals, and some animals to colour fabrics (Kant, 2012; Simpson; Ogorzali, 2001). However, with the advent of chemical dyes, natural dyes were largely replaced in both industrial and artisanal dyeing processes (Kant, 2012; Ramadhanti *et al.*, 2019). This shift occurred mainly due to their lower cost, ease of use, and greater colour stability (Kant, 2012). Nevertheless, natural dyes can also provide effective colour fixation while offering environmental benefits and reducing production costs through the use of locally available dye plants (Che; Yang, 2022).

It is estimated that 100 million tons of dyes per year would be needed to meet the global demand for coloured fibres, making the use of plant-based dyes in large-scale industrial processes challenging (Ramadhanti *et al.*, 2019). However, in artisanal production processes, the use of natural dyes is viable, eco-sustainable and can add value to the final product. It provides originality and a distinctive design, meeting the growing demand for eco-friendly products (Che; Yang, 2022; Costa *et al.*, 2020). Growing consumer awareness of environmental issues has further increased the demand for such products (Costa *et al.*, 2020; Ramadhanti *et al.*, 2019).

Several kinds of natural dyes have been reported, whose specificity is related to the chemical composition of textile fibres (Che; Yang, 2022). Animal-derived fibres, such as wool and silk, are primarily protein-based and therefore require specific dyes. In contrast, plant-derived fibres are composed mainly of cellulose and lignin, with proportions varying by species (Simpson; Ogorzali, 2001). Thus, some dyes

are more suitable for primarily cellulosic cotton fibres, while others perform better on more lignified fibres such as sisal (Chand; Rohatgi, 1994). Most studies on natural dyes have focused on cotton and wool fibres, widely used in clothing fabrics (Che; Yang, 2022). Few studies, however, have investigated natural dyes for sisal fibres.

Sisal fibres (*Agave sisalana* Perrine ex Engelm., Asparagaceae) are classified as hard fibres, which limits their use to textiles not intended for clothing (Simpson; Ogorzali, 2001). However, the use of sisal fibres for crafting artisanal items has been reported in various parts of the world, especially in tropical regions (Gooroochurn; Socheta, 2016; Kumar; Allamraju, 2019). The production of these artefacts provides a source of employment and income, fostering women's empowerment and strengthening rural communities (Gooroochurn; Socheta, 2016). In Brazil, the crafting of rugs and other decorative artefacts from sisal is part of the cultural heritage of some communities. In the historic city of Mariana, in the state of Minas Gerais, the use of these fibres in artisanal work dates back over three centuries (Gonçalves, 2023). According to this author, traditional methods of fibre extraction and natural dyeing were originally used in the region but were gradually replaced over time. By the late 20th century, processed fibres began to be imported from the country´s northeastern region, and dyeing shifted to synthetic dyes, which can contaminate water resources with toxic effluents. The dyed fibres are used to create various artefacts, mainly rugs, as well as other artisanal items such as bags and wall hangings.

Sustainable practices must integrate environmental, economic, and social dimensions while prioritising social justice and the intrinsic value of ecosystems. Building a truly equitable green economy requires the sovereignty and active leadership of local communities who hold traditional ecological knowledge for biodiversity management and a holistic worldview that recognises the interdependence between humans and nature (Bina, 2013). Ethnobotanical studies play an important role in documenting and valuing traditional plant knowledge, including dye plants used in artisanal textile production. Artisan communities are key actors in socio-biodiversity value chains, as their activities rely on local biological resources and specialised knowledge related to the selection and processing of plant materials (Balik; Cox, 2020; Luczaj, 2023; Ramadhanti *et al.*, 2019). Crafts also embody community history, symbolism, and spirituality, reinforcing social ties through the intergenerational transmission of knowledge (Simpson; Ogorzali, 2001). However, traditional knowledge in artisan communities faces increasing pressures from modernisation, limited institutional support, and disruptions to knowledge transmission as younger generations adopt more globalised lifestyles (Ghose; Ali, 2023). Despite their cultural and economic importance, dye plants in artisanal production systems—particularly in fibre-based crafts and socio-biodiversity value chains—remain understudied. Research on dye plants and artisanal fibres, therefore, contributes to understanding how traditional knowledge sustains cultural identity, local economies, and more sustainable socio-biodiversity value chains (Ghose; Ali, 2023).

Brazil is the country with the greatest plant biodiversity in the world and also encompasses a rich traditional knowledge of plant use, including dye plants (Forzza *et al.*, 2012). Thus, to contribute to the sustainability of artisanal production and the biocultural conservation of a Brazilian artisan community, as well as to expand knowledge about natural dyes for dyeing sisal fibres, this study aimed to document plant species historically used as dye sources and to assess the potential for reintroducing natural dyeing practices within this community. We hypothesised that community members still possessed knowledge of using natural dyes to dye sisal fibres. Additionally, we assumed that plant species were available in the region for this purpose, thereby expanding the list of known dyeing taxa. Furthermore, we believed that conducting this action research in a participatory manner with the community would revitalise interest in using natural dyes for fibre dyeing, contributing to the sustainable development of the region.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The study was conducted in the district of Cachoeira do Brumado, municipality of Mariana, Minas Gerais, Brazil (Figure 1). Mariana is recognised as a national historical heritage site (Law No. 7,713 of July 6th, 1945) for its historical and cultural significance and its Baroque architectural style. The region's main economic activity is iron mining, followed by tourism (IBGE, 2010).

Mild temperatures, dry winters, and rainy summers characterise the region's climate. The relief is undulating, with altitudes ranging from 451 to 2,065 meters. The vegetation fits within the Atlantic Forest and *Cerrado* domains (IBGE, 2010). Cachoeira do Brumado is located at 21 Km from the municipal seat, with a population of 1,151 women and 1,110 men living in 824 households (IBGE, 2010). The population is multi-ethnic, resulting from the intermixing of indigenous peoples with African and European groups who settled in the region since the colonial period, in the early 17th century (Costa *et al.*, 2021).

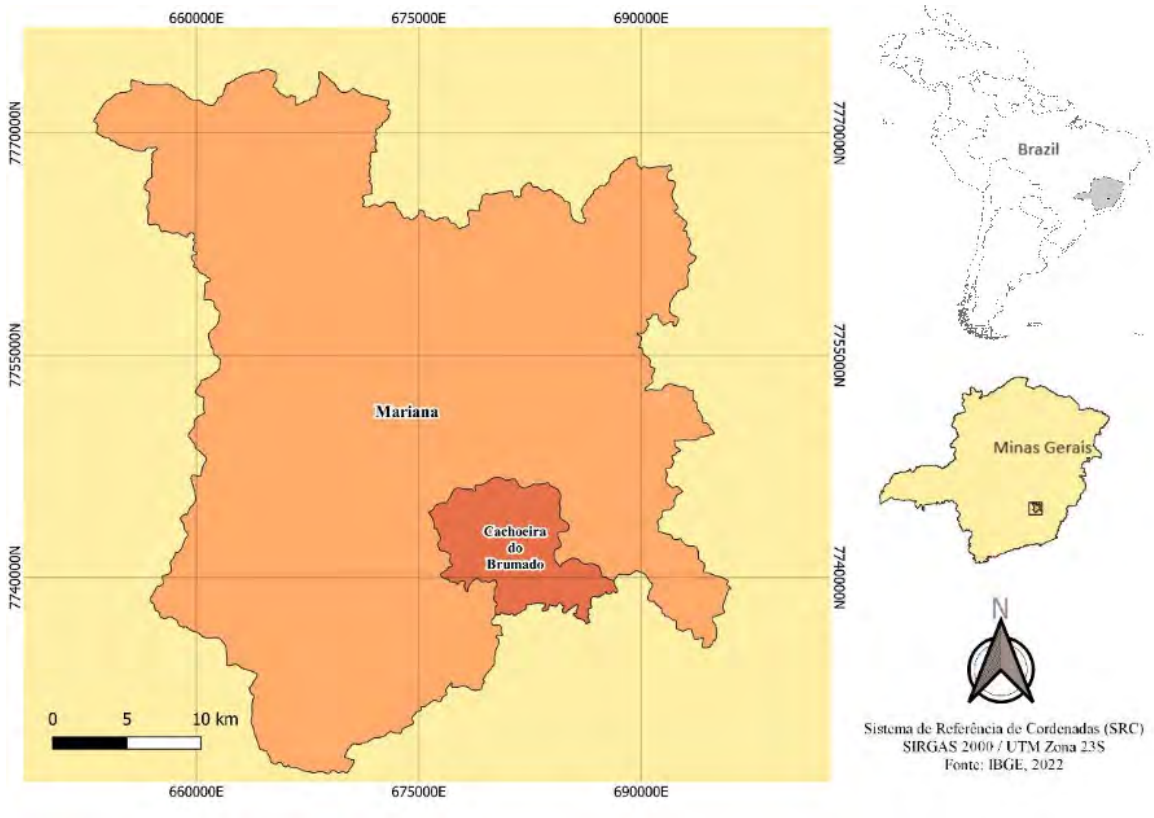


Figure 1 – Location of the district of Cachoeira do Brumado, Mariana, Minas Gerais, Brazil.

Source: Own elaboration.

The district of Cachoeira do Brumado is renowned for its craftsmanship, particularly sisal tapestry and soapstone cookware, which are important sources of local income (Gonçalves, 2023). It was estimated that there were around 260 sisal artisans in the district, with 60 of them organised since 1999 into an association, the AACB - Association of Artisans and Home Producers of Cachoeira do Brumado (IBGE, 2010). Most of the female population is involved in sisal tapestry. Although men also participate in this activity, they primarily work in the production of soapstone artefacts or in mining companies. The artisanal work relationships are familial, with artefact production taking place in artisans' own homes. In addition to rugs, other handcrafted products such as bags, curtains, and wall hangings are

also produced on a smaller scale. The fibres used in the tapestry primarily come from sisal (*Agave sisalana*) leaves, obtained from plantations of Bahia, northeastern Brazil. To a lesser extent, pita fibre (*Furcraea foetida* (L.) Haw.), cultivated and processed within the district, is also used (Gonçalves, 2023).

2.2 ETHNOBOTANICAL STUDY

The ethical procedures for this ethnobotanical study adhered to internationally recognised principles of ethnobiological research. The study adhered to the guidelines of the International Society of Ethnobiology, particularly the International Society of Ethnobiology Code of Ethics, which emphasises prior explanation of research objectives, voluntary participation, respect for local knowledge, and informed consent (http://ethnobiology.net/code-of-ethics/). These procedures were also consistent with Brazilian legislation in force in 2002, when the data were collected.

The project was first presented to the community to explain its objectives and invite artisans to participate in the research. After obtaining participants' consent, all informants aged 18 or older who agreed to participate were interviewed. The interviews were carried out from June to September 2002. The participants were selected using the snowball sampling technique (Albuquerque *et al.*, 2014a), and the initial participants were identified at the meeting where the project was presented to the community. Semi-structured interviews were conducted (Albuquerque *et al.*, 2014b) to assess the traditional knowledge about the use of natural dyes and other aspects of fibre craftsmanship. Interviews were conducted using open-ended questions, allowing them to respond according to their own logic and concepts. A basic interview guide was used, including questions about the historical background of sisal tapestry craftsmanship in Cachoeira do Brumado, the sources and processing of raw materials, and aspects of dyeing and weaving. Regarding known plant species for dyeing sisal fibres, inquiries were made about the species used, the plant parts employed, methods of dye preparation, dyeing processes, and the colours achieved.

In addition to the interviews, guided tours were conducted (Albuquerque *et al.*, 2014b) to collect, herbarise, and taxonomically identify plant species mentioned for their dyeing properties. These tours also aimed to enrich the repertoire of recognised species with this potential.

The herbarium specimens were deposited at the Professor José Badini Herbarium (OUPR) at the Federal University of Ouro Preto. Commercial species and those lacking reproductive structures were not herborised. Species identification was conducted through morphological studies and by comparison with materials previously deposited in herbaria. Species nomenclature was verified using the Flora e Funga do Brazil (2026) and the World Flora Online (WFO, 2022) databases.

2.3 TRIALS WITH PLANT DYES

The trials were carried out in participatory workshops, together with community members. Trials were conducted to dye sisal fibres using 21 plant species cited in the ethnobotanical study, whose parts were available. These parts were collected and processed to extract pigments following local knowledge recorded in the survey. The dyeing procedures were based on community practices, with adaptations proposed by Ferreira (1998).

Following traditional dyeing procedures, the dyes were extracted by maceration for 72 hours, using a ratio of 100g of dyeing plant parts to 800mL of water and 2mL of 25% ammonium hydroxide (commercial ammonia). Ammonia replaced the previously used cattle urine in the processes (Ferreira, 1998). After maceration, the mixture was decocted for 1 hour. Subsequently, once it reached room temperature, the liquid was filtered to remove the dyeing plant parts. For dyeing the fibres, they were added to the obtained liquid (in an approximate 1:4 (v/v) ratio) and decocted again for 1 hour. After this process,

a mordant was applied to stabilise and enhance the effectiveness of the dyeing, and the mixture was decocted once more for 1 hour. The mordants evaluated were: 1) Iron acetate, obtained by macerating and manually stirring daily for three days 20g of steel wool in a solution containing 200mL of water, 30g of wheat flour, and 20mL of vinegar, which was then filtered as suggested by Ferreira (1998). The ratio used was 20mL of mordant per litre of dye. 2) Salt (sodium chloride), in the proportion of 20g per 10L of dye solution. After the solution reached room temperature, the fibres were removed and placed to dry on clotheslines under the sun. The results of these trials were presented and discussed in a subsequent workshop.

3 RESULTS

A total of 154 artisans were interviewed (127 women and 27 men). At the time of the study, their ages ranged from 18 to 72 years; most were younger than 20. This ethnobotanical study allowed us to document aspects of the craftsmanship involving sisal and pita fibres, identify available dye plant species, and describe traditional dyeing processes with natural dyes, as detailed below.

3.1 ASPECTS OF CRAFTSMANSHIP USING FIBRES IN THE CACHOEIRA DO BRUMADO DISTRICT

According to the interviewees, plant-fibre weaving in the region began in the 18th century, with fibres extracted from *Furcraea foetida*, locally known as pita. The earliest artefacts were tools used for gold panning in watercourses. Later, artisans began weaving saddle pads, placed between the backs of pack animals and the saddles of muleteers who connected regional economic centres. The art of weaving diversified over generations, including new products such as rugs, curtains, bags, and decorative objects. These artefacts are crafted at home, employing family labour.

Although the first rugs were adorned with hues from plant-based dyes, by the end of the 20th century, all artisans had adopted industrial chemical dyes. The residues from this process were discarded into the soil or watercourses. To dye the rugs, the artisans dissolved 30g of synthetic aniline in 1 litre of boiling water. This solution was then diluted in a container with water, in a proportion that varied according to the intended shade. The fibres were submerged in the liquid, left to soak for about 3 hours, rinsed and hung to dry in the sun. A 30g bottle of synthetic aniline was priced at approximately R$10.00 (~US$ 2.00) and was sufficient to dye about 3 kg of sisal fibres. The fibres used for dyeing were usually the darker parts of the lot acquired. The dyed fibres were used to create geometric patterns that decorate the artefacts, with the base weave made of undyed sisal fibre (Figure 2). The colours obtained with synthetic aniline result in vivid and striking hues.

Most artisans reported that the use of natural dyes was in decline due to the ease of processing and acquiring synthetic dyes, as well as a lack of knowledge and familiarity with the process of dyeing with plant-based dyes. Approximately 40% of the interviewees reported some knowledge about natural dyes, mainly acquired through parental transmission. According to their accounts, this knowledge still existed, especially among the older residents of the district. Despite their then-current reliance on synthetic dyes, artisans emphasised that the cost of these materials strained their production budgets. Additionally, they had been unaware of the toxicity of chemical dyes to both humans and the environment, which raised their concern when these risks were presented in this study. As a result, they expressed interest in reviving the knowledge of plant-based dyes and dyeing techniques previously used in the region.



Figure 2 – Aspects of sisal craftsmanship in the district of Cachoeira do Brumado, Mariana.

Source: The authors

To extract dyes from plants, it was reported that the dyeing parts were macerated in water with an ammoniacal compound. Traditionally, this compound came from animal urine (mainly cattle), but it was later replaced by commercial ammonium hydroxide solution. After at least 12 hours of maceration, which varies depending on the species used, the material was boiled for 1 hour and then strained. The fibres were then immersed in the dye solution, ensuring complete coverage. To stabilise the colours, salt (sodium chloride) and iron acetate were used as mordants. The iron acetate was obtained by macerating rusty nails (approximately 20g) for at least three days in a solution of water (500mL), vinegar (15mL, 1 tablespoon), and wheat or cassava flour (30g or 2 tablespoons). This solution was strained and added after the fibres were boiled with the dye material, at an approximate ratio of 1:50 (v/v), followed by another hour of boiling. The mordant solution could be refreshed by adding more water, vinegar, and flour to the container with the rusted nails, using the same proportions. Other iron sources, such as steel wool or metal fragments, could replace nails. Salt, as a mordant, was also added to the boiling fibres at a ratio of 20g (1 tablespoon) per 10 litres of the dye solution.

3.2 THE DYEING SPECIES

A total of 33 species with dyeing properties were reported, belonging to 24 families. The Fabaceae family had the highest number of dyeing species (Table 1).

Table 1 – Plant species and respective families, local (Portuguese) and English common names, and parts used in the dyeing of sisal fibres reported by artisans from Cachoeira do Brumado, Mariana, MG, Brazil. Voucher=Herbarium OUPR registration number.

Family / Species	Local common names	English common names	Used parts	Voucher
Adoxaceae *Sambucus australis* Cham. & Schltdl.	Sabugueiro	Elder	Aerial parts	23244
Amaranthaceae *Beta vulgaris L.* *	Beterraba	Sugar beet	Roots	
Amaryllidaceae *Allium cepa* L.	Cebola	Onion	Bulb cataphylls	
Anacardiaceae *Schinus terebinthifolia* Raddi	Aroeira	Brazilian peppertree	Aerial parts	15590
Arthoniaceae *Herpothallon rubrocinctum* (Ehrenb.) Aptroot & Lücking	Mancha-vermelha		Whole plant	
Asteraceae *Baccharis crispa* Spreng.	Carqueja		Whole plant	22410
Bidens pilosa L.	Picão		Whole plant	22356
Bignoniaceae *Handroanthus albus* (Cham.) Mattos. *	Ipê-amarelo		Stem bark	
Pyrostegia venusta (Ker Gawl.) Miers	Cipó-de-são-joão		Flowers	22113
Bixaceae *Bixa orellana* L.	Urucum	Annatto	Seeds	22408
Commelinaceae *Tradescantia pallida* (Rose) D.R.Hunt	Trapoeraba-roxa	Purple heart	Aerial parts	22116
Convolvulaceae *Ipomoea batatas* (L.) Lam. *	Batata-doce	Sweet potato	Leaves	
Fabaceae *Andira anthelmia* (Vell.) Benth. *	Angelim		Stem bark	
Indigofera suffruticosa Mill.	Anileira	Indigo	Aerial parts	15189
Paubrasilia echinata (Lam.) Gagnon, H.C.Lima & G.P.Lewis	Pau-brasil		Stem sawdust	
Piptadenia gonoacantha (Mart.) J.F.Macbr. *	Angico		Stem bark	16326
Senna occidentalis (L.) Link. *	Fedegoso	Coffee senna	Aerial parts	
Lauraceae *Persea americana* Mill.	Abacate	Avocado	Seeds	
Loranthaceae *Struthanthus podopterus* (Cham. & Schltdl.) G.Don	Erva-de-passarinho	Mistletoe	Whole plant	29913
Marantaceae *Maranta arundinacea* L. *	Araruta	Arrowroot	Rhizomes	
Melastomataceae *Clidemia urceolata* DC.*	Olho-de-pombo		Leaves	22408
Pleroma estrellense (Raddi) P.J.F.Guim. & Michelang.	Quaresmeira		Leaves	22409
Meliaceae *Cedrela fissilis* Vell.	Cedro	Acajou wood	Stem sawdust	
Moraceae *Ficus carica* L.	Figo	Fig	Leaves	

Family / Species	Local common names	English common names	Used parts	Voucher
Musaceae *Musa paradisiaca* L.	Banana	Banana	Pseudo stem sap	
Myrtaceae *Myrcia guianensis* (Aubl.) DC.*	Caá		Stem bark	15591
Plinia peruviana (Poir.) Govaerts	Jabuticaba		Pericarp	
Psidium guajava L. *	Goiaba	Guava	Leaves	
Onagraceae *Fuchsia regia* (Vell.) Munz	Brinco-de-princesa	Fuchsia	Flowers	15195
Pinaceae *Pinus* sp.*	Pinus	Pine	Stem sawdust	
Poaceae *Andropogon bicornis* L.	Capim-rabo-de-burro		Aerial parts	16214
Rubiaceae *Coffea arabica* L. *	Café	Coffee	Seeds	
Zingiberaceae *Curcuma longa* L.	Açafrão	Turmeric	Rhizomes	

** Species not tested in the dyeing trial*

Source: Organized by the authors

Some dyeing materials came from inedible parts of cultivated fruit species, such as avocado (seeds), fig (leaves), jabuticaba (fruit pericarp), and banana (pseudo stems), or from the outer cataphylls of onion bulbs. Others were derived from species often cultivated for different purposes, such as turmeric (*Curcuma longa*) and annatto (*Bixa orellana*), whose rhizomes and seeds, respectively, were also used as food colourants. Other sources included elder (*Sambucus australis*), used for medicinal purposes, and ornamental species such as fuchsia (*Fuchsia regia*) and purple heart (*Tradescantia pallida*).

