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Social metabolism and oil palm territories in Colombia (2020–2024): material flows, water, biodiversity, and socio-ecological conflicts

Metabolismo social y territorios palmeros en Colombia (2020–2024) flujos materiales, agua, biodiversidad y conflictos socioecológicos

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Resumen

Comprender las implicaciones socioecológicas de las dinámicas metabólicas agroindustriales es fundamental para evaluar la sostenibilidad de sistemas productivos tropicales en rápida expansión. El objetivo general de este estudio fue analizar el metabolismo social de la agroindustria de la palma de aceite en Colombia durante el periodo 2020–2024, identificando cómo los flujos materiales y energéticos reconfiguran las relaciones sociedad–naturaleza y afectan el agua, la biodiversidad y la sostenibilidad territorial. La metodología adoptó un enfoque mixto explicativo–secuencial que integró el análisis cuantitativo de la producción, el consumo hídrico, la biomasa y la eficiencia extractiva mediante el Análisis de Flujos de Materiales (MFA), con un componente cualitativo basado en entrevistas semiestructuradas, cartografía social y análisis temático orientado a comprender percepciones y conflictividades socioecológicas.

Los resultados evidenciaron una agroindustria caracterizada por alta intensidad metabólica, presiones diferenciadas sobre subcuencas y procesos de homogeneización del paisaje que afectan la biodiversidad funcional. Estos hallazgos muestran que la configuración metabólica del sector opera no solo como un mecanismo productivo, sino también como una fuerza territorial que reorganiza estructuras ecológicas y moldea interacciones socioambientales locales.

El estudio integró métodos cuantitativos (MFA, huella hídrica y análisis espacial) y técnicas cualitativas (entrevistas, cartografías participativas y codificación temática), permitiendo una comprensión integral de la articulación entre productividad, presiones ecosistémicas y conflictividad socio-territorial. El aporte principal consistió en demostrar cómo el metabolismo social de la agroindustria palmera redefine la sostenibilidad del agua, la biodiversidad funcional y la gobernanza territorial en Colombia. En conjunto, la evidencia sugiere que la sostenibilidad del sector depende de una gobernanza territorial participativa, la restauración ecológica y la gestión integral del agua.

Palabras clave: Metabolismo Social, Palma De Aceite, Agroindustria, Sostenibilidad Territorial, Biodiversidad Funcional.

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Abstract

Understanding the socio-ecological implications of agroindustrial metabolic dynamics is essential for assessing the sustainability of rapidly expanding tropical commodity systems. The general objective of this study was to analyze the social metabolism of the oil palm agroindustry in Colombia during the period 2020–2024. The research identified how material and energy flows reconfigure society–nature relations and influence water availability, biodiversity, and territorial sustainability. The methodology adopted a mixed explanatory–sequential approach that integrated quantitative analysis of production, water consumption, biomass, and extractive efficiency using Material Flow Analysis (MFA), with a qualitative component based on semi-structured interviews, participatory mapping, and thematic analysis to understand perceptions and socio-ecological conflictivity.

The results showed an agroindustrial system characterized by high metabolic intensity, differential hydrographic pressures across sub-watersheds, and landscape homogenization processes that affect functional biodiversity. These findings indicate that the metabolic configuration of the sector operates not only as a productive mechanism but also as a territorial force that reorganizes ecological structures and shapes local socio-environmental interactions.

The study integrated quantitative methods (MFA, water footprint assessment, and spatial analysis) and qualitative techniques (interviews, social cartography, and thematic coding), enabling a comprehensive understanding of the interplay between productivity, ecosystem pressures, and socio-territorial conflict. The main contribution lies in demonstrating how the social metabolism of the palm oil agroindustry redefines water sustainability, functional biodiversity, and territorial governance in Colombia. Overall, the evidence suggests that the long-term sustainability of the sector depends on participatory territorial governance, ecological restoration strategies, and integrated water-resource management.