The species picão (*Bidens pilosa*), anileira (*Indigofera suffruticosa*), erva-de-passarinho (*Struthanthus podopterus*), and carqueja (*Baccharis crispa*) were spontaneous plants occurring abundantly in anthropogenic landscapes. Some native forest species were also reported in this survey, such as angelim (*Andira anthelmia*), angico (*Piptadenia gonoacantha*), cedro (*Cedrela fissilis*), caá (*Myrcia guianensis*), olho-de-pombo (*Clidemia urceolata*), and quaresmeira (*Pleroma estrellense*). The vine cipó-de-são-joão (*Pyrostegia venusta*) and aroeira (*Schinus terebinthifolia*) were abundant in open areas, forest edges, and anthropised zones. Pulverised sawmill residues (sawdust) from various species were also mentioned as dyeing materials, such as pau-brasil (*Paubrasilia echinata*), angelim (*Andira anthelmia*), cedro (*Cedrela fissilis*), and *Pinus* sp. (Table 1).

About 40% of the interviewees reported knowing about natural dyes, but most of them mentioned only one species. The average number of dye species known per artisan was 1.6, and none of them cited more than four dyeing species. The most cited species was Curcuma longa, followed by Bixa orellana.

3.3 DYEING TRIALS

Extraction and dyeing tests of sisal fibres were carried out with 21 species out of the 33 species mentioned in the ethnobotanical survey (Table 1). The species that were not tested either did not have sufficient material available for testing, or their extraction would impact their populations. The parts of the species used, as well as the pigment extraction and dyeing procedures for sisal fibres described in the ethnobotanical survey (Table 1), were utilised.

A wide variety of colours and shades was obtained from the tested dye plants in the local flora (Figure 3).

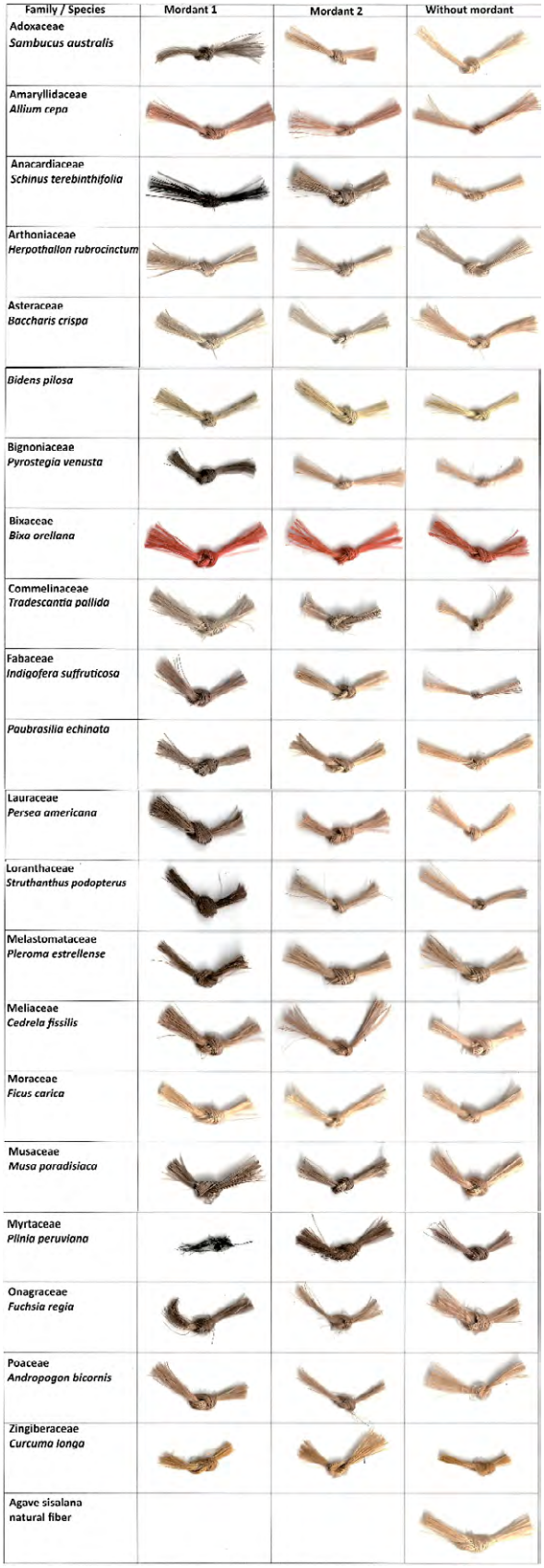


Figure 3 – Original and dyed sisal (*Agave sisalana*) fibres using plant-based dyes and different mordants in the artisan community of Cachoeira do Brumado, Mariana, Minas Gerais, Brazil. (Mordant 1: salt, Mordant 2: Iron acetate).

Source: The authors

4 DISCUSSION

Although artisans in Cachoeira do Brumado no longer used natural dyes to dye sisal fibres at the time, the community still held traditional knowledge of this practice. About 40% of the interviewees reported some knowledge of natural dyes; however, the richness of recognised dyeing species was low, with most artisans citing only one species (average=1.6 species/artisan) and no more than four. Similar values for known dyeing species richness have been reported in Sierra Leone (MacFoy, 2004), Zimbabwe (Ganduri *et al.*, 2011), and India (Mahanta; Tiwari, 2005), with even lower values found in traditional communities in regions such as China (Liu *et al.*, 2014), India (Kala, 2009), Timor (Sabuna; Nomleni, 2020), Indonesia (Sabuna *et al.*, 2018; Seran *et al.*, 2022), as well as in other Brazilian regions (Sá *et al.*, 2007).

Although the art of fibre dyeing with natural dyes is an ancestral practice in the region, it declined with the introduction of synthetic dyes in the mid-19th century, as occurred in many parts of the world (Bechtold *et al.*, 2003; Kant, 2012; Liu *et al.*, 2014). The shift was mainly attributed to the ease of using synthetic dyes and the subsequent loss of practical knowledge required for natural dyeing. At the time of the survey, most sisal artisans were younger than 20 years old, and their knowledge was often limited to the names of a few species transmitted by older relatives, signalling an ongoing process of cultural erosion. Given that traditional knowledge is typically transmitted orally, it is highly vulnerable to disappearance (Toledo; Barrera-Bassols, 2015). Ethnobotanical studies, therefore, play an important role in documenting and reviving this knowledge, particularly in traditional communities that are its main custodians (Hart; Cox, 2000; Liu *et al.*, 2014). However, the revival of this practice also depends on the community's recognition of its value. In this action-research, artisans acknowledged the cultural, environmental, and economic benefits of dye plants, as discussed below.

Indeed, synthetic dyes provide a wide range of stable and vibrant colours, along with reproducibility and ease of processing. However, their toxic nature has become a critical concern due to the harmful effects on several life forms, including humans. The presence of toxic substances such as sulphur, naphthol, nitrates, formaldehyde, and heavy metals like chromium, copper, arsenic, lead, cadmium, mercury, nickel, and cobalt can affect artisans' health during handling. Additionally, these dyes produce highly toxic effluents that could contaminate soil and water (Bechtold *et al.*, 2003; Che; Yang, 2022; Kant, 2012). This information, shared during the discussions throughout the development of this work, was previously unknown to the artisans and helped increase their interest in using natural dyes. Thus, the fact that natural dyes are biodegradable and therefore more environmentally sustainable has further attracted the community's attention. Additionally, the economic benefits generated by using natural dyes also contributed to the renewed interest in this technique. Firstly, the process required a few inputs to obtain a wide variety of dyeing materials, which were available locally. These materials included by-products from plants used for other purposes, as well as species that were abundant in the local flora. In addition, the potential for natural dyes to add value to local craftsmanship and open new market opportunities for eco-friendly products (Che; Yang, 2022) also attracted the artisans' attention.

An important aspect observed, as noted by the artisans themselves, was that unlike the vivid colours produced by synthetic dyes, natural dyes produced pastel tones. This characteristic provides a better design aligned with contemporary market trends (Becker, 2016), adding value to the products. For example, plant-based dyes from erva-de-passarinho, carqueja, picão, capim-rabo-de-burro, fig, avocado, and onion produced softer shades, which match prevailing design preferences in the sisal craft market. The adoption of synthetic dyes in Andean communities in Peru (Mayolo, 1989) also caused profound changes in the original designs of artefacts, with recent designs prioritising vivid colours. This phenomenon has been observed globally in various other textile products (Che; Yang, 2022; Mayolo, 1989). In addition to pastel shades, the use of plant-based dyes enabled the production of black dye, which was in demand in the market and had not yet been achieved with synthetic anilines on sisal fibres. This colouration was obtained from the use of aroeira leaves (*Schinus terebinthifolia*), a native and abundant species in the region, as well as from the pericarp of jabuticaba (*Plinia peruviana*), a

native species widely cultivated in home gardens. Another interesting observation by the artisans was that fibres processed with natural dyes became softer, making weaving easier, and were pleasantly scented with plant extracts. These extracts, in addition to imparting fragrance to the fibres, are also recognised as antimicrobial agents, providing greater durability to fabrics (Che; Yang, 2022).

Despite the growing interest in natural dyes and sustainable materials (Che; Yang, 2022), studies addressing plant-based dyes for sisal fibres remain scarce in the scientific literature. Most available research has focused on textile fibres such as cotton, wool, and silk, which are primarily used in the clothing industry. In contrast, investigations into hard fibres used in artisanal production remain limited (Che; Yang, 2022). This highlights an important gap in both ethnobotanical research and studies related to socio-biodiversity value chains. In this context, documenting traditional knowledge and evaluating the potential of locally available dye plants for use with sisal fibres contribute to expanding the academic discussion on sustainable artisanal production and the valorisation of biocultural resources.

Sisal craftsmanship is more prevalent in tropical regions of the world, which have higher plant biodiversity, and consequently, a greater number of potentially dyeing species (Das; Kalita, 2016). Moreover, megadiverse countries often have a rich traditional ecological knowledge associated with the use of natural resources (Toledo; Barrera-Bassols, 2015). The richness of traditional ecological knowledge in the studied region is supported by various ethnobotanical studies (Costa *et al.*, 2021; Messias *et al.*, 2015; Prado *et al.*, 2021; Urriago-Ospina *et al.*, 2020). However, none of these studies addressed dye plants. Dye plants have an ancestral use in the region, where indigenous peoples originally used pigments for body painting and artefact dyeing (Sá *et al.*, 2007). Additionally, various dye pigments were used over three centuries ago in the painting of numerous Baroque sacred artworks (Parma *et al.*, 2023) found in the municipality of Mariana and the nearby city of Ouro Preto, both recognised as national and world heritage sites, respectively.

In a study conducted in Mauritius (Gooroochurn; Socheta, 2016), around 12 dye plant species for sisal fibres were identified, including turmeric, coffee, and onion skins, which were also mentioned in the present study. Studies in Brazil (Ferreira, 1998; Sá *et al.*, 2007) and across Latin America (Caparrós, 1995; Mayolo, 1989) report a vast diversity of dye plants for cotton and wool fibres. Some of the cited species overlap with those identified in the present work. Among these common species is turmeric (*Curcuma longa*), an Asian plant cultivated worldwide and introduced to Brazil during the colonial period. Another species common across various dye plant surveys is annatto (*Bixa orellana*), known locally as urucum, a native of South and Central America (Flora e Funga do Brazil, 2026), which was one of the plants taken to the old continent at the beginning of the colonisation of the Americas (Donkin, 1974). Several species of *Indigofera* are also reported as dyes for various fibres, especially cotton, including *I. suffruticosa*, mentioned in this survey (Das; Kalita, 2016; MacFoy, 2004; Mahanta; Tiwari, 2005). In sisal fibres, the usual blue colour produced in cotton fabrics by this species was not obtained (Ferreira, 1998; Simpson; Ogorzali, 2001). However, the pigment extraction and dyeing process used, following locally employed methods, differs from those reported for obtaining blue colouration in cotton and wool fibres, which involve fermentation processes (Simpson; Ogorzali, 2001).

Even though some chemical inputs, such as ammonia used in the extraction processes of natural dyes, need to be purchased by the artisans, adopting the use of natural dyes would significantly reduce processing costs. The expense for dyeing 1 kg of fibre was estimated at approximately R$ 0.35 (~ US$ 0.05), over 60 times lower than the cost of synthetic aniline. Ammonium hydroxide is known to enhance pigment extraction from plants (Dan *et al.*, 2024), as many pigments are not water-soluble. However, careful handling is required to avoid health risks, particularly from toxic gas inhalation. Training workshops are therefore essential to ensure safe practices, including proper handling of substances, the use of protective equipment, and adequate working conditions.

Mastering natural dyeing techniques is a process that requires practice and precision to achieve the desired colour fixation and tone. Colour shades vary according to the adopted procedures and the

products used for pigment extraction and fixation (Ferreira, 1998). Mordants play an important role in this process by promoting the bonding of pigments to cellulosic fibres, which generally have low affinity for natural dyes. However, mordants can alter the pH of the dye solution, often changing the resulting shade (Ferreira, 1998; Prabhu; Buthe, 2012). Thus, different mordants may produce different colours; for example, sisal fibres dyed with Calendula officinalis flowers using different mordants yielded colours ranging from yellow to brown, depending on the mordant used (Mariselvam *et al.*, 2023). The use of mordants is also part of traditional knowledge in natural dyeing across many communities (MacFoy, 2004; Mariselvam *et al.*, 2023), including those in the region under study. The effectiveness of the mordants used by the studied community was demonstrated through the dyeing trials and is also corroborated by Ferreira (1998). The use of similar mordants was also documented among traditional communities in Sierra Leone (MacFoy, 2004).

Many mordants used in the textile industry are toxic and pose environmental risks. In contrast, the mordants employed in artisanal processes are both effective and environmentally advantageous (Bechtold *et al.*, 2003). Metal salts, such as iron acetate, have proven efficacy in darkening tones and enhancing colour stability (Simpson; Ogorzali, 2001). Meta-mordanting, as described by the studied community, proved highly effective. Adding the mordant at the final stage of the dye bath simplified the operation, reduced water consumption, and allowed artisans to adjust the desired final shade, as noted by Bechtold *et al.* (2003). Mordants were particularly effective in producing brown and black hues, as observed in other fibres (Bechtold *et al.*, 2003). In contrast, the yellow shade obtained from turmeric and the red shade from annatto seeds showed little change with mordant addition, indicating a strong affinity of these pigments with sisal fibres. Probably, these pigments are less affected by pH variation or because these plants naturally contain substances that act as mordants (Simpson; Ogorzali, 2001).

In line with other developing regions rich in plant and cultural biodiversity (Mahanta; Tiwari, 2005; Mayolo, 1989; Nayak *et al.*, 2011), the adoption of natural dyeing for fibres by artisans can improve the socioeconomic and environmental conditions of communities and reduce the significant environmental damage caused by chemical dyes, which impact soil, air, water, and human health.

Several locally available species proved effective for dyeing sisal fibres, expanding the repertoire of plants known for this use. The results also stimulated artisans' interest, who highlighted the diversity and quality of the colours, as well as the economic, health, and environmental benefits. Consequently, they expressed interest in reviving the use of plant dyes and eco-friendly dyeing techniques. The promising outcomes of this study, together with evidence of ongoing loss of traditional knowledge about dyeing plants, suggest that ethnobotanical studies of this nature should be developed in regions that traditionally use these resources to ensure the preservation of this knowledge.

Ecological responsibility involves not only environmental awareness but also economic and social benefits. The use of natural dyes is economically viable, relies on locally accessible resources, and can add social, cultural, and environmental value to regional crafts. Artisans and vendors should encourage consumers to make responsible purchases by promoting the concept of sustainable products. Adopting eco-friendly practices in artefact production can enhance product value while supporting environmental conservation, ensuring sustainability. This approach could be applied to other regions engaged in sisal crafts, taking into account their cultural and environmental particularities.

5 CONCLUSIONS

The dyeing experiments demonstrated that several plant species cited by artisans can produce a diverse range of colours and shades on sisal fibres, thereby expanding the set of taxa recognised as suitable for dyeing this material, which remains relatively understudied in natural dye research. Beyond colour diversity, artisans emphasised the practical advantages of plant-based dyes, including the use of

locally available resources, reduced production costs, softer fibres, and aesthetic qualities aligned with contemporary artisanal design.

The results support the study's hypotheses that knowledge of dye plants had persisted within the community and that locally available species could be effectively used to dye sisal fibres, highlighting the potential for revitalising these practices. The research process also contributed to raising awareness among artisans about the environmental and health impacts associated with synthetic dyes, while reinforcing the cultural, ecological, and economic value of traditional dyeing knowledge.

Reintroducing plant-based dyes in sisal handicrafts is a promising strategy to strengthen the sustainability of artisanal production by integrating environmental, cultural, and socioeconomic dimensions. Future efforts should focus on strengthening knowledge transmission through training activities and continued experimentation with dyeing techniques. Further research evaluating colour fastness, durability, and production scalability will be essential to support broader adoption of natural dyes and to promote sustainable socio-biodiversity value chains.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors declare that no generative AI or AI-assisted technologies were used inthe creation, writing, or editing of this manuscript.

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Citizen science and engaged visual anthropology for climate justice: a study of the Emergent Ecologies platform

Ciência cidadã e antropologia visual engajada para justiça climática: um estudo da plataforma Emergent Ecologies

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ABSTRACT

Despite advances in explaining the causes of climate change, greater attention is still needed to the unequal distribution of impacts and adaptation modes. This article argues that scientific platforms that integrate social science research, digital media, and socio-environmental activism create spaces for the co-production of knowledge and highlight solutions emerging from affected areas. Critical analyses of the political-epistemological, methodological, and ethical foundations of such initiatives remain scarce. To address this gap, we examine multimodal content from the Emergent Ecologies platform, with a particular focus on the Women in Artisanal Fishing section. Drawing on citizen science and engaged visual anthropology approaches, the analysis is organised around three axes: the visual as co-production; engagement as method; and guidelines and practices as an open field of possibilities. Findings suggest that integrating these approaches can strengthen transformative action toward sustainability and contribute to climate justice.

Keywords: Emergent Ecologies. Citizen science. Engaged research. Visual anthropology. Climate justice.

RESUMO

Apesar de avanços na compreensão das causas das mudanças climáticas, ainda é necessário dedicar maior atenção aos impactos, às formas de adaptação e à sua distribuição desigual. Este artigo argumenta que plataformas científicas que integram ciências sociais, mídias digitais e ativismo socioambiental possibilitam espaços para a coprodução de conhecimento e soluções oriundas dos territórios mais afetados. Análises críticas sobre fundamentos político-epistemológicos, metodológicos e éticos dessas iniciativas, contudo, permanecem escassas. Para preencher essa lacuna, realizamos uma análise dos fundamentos e conteúdos multimodais da plataforma Emergent Ecologies, com foco na linha Mulheres na Pesca Artesanal. Com base nas abordagens da ciência cidadã e da antropologia engajada e visual, a análise organiza-se em três eixos: o visual como coprodução; o engajamento como método; e diretrizes e práticas como campo aberto de possibilidades. Os resultados sugerem que a integração dessas abordagens pode fortalecer ações transformadoras rumo à sustentabilidade e contribuir para a justiça climática.

Palavras-chave: *Ecologias Emergentes. Ciência cidadã. Pesquisa engajada. Antropologia visual. Justiça climática.*

1 INTRODUCTION

Alliances between the environmental movement and grassroots communities whose livelihoods are intertwined with the ecosystems in which they live date back to the 1970s, that is, to the beginning of the process of establishing the epistemological and discursive foundations regarding the global ecological crisis and the need for sustainability. In the 1980s, Brazil played a pioneering role in these alliances, with a key milestone being the formation of the Alliance of Forest Peoples, which influenced other mobilisation efforts between environmentalists and local populations around the world (Cunha; Almeida, 2000). The process continued to gain steam in the 1990s with the holding of Eco-92 in Rio de Janeiro and, in 1998, with the ratification of the Convention on Biological Diversity, which legally[1] recognises indigenous peoples and local communities as an essential part of biodiversity conservation.