Keywords: Social Metabolism, Oil Palm, Agroindustry, Sustainable Development, Ecosystem Functions.

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Introduction

The oil palm agroindustry in Colombia constitutes one of the productive systems with the greatest territorial expansion and economic relevance in the last two decades. During this period, the country has emerged as the leading producer in Latin America and the fourth largest producer worldwide (Gómez, 2022). Between 2020 and 2024, the value chain experienced notable fluctuations in production, yield, and economic performance, alongside profound transformations in land use, water availability, and the configuration of rural landscapes (Fedepalma, 2024; Barrios et al., 2020). These transformations extend beyond productive dynamics and reflect processes of ecological and social reorganization within palm-growing territories particularly in the regions of Magdalena, Cesar, Meta, Casanare, and Tumaco, where agrarian, community, and ecosystem interactions intersect (Fedepalma–SISPA, 2024; Barbosa et al., 2021).

The social metabolism approach provides a robust framework for understanding these dynamics by examining the flows of matter and energy that sustain agroindustrial production and shape its effects on local ecosystems (González de Molina, 2016). From this perspective, oil palm functions not merely as a crop but as a biophysical infrastructure that mobilizes water, fertilizers, residual biomass, fuels, and labor. These flows translate into externalities that exert pressure on watersheds, (Gómez, 2025; Guzmán et al., 2018).

Despite these documented dynamics, important analytical gaps remain. Various studies have documented socio-ecological tensions in palm-growing areas, associated with competition for water, the modification of wetlands, expansion into areas of ecosystemic interest, and the growing need to implement governance and restoration schemes (Martínez Alier, 2015). However, an analytical gap still persists. Hence the need for the present research exercise, which integratively and comparatively evaluates the social metabolism of the palm agroindustry in Colombia for the recent period 2020–2024, simultaneously considering biophysical, territorial, and sociopolitical indicators (Porto-Gonçalves, 2009).

The social metabolism approach offers a rigorous analytical lens for interpreting these dynamics, as it focuses on the material and energy flows that sustain agroindustrial

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production and determine its ecological consequences (González de Molina, 2016). Within this framework, oil palm operates not simply as an agricultural commodity but as a biophysical infrastructure that moves water, fertilizers, residual biomass, fuels, and labor across territories. The circulation of these inputs and outputs generates externalities that intensify pressure on watersheds, reduce agroecological heterogeneity, and weaken functional biodiversity (Gómez, 2025; Guzmán et al., 2018).

Accordingly, this study has three specific objectives: to characterize the material and energy flows of the Colombian palm oil value chain between 2020 and 2024 using Material Flow Analysis (MFA); to analyze their effects on water availability, biodiversity, and landscape structure; and to evaluate the socio-ecological conflicts generated by these metabolic dynamics. These objectives allow addressing the central question of how material and energy flows reshape society–nature relations in palm-growing territories.

Recent literature highlights that high-intensity agroindustrial systems reorganize socio-ecological landscapes through metabolic intensification and unequal distribution of environmental burdens (Suárez & Martínez-Alier, 2022; Haberl et al., 2020). Therefore, a comparative territorial analysis such as this one is essential to understanding environmental and social reconfiguration processes in Colombia.

Methodology

The study employed a mixed explanatory–sequential design that combined quantitative assessments of the material and energy flows of the Colombian oil palm agroindustry with a qualitative examination of socio-ecological dynamics and associated territorial processes (Escobar, 2011; Páramo, 2008). In the first phase, the research team collected and systematized data on production volumes, planted area, yield, crude palm oil extraction, estimated water consumption, fertilizer application, and residual biomass generation for the period 2020–2024. The primary sources included the Statistical Information System of the Palm Sector (SISPA) of Fedepalma, environmental reports issued by territorial authorities,

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and hydroclimatic databases provided by IDEAM (Fedepalma, 2024a; 2024b; 2023a; 2023b; 2022a; 2022b; 2022c; 2021a).

These data supported the development of biophysical indicators that describe the social metabolism of the palm oil value chain. The indicators quantify the relationship between inputs such as water, energy, and agricultural supplies—and outputs, including crude oil, by-products, and residual waste. Their construction followed the methodological principles of Material Flow Analysis (MFA) (Gómez, 2021; González de Molina & Toledo, 2011; see Table 1).

Subsequently, indicators of water footprint (green, blue, and gray) and ecosystemic pressure were estimated for priority sub-basins selected by planting concentration, levels of water stress, and the presence of peasant or ethnic communities (La Rota-Aguilera et al., 2022; Ngan et al., 2022).

To characterize the territorial dimension, the study applied spatial analysis techniques using Geographic Information Systems (GIS). Cartographic inputs from IDEAM and CORINE Land Cover datasets provided the basis for detecting changes in land use, loss or fragmentation of natural cover, and variations in ecological connectivity (Vergara et al., 2025; Ramírez et al., 2020). The spatial component was further strengthened through the construction of a socio-ecological pressure index that integrates biophysical and territorial variables, allowing the identification of both critical areas and zones that demonstrate resilience (Vanegas, 2017; Lodice, 2015).

The qualitative phase aimed to deepen the understanding of society–nature relations in palm-growing territories. This phase incorporated semi-structured interviews with community leaders, peasant associations, representatives of extraction plants, environmental institutions, and local authorities (Barbosa et al., 2020; Bunge, 1997). The interviews addressed perceptions of water availability and quality, transformations in the landscape, disputes over resource access, and the functioning of local governance mechanisms (Maldonado, 2024; Bryman, 2021).

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In addition, the study implemented participatory social-mapping workshops that enabled the reconstruction of socio-ecological conflict timelines and the documentation of community agreements regarding environmental use and protection (Gómez, 2024b; Mukherjee et al., 2022). The analysis of qualitative information employed thematic coding in NVivo or Atlas.ti, which facilitated the systematic comparison of discourses with biophysical indicators and territorial patterns (Aguilera et al., 2020; Castro et al., 2017).

Finally, the study integrated quantitative and qualitative findings through analytical triangulation, which facilitated the validation of convergences, divergences, and causal relationships among social metabolism, territorial configuration, and socio-ecological conflict. This integrative step ensured that the analysis moved beyond a purely productive perspective and adequately captured the complex interactions among the palm oil agroindustry, local ecosystems, and the communities that depend on them. In doing so, the study effectively addressed its central objective and research question (IDEAM, 2024; Infante et al., 2020).

Table 1. *Methodological characterization*

Dimension	Variable	Indicator	Unit / source	Analysis technique
Social Metabolism	Material flows	Input/product ratio (fertilizers, energy, biomass)	kg input / t CPO SISPA / Technical Reports	Material Flow Analysis (MFA)
Social Metabolism	FFB /CPO conversion	Extraction rate in processing plant	% SISPA / Extraction plants	Comparative statistical analysis by zone

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Water	Water footprint (green, blue, gray)	m^3/ha and m^3/t CPO	IDEAM / SIAC / Technical literature	Water footprint estimation (Hoekstra method)
Water	Water stress in sub-watersheds	Relative water availability index	IDEAM / Environmental Authority	GIS + Hydrological Modeling
Landscape and Biodiversity	Ecological connectivity	Length of connected corridors and patches	m/ha IDEAM / CORINE Land Cover	Spatial analysis (QGIS / ArcGIS)
Landscape and Biodiversity	Landscape fragmentation	Land-use diversity index	GIS datasets	Shannon Index / FRAGSTATS
Socio-Institutional	Water governance	Existence and functionality of local agreements	Qualitative Interviews	Thematic analysis (NVivo / Atlas.ti)
Socio-Institutional	Socio-ecological conflict	Frequency / type / level of conflict resolution	Narrative matrix — Interviews	Discourse analysis + Participatory social mapping
Integrated Performance	Socio-ecological pressure	Composite index (water + landscape + conflict)	Index	Multicriteria normalization and weighting

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Source: Authors' elaboration based on Arrazola and Pertuz (2025); Fedepalma (2024a, 2024b, 2023a, 2023b, 2022a, 2022b, 2022c, 2021;Camacho et al. (2023);Téllez et al., (2020); Devi Prasad (2019); Maldonado (2018); González de Molina (2013); and Bunge (1980, 1969).