Brazil is currently an international leader in developing policies for biodiversity conservation and climate change mitigation and adaptation, as evidenced by its recent hosting of COP30 of the UNFCCC, as well as its stated commitment to multilateralism, climate justice, and the fight against environmental racism[2]. However, the effective implementation of policies and the generation of knowledge aligned with these commitments still face significant obstacles, not only in Brazil but worldwide, reflecting the complexity and magnitude of the task.

We live in a world marked by the worsening consequences of global environmental change, which threaten socio-biodiversity and climate stability. The deepening of the planetary crisis is accompanied by the rise of anti-scientific movements and authoritarian governments, which fuel climate denialism and jeopardise the foundations underpinning international collaboration and the collective development of solutions (Saito *et al.*, 2025).

In this scenario, collaboration between academic researchers and local communities can serve as a strategic and fruitful avenue for building bonds of trust, promoting horizontal sharing practices, and advancing common agendas, while challenging disciplinary, institutional, and even national boundaries, even amid international political tensions among states.

Although science has already made significant progress in understanding the causes of climate change, there is a growing recognition that more attention must be paid to its impacts and to ways to adapt to them, particularly given how these impacts disproportionately affect different populations[3]. In light of this, social sciences perspectives on community vulnerability, adaptation, and resilience are gaining relevance. Such studies can offer promising pathways for the formulation of policies and actions oriented toward sustainability and climate justice, complementing and, at times, contrasting with analyses that

have a predominantly technical and quantitative focus and are structured by vertical governance and decision-making arrangements.

Several authors have argued along these lines, noting that sustainability research has benefited from adopting more participatory, situated practices, ones capable of fostering engagement, and which are co-produced, and well-connected to the realities of social actors, linking notions of justice to people's everyday experiences and emotions (Jasanoff, 2004; 2021; O'brien, 2012; Scoones *et al*., 2020). This approach has gained ground internationally and is also present in the Brazilian socio-environmental agenda (Adams *et al*., 2022; Bursztyn; Távora, 2023; Fleury *et al*., 2019).

Similarly, digital scientific platforms have been serving as spaces for connecting, formulating, and expanding discourses on alternatives that originate directly from the communities most affected by climate change and environmental degradation. Added to this is the potential of these platforms as means of conducting research that values the active participation of diverse stakeholders, where networked digital technologies intertwine with the agendas of climate justice movements, directly influencing methodological choices, forms of engagement, and formats for disseminating knowledge (Temper *et al*., 2018).

However, despite this growing imbrication of digital media, socio-environmental activism, and social science research practices (Buscher, 2020), there remains a scarcity of critical analyses that address the conceptual and foundational principles guiding the implementation of such research.

Seeking to help bridge this gap, this article is guided by the following questions: How can research integrate digital tools and platforms, the co-production of situated knowledge, and the engagement of different stakeholders, especially vulnerable populations, into studies focused on sustainability and adaptation in the face of the current climate crisis? And what key considerations does this integration reveal for the socio-environmental agenda? To address these questions, we conducted an analysis of the digital platform Emergent Ecologies, a project of the Behner Stiefel Centre for Brazilian Studies at San Diego State University[4].

The platform is structured around how environmental changes affect traditional rural and urban communities in Brazil, as well as community responses to these changes. The platform constitutes an exercise in visual and engaged anthropology, influenced by the principles and practices of citizen science, aimed at generating knowledge about and for climate justice and the fight against environmental racism in Brazil.

We begin by briefly presenting the theoretical approaches that underpin the analysis proposed here, namely: citizen science and engaged and visual anthropology. Following this, we present the political-epistemological, methodological, and ethical foundations of the Emergent Ecologies platform. Using as our primary empirical corpus the multimodal content of the "Women in Artisanal Fishing" series, which focuses on shellfish gatherers and artisanal fisherwomen in southern Bahia, we develop a critical, qualitative, and documentary analysis structured in three parts: 1) Between platforms and territories: the visual as co-production; 2) Between research and governance: engagement as a method; and 3) Between guidelines and practices: an open field of possibilities. We hope that the analysis and elaboration of this initiative may serve as inspiration for new research theories and practices aimed at transformations toward sustainability and climate justice.

2 CITIZEN SCIENCE

Although there are differing conceptions of what citizen science is[5], according to European Citizen Science Association (2015), Haklay *et al*. (2021), and Hecker *et al*. (2018), its main tenets can be summarised as follows: the promotion of active, informed, and committed citizen participation in research; community engagement in all or multiple stages of the scientific process; the participation of

those involved in data collection, processing, and analysis, including through creative and collaborative communication practices; the public availability of data and results, whenever possible and ethically valid; the implementation of educational processes aimed at building social capacities; and the promotion of mutual benefits for scientists and other participants.

Citizen science places a particular emphasis on the inclusion and engagement of stakeholders beyond the scientific community in the production of knowledge, that is, people who do not possess the academic credentials typically associated with a specific field of science. It is worth noting that in the most established definitions of citizen science, such as those mentioned above, there is a predominant focus on the participation of "citizens" in a broad or generic sense, without necessarily an explicit emphasis on the inclusion and engagement of specific social groups, such as marginalised, local, and traditional communities and Indigenous peoples.

However, significant institutional efforts, including international reference documents and relevant scientific initiatives, have identified this issue as a limitation and a gap that needs to be addressed. Authors such as Paleco *et al*. (2021) and Tengö *et al*. (2021) emphasise that effective inclusion requires special attention to social and cultural diversity, including recognition of the barriers that limit the participation of historically marginalised groups, as well as the recognition and appreciation of the knowledge systems of Indigenous People and Local Communities (IPLCs), which is referred to in Brazil as *Povos e Comunidades Tradicionais* (PCTs), as legitimate and complementary to scientific knowledge.

In the same vein, the report by the United Nations Environment Programme (Unep, 2024), based on an analysis of a series of citizen science projects, highlights the benefits of initiatives that broaden ways of knowing by specifically including indigenous, traditional, and local knowledge. Meanwhile, the document Embedding Citizen Science into Research Policy, produced by the OECD (2025), highlights the need for citizen science research to reflect societal diversity or to focus on marginalised and underrepresented groups.

Another key point regarding public engagement is that, recently, the media and digital infrastructures have begun to substantially transform strategic aspects of the scientific research cycle (Da Silva Neto; Chiarini, 2023). According to Hecker *et al*. (2018, p. 8): "There is need for changing the reference frame that leads people's understanding from a passive knowledge transfer to active two-way knowledge exchange.".

In this regard, citizen science has been developing through methodologies that include the use of social media, open-source and free hardware and software, mobile apps, and even artistic and creative processes, all of which serve as important tools for facilitating the production and circulation of data, as well as for fostering collaboration and interaction among various stakeholders.

Another fundamental aspect, complementary to the points mentioned above, concerns efforts to promote social and scientific capabilities equitably. For example, initiatives focused on the environmental sustainability agenda, in particular, have been illustrative of how such efforts can be put into practice. Although this agenda is not a requirement or a specific focus of all citizen science initiatives, research on environmental topics accounts for a large proportion of existing activities (Van Noordwijk *et al*., 2021).

3 ENGAGED AND VISUAL ANTHROPOLOGY

A political-epistemological project that intersects with the field of citizen science is the branch of anthropology known as engaged anthropology. According to Eriksen (2006), engaged anthropology emerges from a critique of anthropology's isolation from contemporary debates. The author thus advocates for a more visible and socially meaningful role for anthropologists.

In this same vein, Low and Merry (2010) emphasise the role of communication and the strategic use of media as essential components of engagement processes in anthropological research. According to the authors, engaged anthropological practice requires the development of specific ways to translate research findings, whether for policymakers, educational materials, public exhibitions, or collaborations with journalistic media outlets and media platforms with a wide audience.

Engaged anthropology is thus a practice of engaged research oriented toward social justice, that is, a form of knowledge production guided by ethical commitment and the reframing of the terms of public social debates.

Among the different developments of this political-epistemological project, a particular branch stands out, referred to as engaged or applied visual anthropology or ethnography. Although this approach originated from traditional social science methods such as ethnography, systematic observation, and interaction with groups in their own contexts, it has evolved to incorporate digital technologies and collaborative engagement processes. More than a set of techniques, it is a methodology grounded in its own theoretical perspectives and ethical commitments, that is, it is not merely the instrumental use of images in social research (Pink, 2021).

This approach draws on a wide range of tools, including cell phones, tablets, social media, and other contemporary networked digital technologies. These tools form part of a procedural and epistemological framework designed to facilitate “learning with” participants in situated processes of knowledge co-production.

In this sense, engaged visual anthropology emerges as a methodological approach that integrates reflective and dialogical ways of both producing and communicating knowledge, involving ongoing negotiations between researchers and participants regarding the meanings of the images and the experiences they represent. The imaginary is not mobilised merely as a final product, but as a means to enable complex and situated readings of social and cultural phenomena, allowing forms of reflexivity that are not fully achievable through argumentative, linear writing.

It should be added that ethnographic visual data often do not fit within the conventional frameworks of archiving and academic research outputs, which are primarily focused on texts and numerical metadata. To address this issue, Rocha (2021) advocates adopting curatorial practices specific to audiovisual materials that account for their ethical, aesthetic, and relational dimensions, rather than simply making them available on standard scientific platforms.

Audiovisual production serves as a strategic medium for the public dissemination of knowledge. In other words, when used as narrative and pedagogical tools, images and sounds bring together local and academic knowledge, fostering forms of ethnographic feedback that engage directly with research participants and the broader public.

This argument is consistent with the perspective developed by Parguel (2021), who suggests that the results of anthropological research should be disseminated in accessible formats, particularly those tailored to the digital environment, such as blogs, social media, virtual museums, and other forms of communication that are less conventional by the dominant standards of scientific production.

The normative and conceptual frameworks discussed so far provide the critical basis for analysing the Emergent Ecologies platform in the following sections. In these sections, we highlight certain aspects that demonstrate the extent to which the platform embodies and/or challenges the political-epistemological projects of citizen science and its interfaces with engaged and visual anthropology.

4 EMERGENT ECOLOGIES

The digital platform 'Emergent Ecologies: Living with Environmental Change in Brazil'[6] is a project of the Behner Stiefel Centre for Brazilian Studies at San Diego State University in California[7]. The platform aims to investigate how environmental changes affect the lives of rural and urban communities in contemporary Brazil, examining their complex relationships and impacts.

Adopting a co-production approach, the platform uses ethnography not only as a research methodology but also as a means of engaging with IPLCs and vulnerable communities in urban peripheries. This is achieved primarily by addressing issues such as gentrification, real estate speculation, and communities' access to natural resources, as well as how large infrastructure projects, such as ports, are transforming landscapes and intensifying environmental changes.

The platform's content is grounded in the perspective that environmental changes disproportionately affect vulnerable communities, and that issues of race and gender shape their impacts; that is, it is based on the theoretical framework of recognising environmental racism and the pursuit of climate justice

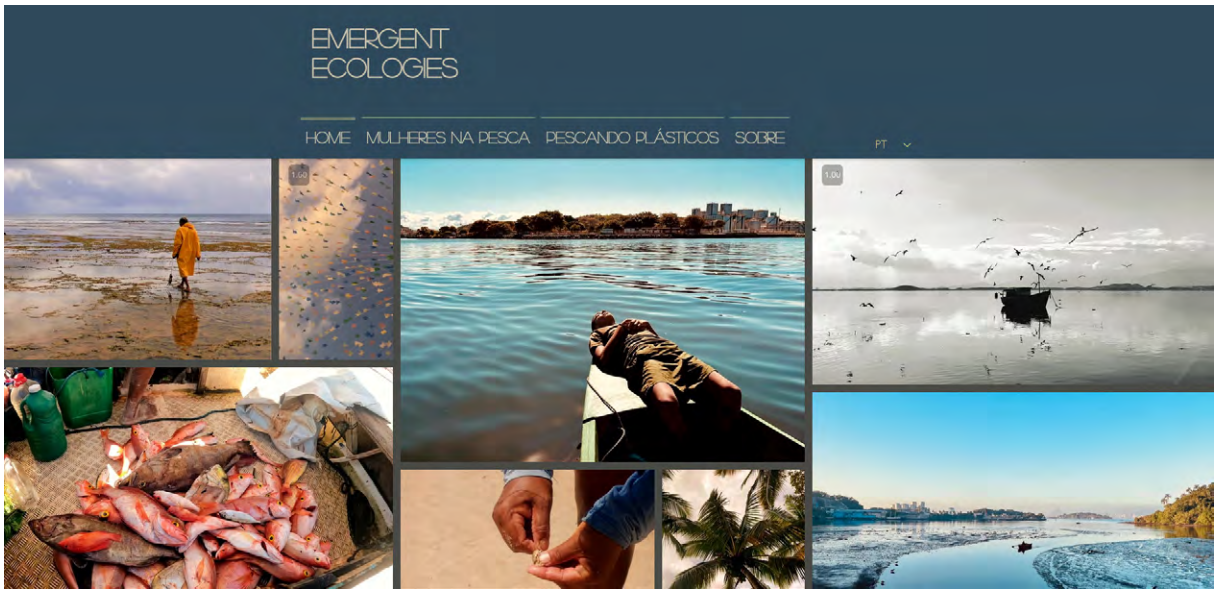


Figure 1 – 'Emergent Ecologies' homepage

Another focus of the platform is the solutions that vulnerable traditional rural and urban communities, drawing on their daily experiences and creativity, have been finding to adapt to, mitigate, and address environmental changes. The platform highlights that these communities possess deep knowledge of environmental patterns and have established specific relationships with fauna, flora, water, air, and spirituality. It asserts that through these ways of knowing and acting, these communities are fostering emerging ecologies.

According to the platform's description:

> Working equitably with them [local communities] not only gives us a concrete understanding of the impacts of environmental change but also elevates awareness of solutions devised by those most directly affected. (Emergent Ecologies, 2024)

There is a growing recognition that it is necessary to acknowledge and, moreover, value the emerging ecological perspectives of communities, as this not only enriches academia with new insights and data but also promotes the dissemination of practical solutions to pressing environmental challenges, while amplifying the voices of these communities in discussions about climate justice, access to rights, and public policy.



Figure 2 – Image of the 'Women in Artisanal Fishing' research line

'Emergent Ecologies' is divided into two lines of research, or projects, with distinct geographic focuses and social groups in Brazil, namely: a) Women in artisanal fishing; b) Fishing for plastics. Although there is a strong connection between the two projects that are part of the platform, for example, the research is united by issues surrounding artisanal fishing in Brazil, it is clear that there are also differences in methods and objectives.

For the purposes of this article, we will focus our descriptions and analyses on the "Women in Artisanal Fishing" initiative. This initiative was carried out in southern Bahia, in predominantly rural areas with strong ties to the cultural identity of traditional fishing communities (*Povos e Comunidades Tradicionais*) within Federal Marine Extractive Reserve Conservation Units (Resex Marinha).

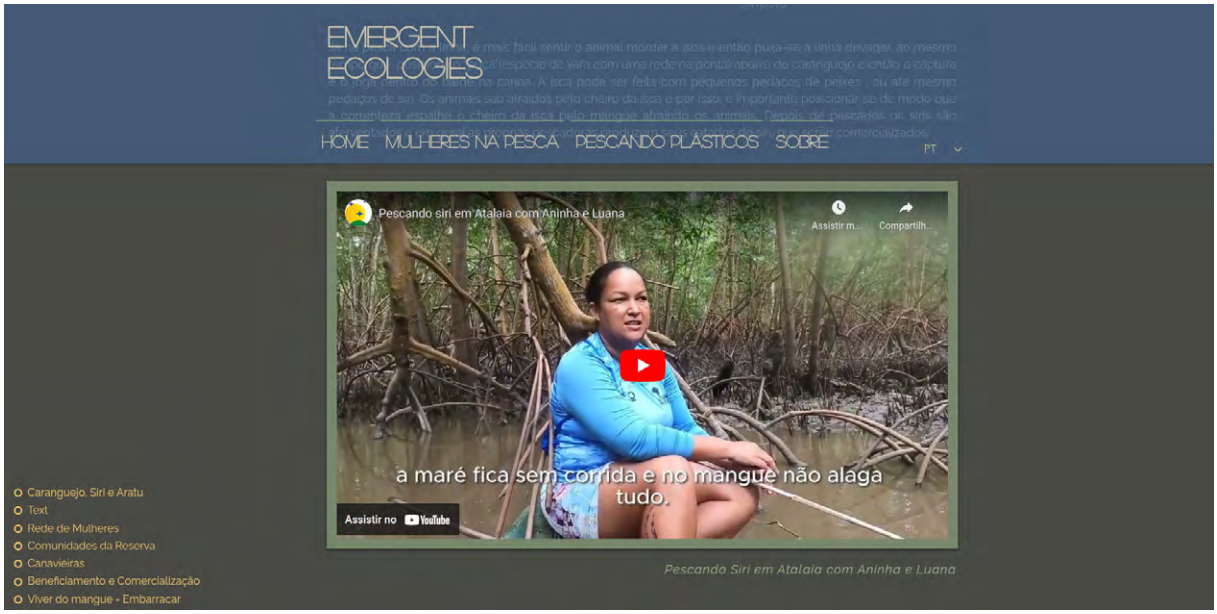


Figure 3 – Video of a 'marisqueira' catching crab

Through collaboration with women shellfish gatherers and artisanal fisherwomen, specifically in the communities of Serra Grande, Barra Grande, Canavieiras, and Baía do Iguape, this series highlights the complex world of small-scale artisanal fishing in Brazil through the lens and perspectives of the women members of the IPLCs.

The study focuses on the use of small boats, the emphasis on household consumption and the sale of produce in local markets, and the oral transmission of traditional knowledge, which is essential for maintaining sustainable subsistence practices in these communities. It highlights the harsh reality faced by these women who, despite their vital techniques and contributions to the fishing, processing, and sale of octopus, small fish, and shellfish, often see their work and ways of life undervalued and rendered invisible. A key aspect of the research is the focus on the challenges women face in maintaining their connection to artisanal fishing and shellfish gathering (mariscagem), highlighting how essential this connection is to their cultural identities and communities.



Figure 4 – Image of an artisanal fisherwoman in 'Emergent Ecologies'

Another key point is that women have adapted artisanal fishing and shellfish gathering techniques due to restrictions imposed by tourism and real estate development in the region, as well as environmental changes from climate change that limit access to natural resources. These adaptations serve to mitigate and address the daily challenges imposed on their way of life, with practical and innovative solutions developed that reflect a deep understanding of local marine ecosystems, environmental policies at various scales, and strategies for conserving biodiversity.

Examples of fishing techniques adapted to current conditions include adjusting fishing seasons and selecting new, less-fished locations. Other examples include sustainable resource management, such as refraining from catching species during their reproductive seasons and using equipment that minimises environmental impact.

It is also worth noting, in this same vein, how women have been pioneers in creating community support networks that strengthen local capacities to address socio-environmental challenges and adapt to new environmental realities. This occurs through the creation and maintenance of community associations that promote, among other things, training and the exchange of knowledge on fishing techniques and resource management, in addition to fighting for their rights and bringing the issue of sustainability to

the negotiating table with authorities and tourists alike. The platform portrays these and other aspects of these women's interaction with their environment, their work, and their community.

4.1 BETWEEN PLATFORMS AND TERRITORIES: THE VISUAL AS CO-PRODUCTION

The central role that digital and networked communication technologies play in shaping contemporary ways of life has been reshaping not only market and governance structures, but also the methodological and ethical processes involved in cultural, artistic, and scientific production (Van Dijck *et al*., 2018). The growing access to and adoption of these technologies by broad segments of the population, including socio-environmental movements, indigenous peoples, and local and traditional communities, have significantly expanded the possibilities for collaboration and interaction among these underrepresented groups in scientific knowledge production processes. Barriers previously imposed by geographic distance, time constraints, resource inequalities, or linguistic differences are becoming increasingly easy to overcome.

The Emergent Ecologies platform fits into this context and bridges the gap between socio-environmentalism and digital media. Added to this is a strong artistic presence, particularly in the visual arts, which broadens modes of expression and extends beyond academic circles and the conventional spaces of production and circulation in the social sciences. By making extensive use of audiovisual resources, such as photographs and videos, produced with and by the participants themselves, 'Emergent Ecologies' exemplifies a research practice oriented toward the co-production of knowledge.

It is worth noting that the platform seeks to value diverse forms of knowledge, shifting away from the exclusive centrality of academic institutions as both producers and recipients of knowledge (Polk; Knutsson, 2008). This methodological reconfiguration paves the way for critical reflection on new dynamics of participation, engagement, and collaborative knowledge production.

This approach implies not only new forms of interaction between researchers and communities but also a transformation in how the knowledge generated is collected, analysed, disseminated, and integrated into social and institutional contexts. The potential of visual and engaged anthropology stands out as a tool for jointly formulating research agendas on climate adaptation and sustainability, due to its ability to articulate sensitive dimensions of communities' lived experiences and to produce situated, politically relevant knowledge that is communicable to multiple audiences.

Audiovisual mediation, combined with engagement methods, broadens the scope of collaboration in the research and deepens the collective understanding of how to confront environmental racism and adapt to climate change. As Luciane Cruz, a quilombola woman (maroon), a community field collaborator (interlocutor) for Bacia e Vale do Iguape fieldwork, explained it:

> "[…] this project has been giving a lot of strength, giving a lot of support to the marisqueiras, where they recorded several videos, where they spoke and were able to express themselves, I mean, express themselves in their own way, talking about how much they like shellfish gathering, how much they love to go to the tide, the suffering too, the impacts too, they put it very well, talking about the impacts here in the communities, you know"[8] (our translation).

In this sense, visual and engaged anthropology emerges as a particularly effective approach within 'Emergent Ecologies', as it strengthens communities' expressive capacities, enabling them to represent and reframe their challenges and solutions through images, videos, and other sensory forms of communication. In the case of the Brazilian artisanal fisherwomen and shellfish gatherers who participated in 'Emergent Ecologies', this process allowed them not only to highlight the transformations

underway in their territories but also to imagine possible futures based on their own experiences and innovations, bringing to light positive stories of adaptation crafted by the communities themselves.

A concrete example of this can be seen in how shellfish gatherers link the practice of gathering to family and community memory, recounting lessons passed down by mothers and grandmothers. In Janete Barbosa from the Guaí Community's words: "I come from a lineage of people who were enslaved and had to fight for their survival, fight for their freedom. I come from a humble family, a poor family, like all Black people and fishermen, and so I carry on my family's legacy [...] My mother was a shellfish gatherer, and I learned to gather Sururu, Lambreta, and Mapê with her […]" (our translation).

This recognition of the relationship between ancestral tradition and ways of living and producing is accompanied by an emphasis on the enduring and time-tested nature of their knowledge and techniques, as well as a critique of the devaluation of their knowledge. As can be seen in the words of a shellfish gatherer from Ponta de Souza:

> "Preserving the mangrove is essential, but to what extent does this preservation preserve the fisherman's livelihood? We know how to cut it down and let the mangrove grow back; the Paraguaçu shipyard cut down the equivalent of 20 soccer fields of mangrove, where is the oversight? Then the fisherman takes a mangrove branch to cook the fish and is accused of going against nature. What does it mean to go against nature? Is it our ancestral knowledge? Alternatively, is it these companies that take everything?"[9].

From this perspective, the platform can be seen as a way to strengthen local perspectives, while also contributing to enriching, complementing, and diversifying the horizons of political imagination and scientific research regarding sustainability. After all, the narratives and solutions that emerge from communities are shared through the platform, which offers open access and wide international dissemination.

It is also worth noting that the choice of multimedia, interactive formats that are sensitive to the sociocultural context of the communities contributes to an innovative practice of ethnographic feedback. There is a shift away from the notion that research comes first and feedback later, as the images and sounds created by the research participants themselves enhance their control over the research process and contribute to greater contextual precision and relevance of the data generated and analysed (Liebenberg, 2009).

It should further be emphasised that the platform is free of charge and easily accessible, combining content in lay and academic language, in contrast to the traditional format of ethnographies, normally long monographs, whose circulation is restricted to academic circuits and behind paywalls. Such orientations build on the recommendations on data governance in anthropology made by Parguel (2021) and Rocha (2021), by recognising that research results should not be limited to technical archiving or the traditional documentary formats, but should instead assume accessible, dialogical, and politically situated forms that allow for a wider circulation of information.

By adopting this perspective, the platform also reinforces the idea of active, multidirectional knowledge exchange and, in the specific case we are analysing, integration between IPLCs and the agendas of social and environmental justice movements in the development of scientific knowledge.

4.2 BETWEEN RESEARCH AND GOVERNANCE: ENGAGEMENT AS METHOD

The emphasis on engagement as a scientific method in 'Emergent Ecologies' is evident in the way the research was conducted. Notable aspects include the transparency of objectives and methods related to local socio-environmental movements, collaboration with stakeholders throughout the research, the embrace of multiple forms of knowledge and practice, and active participation in associations and



Figure 5 – Marisqueira removing oysters from mangrove roots

The explicit orientation toward promoting epistemic diversity and fostering inclusive dialogue among distinct systems of knowledge seeks to create spaces for interlocution that transcend their original contexts. It is a matter of fostering arenas where multiple perspectives can coexist and interact, contributing to reducing historical power asymmetries and confronting hierarchies that frequently mark interactions between researchers and the "researched."

This process, in turn, has the potential to reconfigure not only the methods and practices of scientific production but also the very discursive and theoretical frameworks traditionally dominant in the academic field, especially by incorporating social and epistemological critiques anchored in different cultures and socio-environmental experiences. The protagonism of IPLCs in the representation and dissemination of their everyday lives, perspectives, and environmental practices thus constitutes a counterpoint to a possible reification and calcification of their traditional ecological knowledge (Ingold; Kurttila, 2000).



Figure 6 – Sururu, oyster, and crab stew depicted by a research interlocutor

This approach echoes perspectives in anthropology, engaged research, and citizen science that emphasise the active and conscious participation of the "researched" in all stages of the scientific process. This includes everything from formulating research questions to collecting, processing, and analysing data, as well as disseminating results (Lassiter, 2005). Such an emphasis brings into view the

tension between expert actors, in this case, researchers holding doctoral degrees, and those often considered lay actors, the "researched."

From the perspectives of citizen science and engaged anthropology, the tension between these two poles is not viewed as an obstacle, but rather as a productive dimension and an integral part of the research practice itself, from which opportunities arise to adequately include the viewpoints of vulnerable or marginalised groups in the public sphere. The aim is to strike a balance between scientific rigour and objectives that generate benefits for all participants, not just scientists.

This perspective is deepened by Lozano (2022), who criticises approaches that reduce collaboration in ethnographic production to a simple division of tasks between researchers and interlocutors, limited to operational phases of the research. For the author, collaboration should be conceived as a dialogical and recursive process in which the researcher adopts a posture of decentering, acting as a kind of facilitator rather than as the final authority in knowledge production.

This posture requires from researchers a degree of reflexivity that makes it possible to avoid the risk that, in the face of divergent views, research will be conducted in ways that privilege academic relevance to the detriment of practical usefulness for non-academic interlocutors.



Figure 7 – Noca performing the thermal opening of oysters shells (blanching)

In the same vein, another equally significant aspect when analysing 'Emergent Ecologies' is its explicit effort to address environmental racism, defined in the platform as follows: "Environmental racism refers to the way in which ethnic and racial minorities are disproportionately affected by environmental problems due to discriminatory practices and social and economic inequalities." (Emergent Ecologies, 2024).

The platform emphasises the fact that the communities participating in the research have historically been and continue to be racialised, and thus suffer the harmful consequences of this specific form of racism. It is also noted that the platform explicitly aims to address concrete socio-environmental themes and issues that truly resonate with the material needs and concerns of the IPLCs who participated in the research. That is, the platform focuses its efforts on emphasising the ethics and aesthetics of artisanal fisherwomen and shellfish gatherers, on the impact of knowledge through its translation into accessible languages capable of reaching diverse audiences, on promoting and participating in

community organising and mobilisation, and on strengthening debates surrounding traditional rural cultures within the academic sphere.

4.3 BETWEEN GUIDELINES AND PRACTICES: AN OPEN FIELD OF POSSIBILITIES

Another aspect that merits reflection concerns the platform's predominant focus on social and ethnographic research. Although we recognise that this orientation constitutes one of the main strengths of 'Emergent Ecologies', we note the research impact could be expanded if it were to incorporate, in an even deeper, more systematic, and more evident way, approaches and tools typical of citizen science as an epistemological approach, capable of integrating the natural and environmental sciences with the social sciences and humanities. After all, this element could contribute significantly to the research's greater success and impact, and provide local communities with additional data to inform their work (Albert *et al*., 2021; Hecker *et al*., 2018).

Considering the platform's objective of understanding the impacts of environmental changes on Indigenous peoples and local communities, as well as their capacities for adaptation, there is significant potential for strengthening more robust interdisciplinary partnerships, integrating research fields such as agroecology, conservation biology, geography, and applied environmental studies, including those oriented toward sustainable development and participatory territorial management. Particularly noteworthy are possibilities for incorporating agroecological indicators, geospatial/climate data, and territorial management and monitoring procedures.

In dialogue with the works of Tsing *et al*. (2024), the articulation between anthropology and technical biophysical measurements may be understood not as a loss of the research social dimension but, rather, as the cultivation of situated knowledges and a deepening of the arts of attention grounded in fieldwork. In this direction, sensors, metrics, indicators, and databases do not necessarily render the investigation technocratic. On the contrary, they open space for ethnographic attunement (Tsing, 2022) and for the material-ecological dynamics of territories to express themselves and enter the political arena (Latour, 2004).

It is in this sense that we understand that the expansion of the epistemological and methodological bases of 'Emergent Ecologies' could contribute to more integrated readings of the interrelations that affect the territories researched, favouring the construction of a plurality of empirical evidence and theoretical inferences about emergent ecological dynamics and the ongoing processes of socio-environmental transformation. This expanded focus, based on multiple types of empiricism, could potentiate the public legitimacy and the strategic use of research results in processes of environmental and territorial planning and management, public policies oriented toward sustainable development, and struggles for the guarantee of rights on the part of climate justice movements.

A central reference in this regard is the work of Gabrys (2019, 2022), which, through the notion of 'citizen sensing,' explores the intersection of environmental data and the social sciences, connecting environments, low-cost technologies, collective organisational forms, and situated practices.

We also highlight another aspect of 'Emergent Ecologies' in relation to citizen science: the intense cooperation and capacity-building among research teams in the United States and Brazil, as well as the adoption of the bilingual format (English and Portuguese). There is also promotion of exchanges and training among researchers at universities and research centres in the Global North and South. These characteristics reinforce a commitment to decentralised, multicultural, and interinstitutional scientific production that seeks to reduce historical asymmetries in the production and circulation of knowledge.

At this point, we would like to reflect on how the various guidelines on what citizen science is or should be encompass an overly broad spectrum of actions and recommendations. In this context, not all research can or should fully comply with the extensive recommendations and guidelines that define

citizen science. For example, the Emergent Ecologies platform is not specifically dedicated to producing large datasets through crowdsourcing techniques or to creating and providing infrastructure such as open data repositories or physical research facilities accessible to the general public, elements that are highly relevant and characteristic of citizen science.

Nevertheless, it is important to emphasise that, although we recognise that the pillars, values, and principles of citizen science, and likewise of engaged research, are interdependent and that a focus on this aspect potentiates their practices, the guidelines do not need to be fully met for a platform or research project to be recognised as, as well as to contribute to, these approaches. Instead, these guidelines may be seen as a set of adjustable possibilities that should be considered and welcomed on a case-by-case basis, as well as references for inspiring new developments in research.

Finally, following Kythreotis *et al*. (2019), we emphasise that contemporary climate policies predominantly based on technocratic-managerial and "top-down" languages, that is, hierarchical languages, have failed to achieve legitimacy and the necessary ambitious targets to confront the climate crisis. Scientific research that operates in a different key, for example, through the co-production of knowledge, can reposition citizens as co-learners and co-decision-makers, capable of challenging institutional structures and expanding the repertoire of knowledges, and may be an effective way of addressing these issues.

It is further necessary to emphasise that methodologies of co-producing knowledge need to incorporate a reflexive character in order to deal with prior inequalities, such as time, resources, and epistemic status that favor "elite actors" (State, large NGOs, renowned scientists), who not infrequently define scopes and criteria of relevance, reinforcing hierarchies between scientific knowledge and other systems of knowing. Added to this is the fact that, in North–South contexts, as is the case of 'Emergent Ecologies', the high degree of inequality in technical, institutional, and budgetary capacities further aggravates these asymmetries. A reflexive approach requires that research not suppress conflicts; on the contrary, it should accept contestation and dissensus around divergent interests and visions and, with a posture of humility, strengthen pluralism as a creative driver (Turnhout *et al*., 2020).

5 FINAL CONSIDERATIONS

The Emergent Ecologies platform, analysed in this article, seeks to generate knowledge about emerging ecologies in regions of Brazil inhabited by local and traditional rural communities and rich in biodiversity, regions that are heavily impacted by the climate crisis and serve as sites of profound uncertainty and rapid change. That is, it addresses the capacity of communities to create innovative solutions and adapt in the face of the negative impacts of environmental and social changes, as well as the unique cultural, social, political, and, of course, ecological relationships they establish with their respective local environments.

In other words, the platform examines the creative and context-specific responses of communities to external pressures, such as public policies, markets, and climate change, as well as internal dynamics, such as sociopolitical conflicts, institutional reorganisations, and cultural transformations. Far from representing predetermined responses or spontaneous reactions, these configurations highlight continuous processes of creation, negotiation, adaptation, and also conflict that unfold within the collective and concrete dynamics of these communities' everyday socio-environmental lives.

Citizen science and engaged visual anthropology, as mobilised by the Emergent Ecologies platform, provide access to layers of emerging ecologies and meanings that might not initially be visible, or sufficiently considered, by academic actors, and that often elude strictly technical and scientific languages. The aim is thus to produce knowledge through the mediation of different rationalities,

fostering a mode of collective deliberation and negotiation of alternatives, particularly useful in contexts of profound uncertainty and rapid change.

Given that the challenge of addressing the climate crisis is global, even though its impacts are locally contextualised, and that the urgency of action requires prioritising a wide range of approaches, including those considered "unconventional" from the perspective of mainstream science, we believe that scientific platforms such as 'Emergent Ecologies' represent a promising avenue for addressing this challenge. By avoiding excessive technocracy, articulating scientific, social, and environmental objectives, and valuing methodologies and languages that are not strictly scientific, based on digital and networked technologies, this type of platform can help overcome the tendency to treat society as a mere "end user" of information produced by scientific institutions and projects, building a repertoire of successful adaptations and solutions that can contribute to broadening the horizons of political and scientific imagination and fostering social engagement.

'Emergent Ecologies', while not a predetermined solution, offers a reconfigurable sociotechnical infrastructure applicable to other territories, environmental issues, and forms of collective mobilisation. This architecture incorporates ethical commitment as a constitutive dimension of research practice, conceived as a process of becoming and a fundamental element ensuring that the co-production of knowledge connects mechanisms of historical reparation and power redistribution to transformative actions for sustainability and climate justice.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT, version 5.4 by OpenAI, for language editing and stylistic polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

NOTES

1 | See: Brazilian Federal Decree No. 2.519/1998.

2 | See: < https://agenciagov.ebc.com.br/noticias/202309/oficina-reune-demandas-para-adaptacao-as-mudancas-climaticas >.

3 | The concepts of climate justice and environmental racism are crucial to understanding this debate (Acselrad, 2010; Alier, 2007; Bullard, 1993; Schlosberg; Collins, 2014).

4 | The authors of this article are researchers involved in the production of the platform. We recognise that this positionality, while expanding the possibilities for investigation, access to its contents, and insight into the processes of its development, requires reflexivity, in the sense of strong objectivity (Harding, 1993), both in relation to the scope and to the limits of the analyses developed.

5 | At the end of 2021, during Unesco's General Conference, 193 countries adopted the first international standard-setting instrument on open science (Unesco, 2021). A specific development within this broader framework is citizen science, widely recognised as a fundamental pillar (OECD, 2025). It is worth noting that citizen science, since its earliest formulations (Irwin, 1995), has been crossed by an important debate between perspectives more oriented toward the participation of non-academics in data collection for scientific projects and other perspectives oriented toward the democratisation of knowledge production and the expansion of possibilities for constructive relations between science and society. In this article, we develop our arguments from this second perspectives. See: < https://www.emergentecologies.net/en >.

6 | Founded in 2014, the Centre promotes research and collaboration networks with Brazil in the areas of Sustainability, Arts and Culture, Human Rights, and Health, with cross-cutting attention to Politics and Governance. 'Emergent Ecologies' is developed around the Centre, which provides infrastructure, resources, and academic support.

7 | See: < https://www.emergentecologies.net/en/conselho-quilombola >.

8 | See: < https://www.emergentecologies.net/en/pontadesouzacoqueirosenaje >.

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Ciência cidadã e antropologia visual engajada para justiça climática: um estudo da plataforma Emergent Ecologies

Citizen science and engaged visual anthropology for climate justice: a study of the Emergent Ecologies platform

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RESUMO

Apesar de avanços na compreensão das causas das mudanças climáticas, ainda é necessário dedicar maior atenção aos impactos, às formas de adaptação e à sua distribuição desigual. Este artigo argumenta que plataformas científicas que integram ciências sociais, mídias digitais e ativismo socioambiental possibilitam espaços para a coprodução de conhecimento e soluções oriundas dos territórios mais afetados. Análises críticas sobre fundamentos político-epistemológicos, metodológicos e éticos dessas iniciativas, contudo, permanecem escassas. Para preencher essa lacuna, realizamos uma análise dos fundamentos e conteúdos multimodais da plataforma *Emergent Ecologies*, com foco na linha Mulheres na Pesca Artesanal. Com base nas abordagens da ciência cidadã e da antropologia engajada e visual, a análise organiza-se em três eixos: o visual como coprodução; o engajamento como método; e diretrizes e práticas como campo aberto de possibilidades. Os resultados sugerem que a integração dessas abordagens pode fortalecer ações transformadoras rumo à sustentabilidade e contribuir para a justiça climática.

Palavras-chave: Ecologias Emergentes. Ciência cidadã. Pesquisa engajada. Antropologia visual. Justiça climática.

ABSTRACT

Despite advances in explaining the causes of climate change, greater attention is still needed to the unequal distribution of impacts and adaptation modes. This article argues that scientific platforms that integrate social science research, digital media, and socio-environmental activism create spaces for the co-production of knowledge and highlight solutions emerging from affected areas. Critical analyses of the political-epistemological, methodological, and ethical foundations of such initiatives remain scarce. To address this gap, we examine multimodal content from the Emergent Ecologies platform, with a particular focus on the Women in Artisanal Fishing section. Drawing on citizen science and engaged visual anthropology approaches, the analysis is organised around three axes: the visual as co-production; engagement as method; and guidelines and practices as an open field of possibilities. Findings suggest that integrating these approaches can strengthen transformative action toward sustainability and contribute to climate justice.

Keywords: *Emergent Ecologies. Citizen science. Engaged research. Visual anthropology. Climate justice.*

1 INTRODUÇÃO

As alianças entre a pauta ambiental e comunidades territorializadas cujos meios de vida estão entrelaçados com os ecossistemas em que vivem nos remontam à década de 1970, ou seja, ao início do processo de constituição das bases epistemológicas e discursivas sobre a crise ecológica global e a necessidade da sustentabilidade. O Brasil ocupou nos anos 1980 um lugar de sementeira nessas alianças, sendo um marco a formação da Aliança dos Povos da Floresta, que influenciou outras experiências de mobilização entre ambientalistas e populações locais ao redor do mundo (Cunha; Almeida, 2000). Esse processo avançou no Brasil dos anos 1990, destacando-se a realização da Eco-92 no Rio de Janeiro e em 1998 a ratificação da Convenção sobre Diversidade Biológica, onde se reconhece, por força de lei[1], que povos indígenas e comunidades locais são parte essencial da conservação da biodiversidade.

Atualmente, o Brasil se posiciona como líder internacional no desenvolvimento de políticas de conservação da biodiversidade e de mitigação e adaptação às mudanças climáticas, tendo sediado a COP30 da UNFCCC, com um compromisso declarado com o multilateralismo, a justiça climática e o combate ao racismo ambiental[2]. No entanto, é possível observar que a implementação efetiva de políticas e produção de conhecimento alinhadas a esses compromissos enfrenta, não só no Brasil, mas no mundo todo, obstáculos significativos, refletindo a complexidade e a magnitude da tarefa.

Vivemos em um contexto marcado pelo agravamento das consequências das mudanças ambientais globais, ameaçando a sociobiodiversidade e a estabilidade climática. Esse aprofundamento da crise planetária vem acompanhado da ascensão de projetos anticientíficos e governos autoritários que alimentam o negacionismo em relação à crise climática, colocando em risco as bases que sustentam a colaboração internacional e a construção coletiva de soluções para os desafios ambientais contemporâneos (Saito *et al.*, 2025).

Nesse cenário, a colaboração entre pesquisadores acadêmicos e comunidades pode operar como uma via estratégica e fértil para construir vínculos de confiança, promover trocas horizontais e agendas comuns, desafiando fronteiras disciplinares, institucionais e inclusive nacionais, mesmo em cenários de tensão política internacional entre os Estados.

Embora a ciência já tenha avançado muito na compreensão das causas das mudanças climáticas, cresce o reconhecimento de que é preciso direcionar mais atenção aos impactos e formas de adaptação às mudanças, sobretudo na forma como elas impactam de maneira desigual diferentes populações[3]. Diante disso, ganham relevância as contribuições das ciências sociais nos estudos sobre vulnerabilidade, adaptação e resiliência comunitárias, que podem oferecer caminhos promissores para formulação de políticas e ações, orientadas à sustentabilidade e à justiça climática, em complementaridade, e,

por vezes, em contraposição às análises com enfoque predominantemente técnico, quantitativo e estruturadas por arranjos verticalizados de governança e tomada de decisão.

Diversos autores têm argumentado nesse sentido, inclusive apontando que as pesquisas em sustentabilidade se beneficiaram ao adotarem práticas mais participativas, situadas, capazes de produzir engajamento, coproduzidas e conectadas às realidades dos sujeitos sociais, articulando os sentidos de justiça com as experiências cotidianas e os afetos das pessoas (Jasanoff, 2004, 2021; O'brien, 2012; Scoones *et al.*, 2020). Essa abordagem tem encontrado terreno fértil internacionalmente, mas também na agenda socioambiental brasileira (Adams *et al.*, 2022; Bursztyn; Távora, 2023; Fleury *et al.*, 2019).

Da mesma forma, plataformas científicas digitais vêm atuando como locais de conexão, formulação e ampliação de discursos sobre alternativas e soluções que venham diretamente dos territórios mais afetados pelas mudanças climáticas e pela degradação ambiental. Adiciona-se o potencial dessas plataformas enquanto meios para a realização de pesquisas capazes de valorizar a participação ativa de diversos *stakeholders*, onde as tecnologias digitais em rede se entrelaçam com as pautas dos movimentos por justiça climática, influenciando diretamente as escolhas metodológicas, as formas de engajamento e os formatos de disseminação de conhecimento (Temper *et al.*, 2018).

Entretanto, apesar dessa crescente imbricação entre mídias digitais, ativismo socioambiental e práticas de pesquisa em ciências sociais (Buscher, 2020), ainda são escassas as análises críticas que abordam os princípios e fundamentos conceituais e orientadores que norteiam a implementação de tais pesquisas.

Buscando contribuir para o preenchimento dessa lacuna, este artigo se orienta pelas seguintes questões: como pesquisas podem articular ferramentas e plataformas digitais, coprodução de conhecimento situado e engajamento de diferentes *stakeholders*, especialmente de populações vulnerabilizadas, em estudos voltados para a sustentabilidade e adaptação diante da crise climática atual? E que pontos de atenção essa articulação revela para a agenda socioambiental? Para endereçar essas questões, realizamos uma análise da plataforma digital *Emergent Ecologies*, uma produção do Centro de Estudos Brasileiros Behner Stiefel da Universidade Estadual de San Diego[4].

A plataforma se estrutura ao redor de como as mudanças ambientais afetam comunidades tradicionais rurais e urbanas no Brasil, bem como as respostas comunitárias a essas mudanças. A plataforma configura-se como um exercício de antropologia visual e engajada, influenciada pelos princípios e práticas da ciência cidadã, para a produção de conhecimento sobre e para a justiça climática e o combate ao racismo ambiental no Brasil.

Iniciamos apresentando brevemente as abordagens teóricas que embasam a análise aqui proposta, a saber: a ciência cidadã e a antropologia engajada e visual. Após isso, apresentamos os fundamentos político-epistemológicos, metodológicos e éticos da plataforma *Emergent Ecologies* e, tendo como *corpus* empírico principal o conteúdo multimodal da linha Mulheres na pesca artesanal, focada nas marisqueiras e pescadoras artesanais do sul da Bahia, desenvolvemos uma análise crítica, qualitativa e documental, estruturada em três partes: 1) Entre plataformas e territórios: o visual como coprodução; 2) Entre pesquisas e governanças: o engajamento como método; e 3) Entre diretrizes e práticas: um campo aberto de possibilidades. Esperamos que a análise e a explicitação dessa iniciativa possam servir como inspiração para novas teorias e práticas de pesquisa rumo às transformações para a sustentabilidade e a justiça climática.

2 CIÊNCIA CIDADÃ

Apesar de existirem concepções distintas sobre o que é a ciência cidadã[5], seguindo European Citizen Science Association (2015), Haklay *et al.* (2021) e Hecker *et al.* (2018), é possível sintetizar seus principais critérios, como: a valorização da participação ativa, consciente e comprometida dos cidadãos

nas pesquisas; o engajamento comunitário em todas ou em múltiplas etapas do processo científico; a participação dos envolvidos na coleta, processamento e análise de dados, inclusive por meio de práticas comunicacionais criativas e colaborativas; a disponibilização pública dos dados e resultados, sempre que possível e eticamente válido; a realização de processos pedagógicos voltados à construção de capacidades sociais; e a promoção de benefícios mútuos para cientistas e demais participantes.

A ciência cidadã, como se percebe, desenvolve-se com uma ênfase particular na inclusão e no engajamento de *stakeholders*, além da comunidade científica na produção de conhecimento, ou seja, de pessoas que não possuem credenciais tipicamente associadas a um campo específico da ciência. Cabe ressaltar que nas definições mais consolidadas de ciência cidadã, como as supramencionadas, observa-se uma orientação predominantemente voltada à participação de "cidadãos" de forma ampla ou genérica, sem necessariamente uma ênfase explícita na inclusão e engajamento de determinados grupos sociais, como comunidades marginalizadas, locais e tradicionais, e povos originários.

Entretanto, importantes esforços de natureza institucional, incluindo documentos de referência internacionais e iniciativas científicas relevantes, têm identificado essa questão como uma limitação e uma lacuna a ser enfrentada. Autores como Paleco *et al.* (2021) e Tengö *et al.* (2021) destacam que a efetiva inclusão requer uma atenção especial à diversidade social e cultural, inclusive com o reconhecimento das barreiras que limitam a participação de grupos historicamente marginalizados, bem como também o reconhecimento e valorização dos sistemas de conhecimento dos Povos e Comunidades Tradicionais (PCTs) como legítimos e complementares ao conhecimento científico.

Nesse mesmo sentido, o relatório da United Nations Environment Programme (Unep, 2024), a partir da análise de uma série de projetos de ciência cidadã, explicita os benefícios das iniciativas que abriram oportunidades para ampliar os modos de conhecer por meio da inclusão específica de conhecimentos indígenas, tradicionais e locais. Já o documento *Embedding Citizen Science into Research Policy*, produzido pela OECD (2025), destaca a necessidade de que as pesquisas em ciência cidadã reflitam a diversidade das sociedades ou tenham como foco grupos marginalizados e sub-representados.

Outro ponto de destaque em relação ao engajamento público é que recentemente a comunicação social e as infraestruturas digitais passaram a mediar e transformar substancialmente aspectos estratégicos do ciclo de pesquisas científicas (Da Silva Neto; Chiarini, 2023). Para Hecker *et al.* (2018, p.8, tradução nossa.): "Há uma necessidade de mudar o referencial que guia a compreensão das pessoas, passando de uma transferência de conhecimento passiva para uma troca de conhecimento ativa e bidirecional.".

Nesse sentido, a ciência cidadã vem se desenvolvendo a partir de metodologias que incluem a utilização de mídias sociais, hardware e software de código aberto e livre, aplicativos para celular e, inclusive, processos artísticos e criativos, como importantes meios para a facilitação da produção e circulação de dados, bem como para a colaboração e interação entre os diversos *stakeholders*.

Outra dimensão fundamental, complementar aos pontos supracitados, refere-se aos esforços voltados à promoção justa de capacidades sociais e científicas. Nesse sentido, as iniciativas voltadas à agenda da sustentabilidade ambiental, em especial, têm se mostrado um exemplo particularmente profícuo de como tais esforços podem ser concretizados na prática. Embora essa agenda não constitua uma obrigação ou um foco específico de todas as iniciativas em ciência cidadã, as pesquisas com temas ambientais representam uma grande proporção das atividades existentes (Van Noordwijk *et al.*, 2021).

3 ANTROPOLOGIA ENGAJADA E VISUAL

Um projeto político-epistemológico que apresenta múltiplas interfaces com o campo da ciência cidadã é a vertente da antropologia conhecida como antropologia engajada. Para Eriksen (2006), a antropologia engajada configura-se a partir de uma crítica ao isolamento da antropologia em relação às discussões

contemporâneas. O autor defende, assim, uma atuação mais visível e socialmente significativa dos antropólogos.

Nesse mesmo campo de preocupações, Low e Merry (2010) enfatizam o papel da comunicação e do uso estratégico das mídias como componentes essenciais dos processos de engajamento nas pesquisas antropológicas. Segundo as autoras, uma prática antropológica engajada requer o desenvolvimento de formas específicas de tradução dos resultados da pesquisa, seja para formuladores de políticas públicas, para materiais pedagógicos, para exposições públicas ou, especialmente, para colaborações com veículos de comunicação jornalística e espaços midiáticos de ampla audiência.

A antropologia engajada se configura, assim, como uma prática de pesquisa engajada orientada à justiça social, isto é, uma forma de produção de conhecimento pautada pelo engajamento ético e reconfiguração dos termos dos debates sociais públicos.

Entre os diferentes desenvolvimentos desse projeto político-epistemológico, destaca-se um ramo específico denominado antropologia ou etnografia visual engajada ou aplicada. Essa abordagem, embora tenha emergido de métodos tradicionais nas ciências sociais como a etnografia, a observação sistemática e a interação com grupos em seus próprios contextos, evoluiu para incorporar tecnologias digitais e processos colaborativos de engajamento. Mais do que um conjunto de técnicas, trata-se de uma metodologia fundamentada por perspectivas teóricas e compromissos éticos próprios, isto é, não se trata do uso meramente instrumental de imagens na pesquisa social (Pink, 2021).

Nessa abordagem é mobilizada uma variada gama de ferramentas, incluindo celulares, tablets, redes sociais e outras tecnologias digitais em rede contemporâneas. Essas ferramentas integram uma arquitetura procedimental e epistemológica orientada a facilitar o “saber com” os interlocutores, em processos situados de coprodução do conhecimento.

Nesse sentido, a antropologia visual engajada configura-se como uma abordagem metodológica que articula formas reflexivas e dialógicas tanto de produzir quanto de comunicar conhecimento, envolvendo negociações contínuas entre pesquisadores e participantes sobre os significados das imagens e das experiências representadas. O imaginário não é mobilizado apenas como um produto final, mas um meio para que seja possível realizar leituras complexas e situadas dos fenômenos sociais e culturais, permitindo formas de reflexividade que não são plenamente alcançáveis por meio da escrita argumentativa e linear.

Acrescenta-se que dados visuais etnográficos frequentemente não se adequam às lógicas convencionais de arquivamento e resultados de pesquisas acadêmicas, voltadas sobretudo para textos e metadados numéricos. Para contornar essa questão, Rocha (2021) defende a adoção de práticas de curadoria específicas para materiais audiovisuais, que considerem suas dimensões éticas, estéticas e relacionais, em vez da simples disponibilização em plataformas científicas genéricas.

A produção audiovisual se coloca como um meio estratégico de divulgação pública de conhecimento, isto é, tomadas como dispositivos narrativos e pedagógicos, as imagens e sons articulam saberes locais e acadêmicos, promovendo formas de devolutiva etnográfica que dialogam diretamente com os interlocutores da pesquisa e com o público mais amplo, os cidadãos leigos.

Esse argumento está em consonância com a perspectiva desenvolvida por Parguel (2021), que sugere que os resultados das pesquisas antropológicas devem buscar formatos acessíveis de divulgação, especialmente voltados para o ambiente digital, como blogs, redes sociais, museus virtuais e outras formas de comunicação menos convencionais para os padrões dominantes da produção de ciência.

Os marcos normativos e conceituais discutidos até aqui fornecem o arcabouço crítico a partir do qual analisaremos, nas próximas seções, a plataforma *Emergent Ecologie*s. Nelas destacamos determinados

aspectos que apresentam em que medida a plataforma materializa e/ou tensiona os projetos político-epistemológicos da ciência cidadã e suas interfaces com a antropologia engajada e visual.

4 EMERGENT ECOLOGIES

A plataforma digital *Emergent Ecologies: Living with Environmental Change in Brazil*, em português, Ecologias Emergentes: Vivendo com as Transformações Ambientais no Brasil[6] é uma produção do Centro de Estudos Brasileiros Behner Stiefel da Universidade Estadual de San Diego, Califórnia[7]. A plataforma se propõe a pesquisar como as transformações ambientais afetam a vida de comunidades rurais e urbanas no Brasil contemporâneo, observando suas complexas relações e impactos.

Adotando uma abordagem de coprodução, a plataforma usa a etnografia não só como metodologia de pesquisa, mas também como uma forma de engajamento com PCTs e também comunidades em situação de vulnerabilidade em áreas periféricas urbanas. Isso é realizado, principalmente, ao abordar questões como gentrificação, especulação imobiliária, acesso das comunidades aos recursos naturais, bem como grandes projetos de infraestrutura, como portos, que estão transformando as paisagens e intensificando as mudanças ambientais.

Os conteúdos da plataforma partem do prisma que as mudanças ambientais afetam de forma desproporcional comunidades vulnerabilizadas, e que seus impactos são influenciados por questões de raça e gênero, isto é, a partir da chave teórica do reconhecimento do racismo ambiental e da busca por justiça climática.

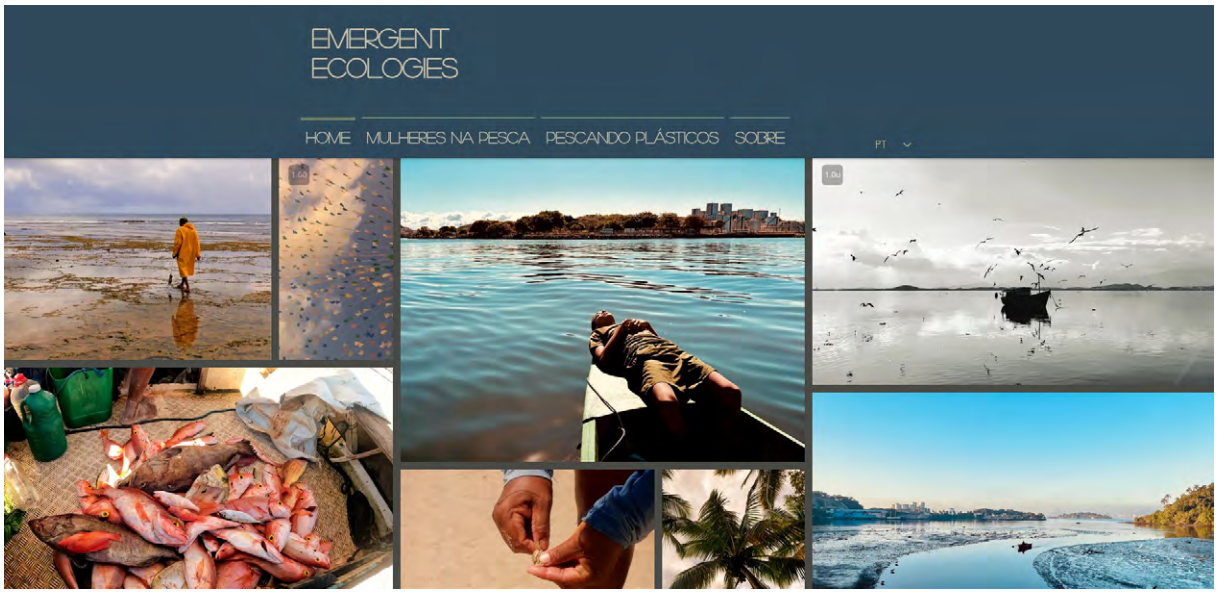


Figura 1 – Imagem da página inicial da plataforma

Outro foco da plataforma são as soluções que as comunidades tradicionais e urbanas em vulnerabilidade, a partir das suas experiências cotidianas e da sua criatividade, vêm encontrando para se adaptar, mitigar e enfrentar as mudanças ambientais. A plataforma destaca que essas comunidades possuem conhecimentos profundos sobre os padrões ambientais, bem como estabelecem relações específicas com a fauna, a flora, as águas, o ar e a espiritualidade. Afirma-se que, a partir dessas formas de conhecer e fazer, essas comunidades estão ativando ecologias emergentes. De acordo com a descrição da plataforma:

> Trabalhar de forma colaborativa com as comunidades locais não só nos dá uma compreensão concreta dos impactos das alterações climáticas como também aumenta a consciência das soluções

> concebidas por aqueles que são diretamente afetados pelas alterações no ambiente. (Emergent Ecologies, 2024)

Há um entendimento que é necessário reconhecer e, mais, valorizar as ecologias emergentes das comunidades, pois isso não só enriquece a academia com novas perspectivas e dados, mas também fortalece a disseminação de soluções práticas para desafios ambientais prementes e as vozes dessas comunidades em discussões sobre justiça climática, acesso a direitos e políticas públicas.



Figura 2 – Imagem da linha 'Mulheres na pesca artesanal'

A *Emergent Ecologies* se divide em duas linhas de pesquisa, ou projetos, com focos geográficos e grupos sociais distintos no Brasil, a saber: a) Mulheres na pesca artesanal; b) Pescando plásticos. Apesar de haver uma grande unidade entre os dois projetos que fazem parte da plataforma, por exemplo, as pesquisas são unificadas pelas questões ao redor da pesca artesanal no Brasil, é possível observar que também há diferenças entre os métodos e objetivos.

Para os objetivos deste artigo, iremos centrar nossas descrições e análises na linha "Mulheres na pesca artesanal". Essa linha da plataforma foi realizada na região do sul da Bahia em áreas majoritariamente rurais e ligadas fortemente a uma identidade cultural de PCTs em Unidades de Conservação Federal de Reservas Extrativistas Marinhas (Resex Marinha).

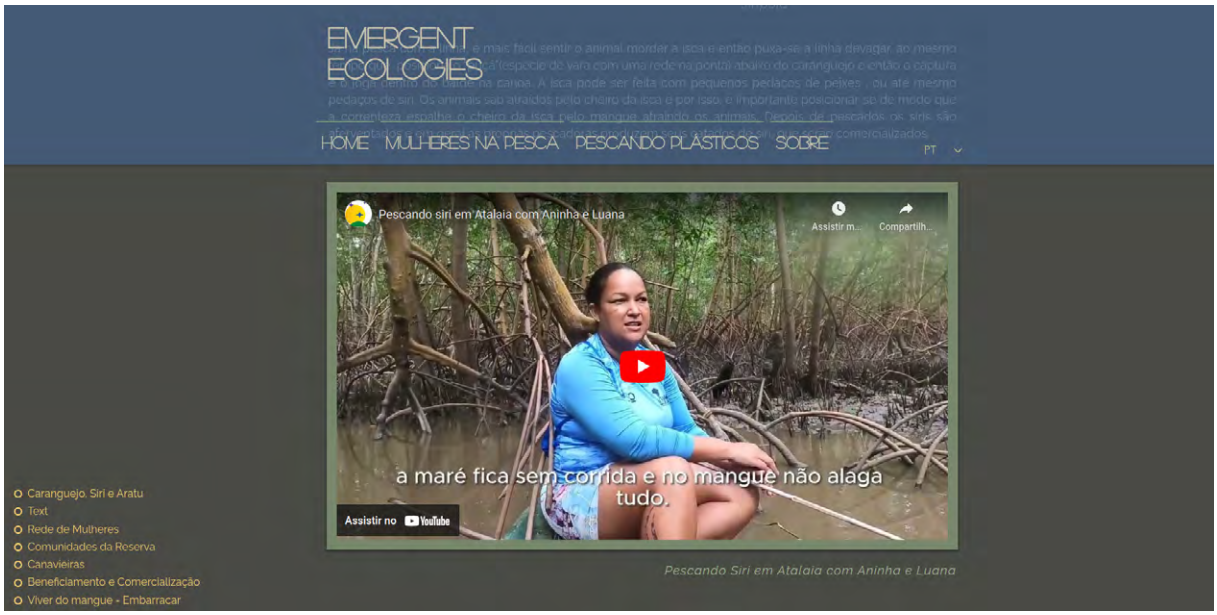


Figura 3 – Vídeo de marisqueira praticando a pesca de siri

Mediante colaboração com as mulheres marisqueiras e pescadoras artesanais, especificamente nas localidades de Serra Grande, Barra Grande, Canavieiras e Baía do Iguape, essa linha destaca o complexo mundo da pesca artesanal em pequena escala no Brasil pelo papel e olhar das mulheres membros de PCTs.

A pesquisa enfoca a utilização de pequenas embarcações, a orientação para o consumo familiar e comercialização da produção em mercados locais, bem como a transmissão oral de conhecimentos tradicionais, fundamentais para a manutenção de práticas sustentáveis de subsistência das comunidades. É apresentada a dura realidade dessas mulheres que, apesar de suas técnicas e contribuições vitais para a pesca, processamento e comercialização de polvos, peixes pequenos e mariscos, têm seu trabalho e modos de vida frequentemente subvalorizados e invisibilizados. Um ponto-chave da pesquisa é o foco nos desafios enfrentados pelas mulheres em manter sua conexão com a pesca artesanal e a mariscagem, sublinhando o quão essencial essa conexão é para suas identidades culturais e comunidades.



Figura 4 – Imagem de pescadora artesanal no *Emergent Ecologies*

Outro ponto de destaque é que as técnicas da pesca artesanal e mariscagem vêm sendo adaptadas pelas mulheres devido às restrições impostas pelo desenvolvimento turístico e imobiliário na região, além das transformações ambientais fruto das mudanças climáticas, que limitam o acesso aos recursos naturais. Essas adaptações servem como forma de mitigar e enfrentar os desafios cotidianos impostos a seus modos de vida, sendo desenvolvidas soluções práticas e inovadoras que refletem um profundo conhecimento dos ecossistemas marinhos locais, políticas ambientais em diversas escalas e formas de conservar a biodiversidade.

Como exemplos da adoção de técnicas de pesca adaptadas às condições atuais, pode-se citar o ajuste dos períodos da atividade e a seleção de novos locais menos explorados. Pode-se citar, ainda, o manejo sustentável dos recursos, a partir da prática de não capturar espécies durante períodos de reprodução e a utilização seletiva de equipamentos que minimizem o impacto ambiental.

Destaca-se também, nessa mesma direção, como as mulheres têm sido pioneiras na criação de redes de apoio comunitário que fortalecem as capacidades locais para enfrentar os desafios socioambientais e se adaptarem às novas realidades ambientais. Isso ocorre através da criação e manutenção de associações comunitárias que promovem, entre outras coisas, a capacitação e troca de conhecimentos sobre técnicas de pesca e gestão de recursos, além de lutarem por seus direitos e trazerem a pauta da sustentabilidade para a mesa de negociação com autoridades e também turistas. A plataforma retrata esses e outros elementos da interação dessas mulheres com seu meio, seu trabalho e sua comunidade.

4.1 ENTRE PLATAFORMAS E TERRITÓRIOS: O VISUAL COMO COPRODUÇÃO

O papel central que as tecnologias digitais e comunicacionais em rede assumem na configuração dos modos de vida contemporâneos vem reconfigurando não apenas as estruturas de mercado e governança, mas também os próprios processos metodológicos e éticos envolvidos na produção cultural, artística e científica (Van Dijck *et al.*, 2018). O crescente acesso e a apropriação dessas tecnologias por amplos segmentos da população, incluindo movimentos socioambientais, povos indígenas e populações locais e tradicionais, têm ampliado significativamente as possibilidades de colaboração e interação desses grupos sub-representados em processos de produção de conhecimento científico. Barreiras antes impostas por distâncias geográficas, limitações temporais, desigualdades de recursos ou diferenças linguísticas tornam-se, progressivamente, mais contornáveis.

A plataforma *Emergent Ecologies* se insere nesse contexto e realiza a interconexão de temas do socioambientalismo com as mídias digitais. Soma-se a isso também a forte presença artística, especialmente visual, que amplia os modos de expressão e extrapola os circuitos acadêmicos e os espaços convencionais de produção e circulação das ciências sociais. A *Emergent Ecologies* ao adotar intensivamente recursos audiovisuais, como fotografias e vídeos, produzidos com e pelos próprios interlocutores, exemplifica uma prática de pesquisa em direção à coprodução de conhecimento.

Vale ressaltar que a plataforma busca valorizar distintas formas de saber, deslocando a centralidade exclusiva das instituições acadêmicas como produtoras e destinatárias do conhecimento (Polk; Knutsson, 2008). Essa reconfiguração metodológica abre caminho para refletir criticamente sobre novas dinâmicas de participação, engajamento e produção colaborativa de conhecimento.

Essa abordagem implica não apenas novas formas de interação entre pesquisadores e comunidades, mas também a transformação dos modos de coleta, análise, circulação e inserção social e institucional dos conhecimentos gerados. Nesse contexto, destaca-se o potencial da antropologia visual e engajada como instrumento que possibilita a formulação conjunta das agendas de pesquisas sobre adaptação climática e sustentabilidade, por sua capacidade de articular dimensões sensíveis da experiência vivida das comunidades e produzir conhecimentos situados, politicamente relevantes e comunicáveis para múltiplos públicos.

A mediação audiovisual, articulada a métodos de engajamento, amplia o escopo colaborativo da pesquisa e aprofunda a compreensão coletiva sobre o enfrentamento ao racismo ambiental e os processos de adaptação em relação às mudanças climáticas. Como sintetiza Luciane Cruz, quilombola que atuou como colaboradora de campo comunitária (interlocutora) na etapa da pesquisa na Bacia e Vale do Iguape:

> "[…] esse projeto veio dando uma força, dando um apoio muito grande para as marisqueiras, onde elas gravaram vários vídeos, onde elas falaram e puderam se expressar, né, se expressar da forma delas, falando o quanto ela gosta da mariscada, o quanto elas vão para a maré, o sofrimento também, os impactos também, elas colocaram muito bem, falando sobre os impactos aqui nas comunidades, né"[8].

A antropologia visual e engajada, nesse sentido, configura-se como uma abordagem particularmente fecunda na *Emergent Ecologies*, pois fortalece as capacidades expressivas das comunidades, que representam e rearticulam seus desafios e soluções por meio de imagens, vídeos e outras formas sensíveis de comunicação. No caso das pescadoras artesanais e marisqueiras brasileiras que participaram da *Emergent Ecologies*, esse processo permitiu não apenas visibilizar as transformações em curso em seus territórios, mas também imaginar futuros possíveis a partir de suas próprias experiências e inovações, trazendo à tona histórias positivas de adaptação, elaboradas pelas próprias comunidades.

Um exemplo concreto disso aparece na forma como as marisqueiras articulam a prática da mariscagem à memória familiar e comunitária, relatando aprendizados herdados de mães e avós. A fala de Janete Barbosa, da Comunidade do Guaí, materializa isso:

> "Eu venho de uma história de remanescente de pessoas que foram escravizadas e tiveram que lutar pela sua sobrevivência, lutar pela sua liberdade. Eu venho de uma família humilde, uma família pobre, como todos os negros e pescadores, e assim dando sequência à minha família e às minhas heranças [...] A minha mãe era marisqueira, e eu aprendi a pegar Sururu com ela, Lambreta, Mapê […]"[9].

Esse reconhecimento da relação entre ancestralidade e modos de viver e produzir é acompanhado da ênfase no caráter duradouro e experimentado de seus saberes e técnicas, bem como na crítica à depreciação de seus conhecimentos. Como pode-se observar na fala de uma marisqueira de Ponta de Souza:

> "Preservar o mangue é essencial, mas até que ponto essa preservação preserva a vida do pescador? A gente sabe cortar e o mangue voltar, o estaleiro do Paraguaçu cortou o equivalente a 20 campos de futebol de mangue, cadê a fiscalização? Aí o pescador tira um galho de mangue para cozinhar o pescado e é acusado de ir contra a natureza. O que é ir contra a natureza? É nosso saber ancestral? Ou é essas empresas que tiram tudo?"[10]

Nesse horizonte é possível entender a plataforma como uma forma de fortalecer as perspectivas locais, ao mesmo tempo que uma contribuição para enriquecer, complementar e diversificar os horizontes da imaginação política e da investigação científica em relação à sustentabilidade. Afinal, as narrativas e soluções que emergem das comunidades são compartilhadas através da plataforma com acesso livre e ampla disseminação internacional.

Destaca-se, ainda, que a escolha por formatos multimídia, interativos e sensíveis ao contexto sociocultural das comunidades contribui para uma prática inovadora de devolutiva etnográfica. Há um estremecimento da noção de que a pesquisa vem primeiro e a devolutiva depois, pois as imagens e sons criados pelos próprios participantes das pesquisas potencializam o controle dos participantes sobre o processo de pesquisa, bem como contribuem para uma maior precisão contextual e relevância dos dados gerados e analisados (Liebenberg, 2009).

Destaque-se também que a plataforma é gratuita e de fácil acesso, combinando conteúdos em linguagem leiga e acadêmica, em contraste com o formato tradicional de etnografias, normalmente monografias longas e de circulação restrita aos circuitos acadêmicos e com *paywalls*. Tais orientações aproximam-se das recomendações sobre governança de dados na antropologia feitas por Parguel (2021) e Rocha (2021), ao reconhecer que os resultados das pesquisas não devem se limitar ao arquivamento técnico ou ao formato documental tradicional, mas, sim, assumir formas acessíveis, dialogadas e politicamente situadas, que permitam uma circulação maior das informações.

Ao adotar essa perspectiva, a plataforma reforça também a proposta de uma troca de conhecimento ativa e multidirecional e, no caso específico que estamos analisando, uma integração entre PCTs e as pautas dos movimentos por justiça social e ambiental no desenvolvimento de conhecimento científico.

4.2 ENTRE PESQUISAS E GOVERNANÇAS: O ENGAJAMENTO COMO MÉTODO

O foco no engajamento enquanto método científico na *Emergent Ecologies* é evidenciado na maneira como as pesquisas foram conduzidas. Destacam-se a transparência dos objetivos e métodos em relação aos movimentos socioambientais locais, a colaboração com os interlocutores ao longo da pesquisa, o acolhimento de múltiplas formas de saber e fazer, bem como a participação ativa nas associações e eventos públicos organizados ou frequentados pelos pescadores e pescadoras artesanais. Soma-se a isso o enfoque nas questões da justiça climática e nas soluções elaboradas pelas próprias comunidades para mitigar e resistir às mudanças ambientais, além de um olhar sensível para a diversidade de gênero e raça.



Figura 5 – Marisqueira retirando ostra no pé dos manguezais

A orientação explícita à promoção da diversidade epistêmica e à construção de diálogos inclusivos entre distintos sistemas de conhecimento busca criar espaços de interlocução que transcendam os contextos de origem. Trata-se de fomentar arenas onde múltiplas perspectivas possam coexistir e interagir, contribuindo para reduzir assimetrias históricas de poder e enfrentando hierarquias que frequentemente marcam as interações entre pesquisadores e "pesquisados".

Esse processo, por sua vez, tem potencial para reconfigurar não apenas os métodos e práticas de produção científica, mas também os próprios marcos discursivos e teóricos tradicionalmente dominantes no campo acadêmico, especialmente ao incorporar críticas sociais e epistemológicas ancoradas em diferentes culturas e experiências socioambientais. O protagonismo dos PCTs na representação e divulgação de seus cotidianos, pontos de vista e práticas ambientais, constitui, assim,

uma contraposição a uma possível reificação e calcificação dos seus conhecimentos tradicionais ecológicos (Ingold; Kurttila, 2000).



Figura 6 – Escaldado de sururu, ostra e siri retratado por interlocutora da pesquisa

Essa abordagem ecoa as perspectivas na antropologia, na ciência engajada e na ciência cidadã que enfatizam a participação ativa e consciente dos "pesquisados" em todas as etapas do processo científico. Isso inclui desde a formulação de perguntas de pesquisa até a coleta, processamento e análise de dados, bem como a disseminação dos resultados (Lassiter, 2005). Essa ênfase, traz o tensionamento entre as posições dos atores especialistas, no caso pesquisadoras doutoras, e aqueles frequentemente considerados leigos, os "pesquisados".

Pelas perspectivas da ciência cidadã e da antropologia engajada, a tensão entre esses polos não é tratada como um obstáculo, mas sim como uma dimensão produtiva e parte integral da própria prática de pesquisa, de onde surgem oportunidades para incluir adequadamente os pontos de vista de grupos vulnerabilizados ou marginalizados na esfera pública. Trata-se de buscar uma articulação entre o rigor científico e propósitos socialmente relevantes capazes de gerar benefícios para todos os participantes, e não apenas para os cientistas.

Essa perspectiva é aprofundada por Lozano (2022), que critica abordagens que reduzem a colaboração na produção etnográfica a uma simples divisão de tarefas entre pesquisadores e interlocutores, limitada a fases operacionais da pesquisa. Para o autor, a colaboração deve ser concebida como um processo dialógico e recursivo, no qual o pesquisador adota uma postura de descentramento, atuando como uma espécie de facilitador e não como autoridade final na produção do conhecimento.

Essa postura exige dos pesquisadores um grau de reflexividade que permita contornar o risco de que, diante de visões divergentes, a pesquisa seja conduzida de forma a privilegiar a relevância acadêmica em detrimento da utilidade prática para os interlocutores não acadêmicos.



Figura 7 – Noca escaldando ostra

Nessa mesma direção, um aspecto igualmente significativo, ao analisarmos a *Emergent Ecologies*, é o esforço explícito de enfrentamento do racismo ambiental, conceituado na plataforma da seguinte forma: "O racismo ambiental refere-se à forma como as minorias étnicas e raciais são desproporcionalmente afetadas por problemas ambientais devido a práticas discriminatórias e desigualdades sociais e econômicas." (Emergent Ecologies, 2024).

A plataforma ressalta o fato que as populações que colaboram com as pesquisas foram e seguem sendo historicamente racializadas e, dessa maneira, sofrem as nefastas consequências desse tipo específico de racismo. Observa-se ainda que a plataforma se propõe explicitamente a abordar temas e questões socioambientais concretas que realmente ressoem as necessidades e preocupações materiais dos PCTs que participaram das pesquisas. Assim, a plataforma centra seus esforços na enfatização da ética e da estética de pescadoras e marisqueiras artesanais, no impacto do conhecimento por meio de sua transposição para linguagens acessíveis capazes de alcançar diferentes audiências, na promoção e participação de articulações e mobilizações comunitárias e no fortalecimento dos debates que circundam as culturas tradicionais dentro do ambiente acadêmico.

4.3 ENTRE DIRETRIZES E PRÁTICAS: UM CAMPO ABERTO DE POSSIBILIDADES

Outro aspecto que merece reflexão refere-se ao foco predominante de pesquisa social e etnográfica da plataforma. Embora reconheçamos que essa orientação constitua uma das principais forças da *Emergent Ecologies*, observa-se também que as pesquisas poderiam ser significativamente enriquecidas caso incorporassem, de forma ainda mais profunda, sistemática e evidente, abordagens e ferramentas típicas da ciência cidadã enquanto vertente epistemológica capaz de integrar as ciências naturais e ambientais às ciências sociais e humanidades. Afinal, esse é um elemento que poderia contribuir significativamente para um maior êxito e sucesso das pesquisas, além de fornecer às comunidades locais dados adicionais que poderiam auxiliar a fundamentação de seus trabalhos (Albert *et al.*, 2021; Hecker *et al.*, 2018).

Considerando o objetivo da plataforma de compreender os impactos das mudanças ambientais nas comunidades tradicionais e locais, bem como suas capacidades de adaptação, há um potencial significativo para o fortalecimento de parcerias interdisciplinares mais robustas, envolvendo de forma

integrativa campos como, por exemplo, a agroecologia, a biologia da conservação, a geografia e os estudos ambientais aplicados, incluindo aqueles voltados para o desenvolvimento sustentável e a gestão territorial participativa. Em especial destacam-se possibilidades de incorporação de indicadores agroecológicos, dados geoespaciais/climáticos e procedimentos de gestão e monitoramento territorial.

Em diálogo com trabalhos de Tsing *et al.* (2024), pode-se argumentar que a articulação entre antropologia e medições técnicas biofísicas pode ser entendida não como perda da dimensão social da pesquisa, mas, sim, cultivo de conhecimentos situados e aprofundamento das artes de atenção baseadas no trabalho de campo. Nessa direção, sensores, métricas, indicadores e bases de dados não necessariamente tecnocratizam a investigação. Pelo contrário, abrem espaço para a sintonização etnográfica (Tsing, 2022) e para que as dinâmicas materiais-ecológicas dos territórios se expressem e entrem na arena política (Latour, 2004).

É nesse sentido que entendemos que a ampliação das bases epistemológicas e metodológicas do *Emergent Ecologies* poderia contribuir para leituras mais integradas das inter-relações que afetam os territórios pesquisados, favorecendo a construção de uma pluralidade de evidências empíricas e inferências teóricas sobre as ecologias emergentes e os processos de transformação socioambiental em curso. Esse enfoque ampliado, baseado em múltiplos tipos de empirismo, poderia potencializar a legitimidade pública e o uso estratégico dos resultados das pesquisas em processos de planejamento e gestão ambiental e territorial, políticas públicas voltadas para o desenvolvimento sustentável e lutas pela garantia de direitos por parte dos movimentos por justiça climática.

Uma referência central nesse sentido é o trabalho de Gabrys (2022, 2019), que, a partir da noção de "sensores cidadãos", explora a interseção entre dados ambientais com ciências sociais, conectando ambientes, tecnologias de baixo custo, formas organizativas coletivas e práticas situadas.

Destacamos ainda outro aspecto da *Emergent Ecologies* em relação à ciência cidadã. A intensa cooperação e desenvolvimento de capacidades entre equipes de pesquisa dos EUA e do Brasil, bem como a adoção do formato bilíngue (inglês e português). Há ainda a promoção de intercâmbios e formações entre pesquisadores em universidades e centros de pesquisa no Norte e Sul Global. Essas características reforçam o compromisso com uma produção científica descentralizada, multicultural e interinstitucional, que busca reduzir assimetrias históricas na produção e circulação de conhecimento.

Nesse ponto, gostaríamos de realizar uma reflexão sobre como diversas diretrizes sobre o que é ou deve ser a ciência cidadã englobam um espectro demasiadamente amplo de ações e recomendações. Nesse contexto, nem todas as pesquisas conseguem e nem deveriam cumprir integralmente com as extensas recomendações e diretrizes que definem a ciência cidadã. Por exemplo, a plataforma *Emergent Ecologies* não se dedica especificamente à produção de grandes conjuntos de dados por meio de técnicas de *crowdsourcing* ou à criação e oferta de infraestrutura, como repositórios de dados abertos ou instalações físicas de pesquisa acessíveis para o público em geral, elementos bastante relevantes e característicos no que tange à ciência cidadã.

Contudo, é importante ressaltar que, embora reconheçamos que os pilares, valores e princípios da ciência cidadã, e da mesma forma das pesquisas engajadas, sejam interdependentes e que o foco nesse aspecto potencializa suas práticas, as diretrizes não necessitam ser atendidas de forma plena para que uma plataforma ou projeto de pesquisa seja reconhecido, bem como contribua para essas abordagens. Em vez disso, essas diretrizes podem ser vistas como um conjunto de possibilidades ajustáveis, que devem ser consideradas e acolhidas de acordo com cada caso específico, bem como referências para inspirar novos desenvolvimentos nas pesquisas.

Por fim, reforçamos, baseados em Kythreotis *et al.* (2019), que políticas climáticas contemporâneas predominantemente baseadas em linguagens tecnogerencial e "top-down", isto é, hierárquicas, têm falhado em atingir legitimidade e as necessárias metas ambiciosas para confrontar a crise

climática. Pesquisas científicas que operam em outra chave, como a coprodução de conhecimento, isto é, reposicionando os cidadãos como coaprendizes e codecisores, capazes de tensionar estruturas institucionais e ampliar o repertório de saberes, podem ser uma forma efetiva de contornar essas questões.

Faz-se necessário ressaltar ainda que metodologias de coprodução do conhecimento precisam incorporar um carácter reflexivo para lidar com desigualdades prévias, como tempo, recursos e status epistêmico que favorecem "atores de elite" (Estado, grandes ONGs, cientistas renomados), que não raramente definem escopos e critérios de relevância, reforçando hierarquias entre conhecimento científico e outros sistemas de saber. Soma-se que em contextos Norte–Sul, como é o caso do *Emergent Ecologies*, o alto grau de desigualdade nas capacidades técnicas, institucionais e orçamentárias agrava ainda mais essas assimetrias. Uma abordagem reflexiva exige que as pesquisas não suprimam conflitos; ao contrário, que aceitem a contestação e o dissenso em torno de interesses e visões divergentes e, com postura de humildade, fortaleçam o pluralismo como motor criativo (Turnhout *et al.*, 2020).

5. CONSIDERAÇÕES FINAIS

A plataforma *Emergent Ecologies*, analisada neste artigo, busca produzir conhecimentos sobre as ecologias emergentes em territórios no Brasil habitados por comunidades locais e tradicionais e ricos em biodiversidade, altamente impactados pela crise climática, *locus* de incertezas profundas e aceleradas mudanças. Assim, aborda a capacidade das comunidades de criar soluções inovadoras e de se adaptar ante os impactos negativos das mudanças ambientais e sociais, bem como nas relações singulares culturais, sociais, políticas e, evidentemente, também ecológicas que estabelecem com seus respectivos ambientes locais.

Em outras palavras, a plataforma aborda as respostas criativas e situadas das comunidades ante a pressões externas, como políticas públicas, mercados e mudanças climáticas, mas também a partir de dinâmicas internas, como conflitos sociopolíticos, reorganizações institucionais e transformações culturais. Longe de representarem respostas predeterminadas ou reações espontâneas, essas configurações evidenciam processos contínuos de criação, negociação, adaptação e também conflito que se desdobram nas dinâmicas coletivas e concretas do cotidiano socioambiental dessas comunidades.

A ciência cidadã e a antropologia visual engajada, mobilizadas pela plataforma *Emergent Ecologies*, possibilitam o acesso a camadas das ecologias emergentes e de sentido que possivelmente não estariam inicialmente visíveis, ou suficientemente contempladas, pelos atores acadêmicos e que muitas vezes escapam às linguagens estritamente técnico-científicas. Busca-se assim produzir conhecimento por meio da mediação entre diferentes racionalidades, produzindo um modo de deliberação coletiva e negociação de alternativas, especialmente útil em contextos que envolvem incertezas profundas e aceleradas mudanças.

Considerando que o desafio do enfrentamento da crise climática é global, mesmo sendo seus impactos localmente contextualizados, e que a urgência das ações exige a priorização de uma ampla gama de abordagens, inclusive as "não convencionais" do ponto de vista da ciência *mainstream*, acreditamos que plataformas científicas, como a *Emergent Ecologies*, constituem-se uma via promissora para enfrentar tal desafio. Ao evitar o excesso de tecnocracia, articular objetivos científicos, sociais e ambientais, e valorizar metodologias e linguagens não estritamente científicas, baseadas em tecnologias digitais e em rede, esse tipo de plataforma pode contribuir para a superação da tendência de tratar a sociedade como mera "usuária final" de informação produzida por instituições e projetos de ciência, compondo um repertório de adaptação e soluções bem-sucedidas que podem colaborar para a ampliação dos horizontes da imaginação política, científica e para o engajamento social.

A *Emergent Ecologies*, apesar de não constituir uma resposta predeterminada, oferece uma arquitetura de infraestrutura sociotécnica reconfigurável que pode ser mobilizada em outros territórios, problemáticas ambientais e formas de mobilização coletiva. Essa arquitetura incorpora o compromisso ético enquanto dimensão constitutiva da prática de pesquisa, concebida como devir e parte fundamental para que a coprodução de conhecimento conecte mecanismos de reparação histórica e redistribuição de poder a ações de transformação para a sustentabilidade e justiça climática.

DECLARAÇÃO SOBRE O USO DE INTELIGÊNCIA ARTIFICIAL

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NOTAS

1 | Cf.: Decreto Federal nº 2.519/1998.

2 | Cf.: < https://agenciagov.ebc.com.br/noticias/202309/oficina-reune-demandas-para-adaptacao-as-mudancas-climaticas >.

3 | Os conceitos de justiça climática e racismo ambiental são cruciais para a compreensão desse debate (Acselrad, 2010; Alier, 2007; Bullard, 1993; Schlosberg; Collins, 2014).

4 | Os autores deste artigo são pesquisadores vinculados à produção da plataforma. Reconhecemos que essa posição, ao mesmo tempo que amplia as possibilidades de investigação, acesso aos conteúdos e perspectiva sobre os processos de sua elaboração, exige reflexividade, no sentido da objetividade forte (Harding, 1993), tanto em relação ao escopo quanto aos limites das análises desenvolvidas.

5 | No final de 2021, durante a Conferência Geral da Unesco, 193 países adotaram o primeiro instrumento internacional de definição de normas sobre ciência aberta (Unesco, 2021). Um desenvolvimento específico dentro desse enquadramento mais amplo é a ciência cidadã, amplamente reconhecida como um de seus pilares fundamentais (OECD, 2025). Cabe notar que a ciência cidadã, desde suas primeiras formulações (Irwin, 1995), é atravessada por um importante debate entre vertentes mais voltadas à participação de não acadêmicos na coleta de dados para projetos científicos e outras orientadas à democratização da produção de conhecimento e à ampliação das possibilidades de relações construtivas entre ciência e sociedade. Neste artigo, desenvolvemos nossos argumentos a partir dessa segunda perspectiva.

6 | Cf.: < https://www.emergentecologies.net/ >.

7 | Fundado em 2014, o Centro promove pesquisas e redes de colaboração com o Brasil nas áreas de Sustentabilidade, Artes e Cultura, Direitos Humanos e Saúde, com atenção transversal à Política e Governança. A Emergent Ecologies nasce e se estrutura a partir do Centro, que oferece infraestrutura, recursos e apoio acadêmico.

8 | Cf.: < https://www.emergentecologies.net/conselho-quilombola >.

9 | Cf.: < https://www.emergentecologies.net/pesca-artesanal >.

10 | Cf.: < https://www.emergentecologies.net/pontadesouzacoqueirosenaje >.

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FIFA standard and environmental sustainability: thinking ahead

Padrão FIFA e sustentabilidade ambiental: pensando no futuro

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ABSTRACT

This study aims to identify opportunities for advancing the environmental sustainability standards established by FIFA. The study adopts a comparative approach to analyse how different environmental certifications relate to FIFA's stadium sustainability requirements. The process includes selecting comparable cases, defining the elements to be compared, and conducting a general comparative analysis. The findings indicate that the environmental sustainability aspects in FIFA's standards, as defined in the 2011 and 2022 documents, encompass dimensions such as carbon reduction, energy efficiency, sustainable water use, biodiversity, waste management, and green certifications. Standards such as B Corp, GRI, Carbon Trust, and ISO 14001 offer advances that could be incorporated into the FIFA standards. It is concluded that future developments of the FIFA Standard should consider incorporating internationally recognised environmental standards.

Keywords: Environment. Sustainability. FIFA. Standards. Smart Stadiums.

RESUMO

Este estudo tem como objetivo identificar possibilidades de avanço nos padrões de sustentabilidade ambiental estabelecidos pela FIFA. O trabalho adota uma abordagem comparativa para analisar como diferentes certificações ambientais se relacionam com os requisitos de sustentabilidade dos estádios da

FIFA. O processo inclui a seleção de séries comparáveis, a definição dos elementos a serem comparados e a comparação. Identificou-se que os aspectos de sustentabilidade ambiental no padrão da FIFA, conforme definidos nos documentos de 2011 e 2022, abrangem dimensões como redução de carbono, eficiência energética, uso sustentável da água, biodiversidade, gestão de resíduos e certificações verdes. Padrões como B Corp, GRI, Carbon Trust e ISO 14001 oferecem avanços que poderiam ser incorporados ao padrão da FIFA. Conclui-se que futuros avanços no padrão FIFA devem considerar a incorporação de normas ambientais reconhecidas internacionalmente.

Palavras-chave: *Ambiental. Sustentabilidade. FIFA. Padrão. Estádios Inteligentes.*

1 INTRODUCTION

The theme of environmental sustainability has become increasingly relevant globally as concerns about climate change, pollution, water scarcity, and other environmental challenges grow. In the academic field, researchers study sustainability in its economic, social, and ecological dimensions (Kashaba; Rehan, 2020; Oliveira; Faria, 2019). In the sports industry, although relatively recent, sustainability has become an irreversible trend, manifesting in various ways, including the need to minimise the environmental impact of sports facility renovations and construction (Kashaba; Rehan, 2020; Tavares *et al.*, 2018).

With the rise of large multi-purpose arenas, their role extends beyond hosting sporting events to include opportunities to promote environmentally responsible practices (Francis *et al.*, 2023). The Fédération Internationale de Football Association (FIFA), football's governing body, recognises the urgent need to promote environmentally sustainable standards in stadiums worldwide (FIFA, 2011; FIFA, 2022). In FIFA competitions, strong environmental sustainability goals have been established and expanded, including efficient energy use, reduced water consumption, and the use of local materials (FIFA, 2022; Khashaba, 2020).

In 2022, Qatar committed to hosting a sustainable FIFA World Cup (Al-Hamrani *et al.*, 2021), following FIFA sustainability guidelines similar to those adopted for the 2014 renovation of the Maracanã Stadium (Tavares *et al.*, 2018). Another important Brazilian example is the Mineirão Stadium, also used in the 2014 World Cup. Achieving the highest LEED certification level **demonstrates** that the project sought not only compliance but also long-term economic benefits (Oliveira; Faria, 2019).

Stadium sustainability has been studied from several perspectives: analyzing zero waste through a stadium case study (Costello; Mcgarvey; Birisci, 2017); technical-economic analysis to improve energy efficiency and sustainability at Flaminio Stadium in Rome (Tiberi; Carbonara; Sforzini, 2017); a case study on sustainability-oriented stadium policy (Bunds *et al.*, 2019); measuring the economic impact of sustainable construction concepts in the Mineirão project (Oliveira; Faria, 2019); analysing social sustainability and the legacy of circular and shared economy in FIFA World Cup organisation (Kucukvar *et al.*, 2021); evaluating the effectiveness of Greenship certification in stadium construction projects in Indonesia (Hanif, 2022); and raising awareness about sustainability in stadiums (Cayolla; Quintela; Santos, 2022).

Despite existing studies, they have not focused on FIFA sustainability guidelines. Addressing this gap, the present study aims to identify opportunities to advance the environmental sustainability standard established by FIFA.

2 METHODOLOGY

The methodology of this study is based on a comparative document analysis to identify gaps in FIFA's environmental sustainability standards and propose recommendations for improvement. Comparative analysis enables the identification of similarities, differences, and patterns among institutional frameworks (Lor, 2019).

1.2 DOCUMENT SELECTION

The study analysed two key FIFA documents addressing sustainability in stadium design and construction: Football Stadiums – Technical Recommendations and Requirements (FIFA, 2011) and Football Stadiums Guidelines (FIFA, 2022). These were selected because they represent FIFA's main sustainability guidelines for stadium development. To develop the comparative framework, these documents were analysed alongside nine internationally recognised environmental standards and certification systems: B Corporation, Global Reporting Initiative (GRI), Carbon Trust, ISO 14001, ISO 26000, Sustainability Accounting Standards Board (Sasb), UN Global Compact, MSCI ESG Ratings, and Leadership in Energy and Environmental Design (Leed). These standards were selected due to their global relevance and broad coverage of environmental sustainability practices.

1.3 COMPARATIVE ANALYSIS

A comparative analysis was conducted to evaluate sustainability requirements in FIFA guidelines and the selected standards. Sustainability themes, requirements, and indicators were identified and organised into comparable categories, including carbon emissions, energy efficiency, water management, waste management, biodiversity, and environmental governance. These categories were then compared with FIFA guidelines to identify practices present in the standards but absent from FIFA's framework. This procedure enabled the identification of gaps and supported the synthesis tables presented in the Results and Discussion section.

1.4 PROPOSITION OF IMPROVEMENTS

Based on the identified gaps, recommendations were developed to improve FIFA's sustainability standards. These proposals draw on best practices observed in the analysed standards and aim to strengthen FIFA's framework by incorporating additional environmental management practices and monitoring indicators.

2 RESULTS AND DISCUSSION

2.1 ENVIRONMENTAL SUSTAINABILITY REQUIREMENTS OF THE FIFA STANDARD

The global commitment to sustainability has become a priority in many industries, and sport, including FIFA, is no exception. The Green Goal programme proposed by FIFA in 2011 outlines an approach to environmental sustainability, with goals such as responsible consumption, waste reduction, energy efficiency, and the promotion of public transport at FIFA events. Its main objective is to achieve climate balance by reducing greenhouse gas emissions (FIFA, 2011). In more recent documents from 2022, FIFA emphasises that its approach to the three sustainability dimensions — Social Development, Environmental Protection, and Economic Development — plays an important role in promoting sustainable actions in football stadiums worldwide.

FIFA aims to develop sustainable stadiums that address environmental and social concerns while supporting local economic growth (FIFA, 2022). This perspective seeks to lead by example and encourage other sectors to adopt responsible practices. FIFA's sustainability standards include key themes such as carbon reduction, energy efficiency, sustainable water use, biodiversity, ecology, waste management, and green certifications. These represent priority areas for promoting sustainability in football stadiums globally.

In stadium construction, carbon reduction has become increasingly important, especially regarding the embodied carbon of materials. FIFA (2022) proposes strategies such as optimising structural design, material substitution, adopting life cycle assessment, and selecting local renewable energy suppliers.

Carbon reduction also extends beyond the design phase through the offsetting of remaining emissions. Energy efficiency is another key pillar for reducing stadium emissions. Strategies include designing efficient thermal envelopes, using renewable energy sources, and adopting technologies such as photovoltaic panels, wind energy, geothermal systems, and solar thermal systems. Energy storage, primarily through battery systems, is also a viable solution for meeting demand during events and providing backup supply (FIFA, 2022). Sustainability also involves the responsible use of water, considering global water scarcity. Strategies include rainwater harvesting, water-saving technologies, and efficient management of sanitary and food facilities serving large audiences.

FIFA encourages innovations such as rainwater harvesting systems on stadium roofs and wastewater recycling (FIFA, 2022). Biodiversity and ecology are also considered in sustainable stadium development. FIFA highlights the importance of avoiding construction in areas with high ecological value and preserving such areas within stadium environments. Strategies include selecting sustainable materials, responsible timber management, creating green corridors, and providing habitats for wildlife. Waste management is another global challenge, and FIFA proposes strategies to minimise waste during construction.

These include selecting recyclable materials, understanding material dimensions, and specifying solutions such as precast concrete. Contractors are encouraged to establish ambitious waste reduction and recycling targets and to reuse existing structures whenever possible. Finally, green certifications such as Leed and Breeam represent a practical demonstration of FIFA's commitment to sustainability. These certifications evaluate the environmental performance of stadiums and recognise sustainable practices in design, construction, and operation.

Despite additional costs, FIFA considers certification an investment that promotes sustainability and aligns projects with development guidelines. FIFA (2011) had already emphasised the importance of these initiatives by highlighting that sustainable construction improves the environment and creates healthier spaces for society. Based on the themes and guidelines presented in FIFA (2011) and FIFA (2022), a synthesis was developed illustrating the sustainability concept within FIFA standards and the requirements for a stadium to become sustainable (Table 1).

Table 1 – Requirements for Sustainable Stadiums according to FIFA 2011 and FIFA 2022

Theme	*Requirement*
Carbon Reduction	Structural optimisation; substitution of steel and concrete with wood; use of local suppliers powered by renewable energy; low-carbon materials; life-cycle assessment.
Energy Efficiency	Efficient thermal envelope; renewable energy use (photovoltaic, geothermal, etc.); energy storage systems; efficient technologies.
Sustainable Water	Rainwater harvesting; water-saving technologies; efficient water management in facilities and irrigation; wastewater treatment and reuse.
Biodiversity and Ecology	Avoid construction in high ecological value areas; preserve ecological zones; create green corridors; use sustainable materials and support habitats.

Theme	Requirement
Waste Management	Recyclable materials; waste reduction during construction; reuse of demolition materials; circular-economy practices.
Green Certifications	Green building certifications (Leed, Breeam, Green Building Star, carbon footprint); environmental performance evaluation and compliance.

Source: The authors.

2.2 ENVIRONMENTAL STANDARDS

Environmental certifications in buildings provide economic, social, and environmental benefits, including cost reduction, improved safety and health, the promotion of sustainability, and the efficient use of natural resources (Lamy *et al.*, 2021). These certifications go beyond FIFA guidelines and play an important role in promoting positive environmental impacts in the global sports context. This section presents the main environmental standards, each accompanied by a synthesis table describing sustainability requirements and recommendations.

The B Corp Certification directly influences business operations and sustainable strategies. Certified companies demonstrate a commitment not only to legal compliance but also to responsible environmental practices. The B Corp certification helps communicate these commitments, strengthening relationships with funders and attracting investors aligned with sustainable values (Paelman *et al.*, 2023).

Regarding environment and sustainability, B Corp Certification requires companies to obtain at least 80 points on a 200-point scale, with 20 points related to environmental criteria. Impact areas include governance, workers, community, environment, and customers. Environmental criteria assess facility efficiency, environmental management, certified products, energy consumption, water management, waste management, and ecosystem conservation practices (Diez-Busto; Sanchez-Ruiz; Fernandez-Laviada, 2022).

Companies with annual revenue below $5 million and fewer than 50 employees may apply for Pending B Corporation certification. The process includes the assessment of environmental efficiency, natural resource management, emissions and waste, products and services, and environmental responsibility. Examples of practices include reducing water and energy use, minimising waste and greenhouse gas emissions, evaluating the environmental impacts of products and services, adopting sustainable purchasing practices, using sustainable transport, ensuring transparent environmental communication, and investing in environmental innovation (B Corporation, 2022).

Table 2 presents a synthesis of environmental requirements by category of the B Corp Certification.

Table 2 – Synthesis of Environmental Requirements by B Corp Certification Category

Category	Aspects considered in the requirements
Environmental Management	Facility efficiency. Environmental management systems. Certified products. Environmental assessment and product development.
Air and Climate	Monitoring of energy use, renewable energy, electricity sources, low-impact energy, eco-friendly equipment, energy reduction, GHG emissions (Scopes 1, 2, 3), carbon intensity, GHG reduction, shipping policies, supply chain emissions management, supplier offsets, local purchasing, and transport impacts.
Water	Monitoring of water use, total consumption, conservation, captured or recycled water, toxic wastewater, disposal, and supply chain water management.
Land and Life	Monitoring of non-hazardous and hazardous waste, disposal, recycling, waste reduction, supply chain waste, packaging impacts, recyclable or biodegradable materials, preferable inputs, hazardous materials, chemical management, and biodiversity impacts in the supply chain.

Source: The authors.

The main areas of study related to the Global Reporting Initiative (GRI) encompass research on the implementation and impact of GRI guidelines in organisational sustainability reporting practices, including the measurement of sustainable performance. In Environmental Science, research covers the assessment of environmental performance, sustainability indicators, and environmental reporting, exploring the environmental impact of corporate practices, among other topics. Additionally, there is a comprehensive analysis of the financial risks and returns associated with sustainability, along with integrating Environmental, Social, and Governance (ESG) criteria into financial assessments (Evahdati; Aripng, 2023). Table 3 provides a synthesis of environmental requirements by GRI category:

Table 3 – Synthesis of Environmental Requirements by GRI Category

Category	*Requirements*
GRI 3: Materials 2021	Report the use of renewable and non-renewable materials. Demonstrate sustainability through the incorporation of recycled materials. Assess efficiency in product and packaging reuse.
GRI 302: Energy 2016	Quantify and categorise organisational energy use. Disclose environmental impacts beyond organisational boundaries. Measure energy efficiency based on organisational characteristics. Demonstrate reductions in energy consumption and improvements in energy efficiency.
GRI 303: Water and Effluents 2018	Report interactions with water and related impacts, including stakeholder engagement and water management. Define effluent discharge standards considering impacts on receiving water bodies. Specify water withdrawal sources, including water-stress areas. Report discharge types and priority substances. Present total water consumption and storage changes causing significant impacts.
GRI 304: Biodiversity 2016	Describe operational sites in biodiversity areas. Report positive and negative biodiversity impacts, affected species, and impacted areas. Identify protected or restored habitats and restoration success. Classify species in affected areas and extinction risk levels.
GRI 305: Emissions 2016	Report direct GHG emissions (Scope 1) including gases and base year. Exclude carbon market transactions and report biogenic CO_2 separately. Distinguish indirect emissions (Scopes 2 and 3). Calculate emissions intensity and demonstrate reductions in emissions and energy use. Report ODS production and significant air emissions.
GRI 306: Waste 2020	Report total generated waste by composition (excluding effluents). Report non-disposed waste and hazardous waste by composition. Report total disposed waste by disposal method.

Source: The authors.

The Carbon Trust Certification is accredited by the United Kingdom Accreditation Service (Ukas) to verify greenhouse gas emissions in accordance with ISO 14065:2007, using PAS 2050 and the Code of Good Practice. PAS 2050, developed by the British Standards Institution, establishes a globally consistent method for assessing greenhouse gas emissions throughout the life cycle of goods and services. It applies to various sectors, including Agriculture, Energy, Finance, Processed Food, Retail, and Tourism (Carbon Trust, 2023). The certification covers essential areas such as Environment, Social, Management and Ethics, and Quality, reflecting Carbon Trust's commitment to promoting sustainable and responsible practices across various industries. Table 4 provides a synthesis of environmental requirements by Areas for Carbon Trust Certification:

Table 4 – Synthesis of Environmental Requirements for Carbon Trust Certification

Areas	*Requirements*
Environment: Energy	Include greenhouse gas emissions and removals related to energy supply and use across the product lifecycle, according to PAS 2050:2011. Demonstrate appropriate emission factors for renewable energy and apply strict conditions for its use in processes. Account for emissions and removals from renewable electricity generation within defined system boundaries. Include emissions and removals from biomass use, covering production and combustion of biofuels, according to PAS 2050:2011.
Environment: Climate	Ensure that the lifecycle GHG assessment is comprehensive, consistent, and accurate in accordance with PAS 2050:2011. Monitor all emissions and removals, considering gases listed in Annex A from fossil and biogenic sources (except food products). Quantify emissions using the PAS 2050:2011 methodology. Implement GHG reduction programs. Exclude soil carbon changes in existing systems unless specific requirements apply. Estimate non-CO_2 emissions from livestock and soils using IPCC guidelines. Do not use GHG offset mechanisms during lifecycle emission assessment.

Source: The authors.

ISO 14001 is a global standard for environmental management that guides organisations in minimising their environmental impacts. It requires an environmental policy, planning, implementation, verification, and continuous review. It emphasises setting goals, considering legal requirements, preventing pollution, and seeking continuous improvement. Implementing it helps reduce impacts, comply with regulations, enhance image, and cut costs. It demands compliance, documentation, constant adjustments, and the prioritisation of environmental efficiency (ABNT, 2015). Table 5 provides a synthesis of environmental recommendations by category of ISO 14001:

Table 5 – Synthesis of ISO 14001 Requirements

Category	*Recommendation*
Environmental Policy	Establish an environmental policy focused on environmental protection and legal compliance. Adapt it to the organisation's nature, scale, and impacts. Document and communicate the policy publicly.
Planning	Conduct an environmental impact analysis to identify significant aspects. Develop action plans with measurable goals. Consider legal and regulatory requirements.
Implementation and Operation	Define roles and responsibilities to ensure resources. Implement procedures to achieve environmental objectives. Control activities with significant environmental impacts.
Verification	Monitor and measure activities with environmental impact. Report results to environmental authorities. Implement corrective actions for non-conformities with ISO 14001. Conduct environmental audits.
Management Review	Review the environmental management system before audits. Evaluate the need for changes in policies and objectives. Promote continuous improvement of environmental performance.

Source: The authors.

ISO 26000 is a global standard that provides comprehensive guidelines on corporate social responsibility and sustainability. Unlike ISO 14001, which focuses on environmental management, ISO 26000 addresses various aspects of social responsibility in organisations of all types (ABNT, 2010). It is not certifiable but serves as a guide for incorporating socially responsible practices.

The standard encompasses seven fundamental principles, emphasising responsibility, transparency, ethics, and respect for human rights. It highlights the importance of integrating social responsibility into daily practices, engaging stakeholders, identifying sustainability issues, transparency and communication, respecting human rights and labour standards, responsible supply chains, and promoting sustainable development (ABNT, 2010).

Implementing ISO 26000 helps organisations manage social and environmental impacts, comply with regulations, enhance their image, and reduce costs, promoting a holistic approach to corporate

social responsibility and sustainability (ABNT, 2010). Table 6 provides a synthesis of environmental recommendations by category of ISO 26000:

Table 6 – Synthesis of ISO 26000 Environmental Recommendations

Category	*Recommendation*
Community Engagement	Identify environmental impacts in operations. Promote transparency. Engage communities in environmental dialogue. Collaborate to address local environmental challenges.
Respect for Human Rights	Consider human rights in environmental decisions. Avoid impacts that violate rights. Protect affected communities. Support workers involved in environmental practices.
Fair Labour Practices	Ensure safe working conditions in environmental activities. Provide training for responsible practices. Promote equality and diversity. Prevent child labour.
Organisational Governance	Integrate environmental practices into governance. Establish environmental policies and goals. Ensure accountability for environmental impacts. Include indicators in governance reports.
Sustainable Consumption	Promote sustainable products and services. Provide transparent environmental information. Adopt sustainable production alternatives. Encourage responsible consumer practices.
Engagement with Governments and Regulation	Comply with environmental regulations. Collaborate with governments on environmental policies. Participate in initiatives promoting responsible practices. Ensure transparency with regulatory bodies.
Community and Society Development	Support sustainable community development. Collaborate with environmental social initiatives. Share knowledge and resources for environmental benefits.

Source: The authors.

The Sustainability Accounting Standards Board (Sasb), adopted by over 100 companies in 2019, is driven by financial motives, aiming to integrate comparable ESG metrics into SEC requirements. Funded by entities such as Bloomberg, Sasb developed 77 ESG standards in 2018. Companies have discretion in selecting relevant items, whereas Sasb focuses on financially material sustainability reporting related to ESG risks and opportunities. Seeking to enhance intangible value, it emphasises the importance of comprehensive disclosure and high-quality data for market discipline. In a context where investors seek sustainability as a competitive advantage, Sasb stands out as an evolution of traditional accounting standards (Parfitt, 2022; Pizzi; Principale; Nuccio, 2022). Table 7 presents a synthesis of environmental recommendations by Sasb category:

Table 7 – Synthesis of Sasb Environmental Requirements

Category	*Recommendations*
GHG Emissions	Control GHG emissions.
Air Quality	Implement actions to control Air Quality.
Energy Management	Conduct Energy Management.
Water and Wastewater Management	Implement actions for Water and Wastewater Management.
Waste and Material Management	Employ practices for Waste and Material Management.
Ecological Impacts	Minimise environmental impacts.

Source: The authors.

The UN Global Compact promotes sustainable development by bringing together businesses, organisations, and UN agencies. Its environmental principles include promoting a preventive approach to environmental challenges, developing initiatives for environmental responsibility, and encouraging eco-friendly technologies. To comply with these principles, companies must adopt environmental

policies, implement management systems, invest in sustainable technologies, and support sustainability initiatives. The UN Global Compact provides resources and support to assist companies in implementing these principles, aiming to contribute to a more sustainable future (UN Global Compact, 2023). Table 8 presents a synthesis of environmental recommendations by category of the UN Global Compact:

Table 8 – Synthesis of Environmental Recommendations from the UN Global Compact

Category	*Recommendations*
Preventive Approach	Operate proactively to identify and mitigate environmental challenges. Adopt preventive environmental policies aligned with the UN Global Compact's values and principles. Incorporate the preventive approach into the company's strategies, policies, and procedures.
Environmental Responsibility	Develop and implement environmental policies aligned with the Ten Principles of the UN Global Compact. Integrate sustainable development into the values and organisational culture. Promote environmental responsibility in all areas of operation.
Eco-Friendly Technologies	Invest in eco-friendly technologies that promote efficiency and sustainability. Encourage the development and dissemination of environmentally friendly technologies. Collaborate with industry partners to promote sustainable innovation. Adopt sustainable production and consumption practices.

Source: The authors.

O MSCI ESG Ratings, developed by MSCI, classifies companies from 'AAA to CCC' based on their environmental, social, and governance (ESG) performance. The environmental focus covers climate change, natural resources, pollution, and environmental opportunities. The environmental assessment considers management, energy efficiency, impact and environmental risks, regulatory compliance, sustainable innovation, and ESG transparency (MSCI, 2023).

The ratings, crucial for investment decisions, range from A to E. Leading companies meet criteria such as environmental policies, emissions disclosure, waste management, and sustainable resource use. These practices highlight companies committed to sustainability and contribute to a more responsible future (MSCI, 2023). Table 9 provides a summary of environmental requirements by category of MSCI ESG Ratings:

Table 9 – Summary of Environmental Requirements from MSCI ESG Ratings

Category	*Environmental Requirement Aspects*
Environmental Management	Assessment of direct and indirect GHG emissions. Measurement of natural resource consumption, including water and energy efficiency. Evaluation of waste management practices, such as recycling and waste reduction.
Energy Efficiency	Assessment of renewable energy use and commitment to renewable sources. Measurement of operational energy efficiency.
Environmental Impact and Risks	Evaluation of environmental risk identification, management, and reporting. Assessment of impacts on biodiversity and conservation areas.
Legal Compliance	Evaluation of compliance with local and international environmental regulations.
Sustainable Innovation	Assessment of investments in research and development of sustainable technologies and practices.
Transparency and Reporting	Evaluation of ESG disclosure and transparency of environmental practices.

Source: The authors.

Leadership in Energy and Environmental Design (Leed) is an internationally recognised certification system for sustainable buildings developed by the U.S. Green Building Council (USGBC). It assesses various areas, including water efficiency, greenhouse gas emissions, indoor air quality, use of recycled materials, resource utilisation, and maintenance and operation costs (GBC, 2023). The system awards points, totalling 110, and Leed ratings range from Certified (40-49 points) to Leed Platinum (80+ points).

The nine main categories include Location, Water Efficiency, Energy Efficiency, Material Selection, Indoor Environmental Quality, Integrative Process, Sustainable Sites, Regional Priority, and Innovation. Points are unevenly distributed among categories, with an emphasis on Energy and Atmosphere (34%) and Indoor Environmental Quality (16%). Leed certification covers various areas such as New Construction, Core and Shell, Schools, Retail, Data Centres, Warehouses, Hospitality, and Healthcare. Requirements include the choice of sustainable sites, water and energy efficiency, selection of sustainable materials, indoor air quality, and innovation in sustainable practices (GBC, 2023). Table 10 provides a synthesis of environmental requirements topics for scoring by Leed category.

Table 10 – Environmental Requirements for Leed Certification

Category	*Topics of Requirements for Scoring*
Location and Transportation	Leed for Neighbourhood Development. Sensitive land protection. High-priority sites in restricted or community-impact areas. High-density and mixed-use locations. Access to public transit. Bicycle facilities. Reduced parking footprint. Green vehicles.
Sustainable Sites	Construction pollution prevention. Site assessment. Habitat protection or restoration. Open space. Stormwater management. Heat island reduction. Light pollution reduction.
Water Efficiency	Reduction of outdoor and indoor water use. Building water metering. Cooling tower water use. Water monitoring.
Energy and Atmosphere	Enhanced commissioning. Optimised energy performance. Advanced energy metering. Demand response. Renewable energy production. Refrigerant management. Green power and carbon offsets.
Materials and Resources	Recycling storage and collection. Construction and demolition waste planning. Building life-cycle impact reduction. Environmental product declarations. Raw material sourcing. Material ingredient disclosure. Waste management.
Indoor Environmental Quality	Minimum indoor air quality. Tobacco smoke control. Enhanced air quality strategies. Low-emitting materials. Construction air quality management. Indoor air quality assessment. Thermal comfort. Interior lighting. Daylight. Quality views. Acoustic performance.
Innovation	Innovation. Leed Accredited Professional.

Note: The Table was constructed based on the general descriptions of the certification and scoring items for the New Construction category. Source: The authors.

In addition to the sustainability criteria themselves, environmental certifications also differ in their verification and auditing processes. Most certification systems require a structured assessment that includes documentation review, performance indicators, and, in some cases, external audits conducted by accredited organisations. These procedures may involve periodic monitoring, reporting of environmental indicators, and verification of compliance with predefined standards. The complexity, duration, and cost of these verification processes may influence organisations' and project developers' selection of a certification system. In the context of football stadiums, these factors may also affect the feasibility of incorporating certain certifications into FIFA sustainability standards, suggesting that the verification process should be considered when evaluating their potential adoption.

2.2 THE FIFA ENVIRONMENTAL SUSTAINABILITY STANDARD BEYOND THE CURRENT STANDARD

When examining FIFA's guidelines, it is evident that although they represent progress in sustainability, further improvements are needed to promote more comprehensive and responsible practices. During the comparison stage, in which the FIFA synthesis framework was compared with environmental certifications, it was possible to identify categories and areas not explicitly required in FIFA guidelines.

These areas were explored as analytical categories through comparative analysis. FIFA suggests implementing green building certifications, but does not explicitly require stadiums to obtain them. In addition, many

certifications establish recommendations or score-based criteria rather than mandatory requirements. These gaps reveal opportunities to strengthen FIFA's approach to environmental sustainability.

While FIFA addresses carbon reduction, energy efficiency, sustainable water use, and biodiversity, certifications such as B Corp, GRI, Carbon Trust, and ISO 14001 place greater emphasis on certified environmental management - seeking green building certifications, continuous environmental performance assessment, and compliance with defined criteria could be more clearly incorporated into FIFA guidelines. Although FIFA proposes optimising structural design and substituting materials to reduce carbon emissions, GRI, Carbon Trust, and MSCI ESG Ratings emphasise detailed monitoring of greenhouse gas (GHG) emissions. Including requirements for reporting direct emissions (Scope 1) and indirect emissions (Scopes 2 and 3) could strengthen FIFA's approach to climate change.

Regarding waste management, FIFA mentions recyclable materials, waste reduction, and the reuse of demolished materials. However, certifications such as B Corp and GRI highlight additional aspects, including supply chain waste management, packaging impacts, and hazardous waste monitoring. Life cycle assessment and energy efficiency, mentioned by FIFA in stadium construction, are addressed more comprehensively by certifications such as Carbon Trust and Leed, which emphasise applying these principles throughout the building life cycle.

Although FIFA promotes renewable energy use, it does not explicitly address energy consumption monitoring, a practice emphasised by certifications such as B Corporation, GRI, ISO 14001, Sasb, UN Global Compact, and MSCI. The UN Global Compact and ISO 26000 emphasise community engagement and transparency in environmental practices. While FIFA mentions local suppliers, clearer guidelines on how stadiums can promote local sustainability and transparency could generate additional benefits.

FIFA mentions sustainable materials, but Carbon Trust and the UN Global Compact highlight investment in environmentally friendly technologies and sustainable production and consumption practices. B Corp Certification highlights the environmental efficiency of facilities, environmental management systems, certified products, and environmental assessment in product development. Incorporating these elements into FIFA requirements could strengthen a holistic approach to environmental management in stadium construction and operation. ISO 14001, one of the most recognised environmental management standards, recommends conducting environmental impact assessments, developing action plans with measurable goals, and considering legal requirements. Integrating these stages into FIFA standards could provide a more structured environmental management framework.

The "Community Involvement" category of ISO 26000 highlights the identification of environmental impacts in operational areas and the promotion of transparency. Including these aspects in FIFA requirements could strengthen stadium integration with local communities and support regional socio-environmental development. Specific metrics for greenhouse gas emissions, energy efficiency, water use, and waste management, emphasised by Carbon Trust and Sasb, could help FIFA improve environmental monitoring indicators, enabling more measurable evaluation of stadium performance.

ISO 26000 and the UN Global Compact also stress engagement with governments, regulation, and community development. Integrating these elements into FIFA requirements could strengthen collaboration with local authorities and align stadium projects with sustainable development goals. The misalignment between FIFA standards and the environmental certifications analysed in this study highlights opportunities to strengthen FIFA's sustainability framework. Improvements are particularly needed in environmental management detail, impact assessment, community engagement, and measurable indicators, especially as climate-related challenges become more frequent.

Table 11 presents a synthesis of the gaps identified in FIFA's environmental sustainability standard based on the analysed certifications.

Table 11 – Summary of Missing Aspects in the FIFA Environmental Sustainability Standard,

Based on Analysed Standards

Requirement	*Standard*
Environmental management systems	B Corporation, ISO 14001.
Monitoring of energy consumption	B Corporation, GRI, ISO 14001, Sasb, UN Global Compact, MSCI.
Total Scope 1 GHG emissions (metric tons of CO2 equivalent)	B Corporation, GRI, Carbon Trust, MSCI.
Total Scope 2 GHG emissions	B Corporation, GRI, Carbon Trust, MSCI.
Total Scope 3 GHG emissions	B Corporation, GRI, Carbon Trust, MSCI.
Carbon emissions intensity	B Corporation, GRI, Carbon Trust, MSCI.
Reduction of greenhouse gas emissions	B Corporation, GRI, Carbon Trust, MSCI.
Shipping policies	B Corporation.
Management of GHG emissions in the supply chain	B Corporation, Carbon Trust.
Compensation for suppliers' GHG emissions	B Corporation.
Improvement in supply chain GHG emissions	B Corporation.
Percentage of purchases from local suppliers	B Corporation.
Percentage of raw materials purchased from local suppliers	B Corporation.
Management of transportation impact	B Corporation.
Monitoring and management of water usage	B Corporation, GRI, ISO 14001, SASB, UN Global Compact, MSCI.
On-site or recycled source water capture	B Corporation.
Monitoring of toxic wastewater	B Corporation.
Water management in the supply chain	B Corporation.
Improvement of water consumption in the supply chain	B Corporation.
Monitoring and recording of non-hazardous waste	B Corporation, GRI, ISO 14001, SASB, MSCI.
Waste disposal methods	B Corporation, GRI, ISO 14001, Sasb, MSCI.
Total disposed waste	B Corporation, GRI, ISO 14001, Sasb, MSCI.
Total recycled waste	B Corporation, GRI, ISO 14001, Sasb, MSCI.
Recycling programs	B Corporation, GRI, ISO 14001, Sasb, MSCI.
Waste reduction programs	B Corporation, GRI, ISO 14001, Sasb, MSCI.
Supply chain waste management	B Corporation.
Improvement in supply chain waste generation	B Corporation.
Environmental impact of packaging	B Corporation, GRI.
Percentage of recyclable/biodegradable materials	B Corporation, GRI.
Percentage of environmentally preferable input materials	B Corporation.
Monitoring of hazardous waste	B Corporation, GRI, ISO 14001, Sasb, MSCI
Total hazardous waste produced	B Corporation, GRI, ISO 14001, Sasb, MSCI
Waste reduction	B Corporation, GRI, ISO 14001, Sasb, MSCI

Requirement	Standard
Disposal of hazardous waste	B Corporation, GRI, ISO 14001, Sasb, MSCI
Management of hazardous materials on-site	B Corporation, GRI
Chemical substance management in the supply chain	B Corporation
Improvement in the generation of chemical substances in the supply chain	B Corporation

Source: The authors.

The comparative analysis of FIFA's sustainability guidelines with existing environmental certifications reveals important avenues for strengthening the FIFA standard. While FIFA's current guidelines address crucial aspects such as carbon reduction, energy efficiency, and waste management, incorporating specific elements from certifications such as B Corporation, ISO 14001, GRI, Carbon Trust, and others could provide a more comprehensive and detailed approach.

The inclusion of specific metrics, such as carbon intensity, the percentage of local purchases, and supply chain waste management, enables more detailed, measurable monitoring of the stadium's environmental performance. Furthermore, considering aspects such as the environmental impact of packaging and chemical management in the supply chain could significantly broaden the scope of sustainability in stadiums.

By following the best practices outlined in internationally recognised certifications, such as ISO 14001 and B Corporation, FIFA would have a more comprehensive framework for managing stadium environmental performance, promoting a proactive and integrated approach. This evolution in sustainability standards would not only align FIFA with global sustainable development goals but also contribute to the construction of more ecological and community-integrated stadiums. Additionally, the study's findings guide best practices for constructing various eco-friendly sports facilities, extending their impact beyond FIFA stadiums to other sports infrastructure projects globally.

This study presents some significant limitations that should be considered when interpreting its results. Firstly, the adopted comparative approach may be subject to selection bias, as the choice of environmental certifications for comparison was based on specific criteria. Additionally, covariance analyses rely on comparable data across certifications, which may affect the validity and generalisability of the results. Another limitation is the constant evolution of environmental standards and criteria, which may change over time. Furthermore, the analysis focuses on specific dimensions outlined in FIFA documents and may not comprehensively address all relevant aspects of each standard. Finally, it is essential to acknowledge that the study did not assess the practical implementation of these standards in specific stadiums, limiting the understanding of their real impact within the FIFA context.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

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In its first edition of 2026, *Sustainability in Debate* reaffirms its commitment to rigorous, critical and socially engaged science. This issue brings together contributions that examine sustainability transitions, socio-environmental governance, climate adaptation and knowledge co-production across diverse territorial and institutional contexts. In a moment when the urgency of the energy transition and the persistence of structural inequalities demand ever greater analytical clarity, Sustainability in Debate reasserts its role as a space for critical reflection in defence of science, justice and socio-environmental sustainability.

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