Design and methodological structure.

The study adopted an explanatory–sequential mixed design. In the quantitative phase, the Material Flow Analysis (MFA) framework was applied following EUROSTAT (2018) and Haberl et al. (2019). In the qualitative phase, theoretical sampling was used to select key actors (community leaders, institutions and processing plants). Triangulation integrated biophysical indicators, spatial patterns, and social perceptions, ensuring internal validity and coherence with the study objectives.

Results

Productive dynamics and social metabolism of the palm value chain (2020–2024)

Table 1. *Productive trends of the social metabolism (2020–2024)*

Year	CPO Production (t)	Planted area (ha)	Yield (t/ha)	Key observation
2020	1.56 million	575	3.50 / 3.60	Post-pandemic recovery
2021	1.74 million	585	3.55 / 3.65	Favorable climatic conditions and increased harvest

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2022	1.77 million	576,8	3.63	Partial industrial optimization
2023	1.84 million	596	3.66	Peak production
2024	1.72 million	590	3.50 / 3.60	Decline due to water stress

Source: Authors' elaboration based on Bustillo (2025); Fedepalma–SISPA (2024); Gómez & Barreto (2024); Fedepalma (2024a, 2024b, 2023a, 2023b, 2022a, 2022b, 2022c, 2021a, 2022b); and Rendón & Gómez (2022).

Between 2020 and 2024, the Colombian oil palm agroindustry maintained a moderate production expansion, with an accumulated increase of approximately 18% between 2020 and 2023, followed by a decrease in 2024 associated with climate variability and episodes of hydric stress (Table 1; Ostfeld et al., 2024). This behavior indicates that productive intensification was more closely linked to the expansion and consolidation of planted area rather than structural improvements in biophysical efficiency (Gómez et al., 2025).

Material Flow Analysis (MFA) results indicate that the input–output ratio remained stable throughout the study period, revealing a social metabolism marked by intensive use of water, nitrogen-based fertilizers, and thermal energy in oil extraction processes (Gudynas, 2021; Caixeta et al., 2018). Although some extraction plants adopted technological innovations—such as the use of biomass for internal energy generation—the overall production system continues to rely on substantial material flows to maintain crude palm oil output. This dependency intensifies ecological pressures on local environments (Abideen et al., 2023; Escobar, 2015).

Within this context, palm-growing territories function not merely as agricultural production zones but as socio-ecological systems shaped by the circulation and availability of energy, water, and biomass (Gómez, 2025b; Carrillo, 2015). The relative stability in production levels does not reflect the absence of impacts; rather, the evidence indicates that the sector's

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metabolic profile reorganizes society–nature relations by altering land-use patterns, reshaping water-governance dynamics, and transforming the interactions among communities, corporate actors, and ecosystems (Junquera, 2020; Infante et al., 2017).

Water, water footprint, and territorial pressures

Table 2. Comparative water footprint by palm-growing zone

Dimension	Observed evidence	Implication
Water	Competition over water allocation in critical sub-watersheds	Socio-environmental conflicts
Landscape	Reduction of ecological heterogeneity and corridors	Decline in functional biodiversity
Governance	Emergence of local water-use agreements	Potential for territorial sustainability
Community	Changes in land-use perception and practices	Reconfiguration of identities and rural economies

Source: Authors' elaboration based on (Fedepalma–SISPA, 2024; Rodríguez, 2024; IDEAM, 2024; Gómez & Barreto, 2024; Fedepalma, 2024a;2024b; 2023a;2023b; 2022a;2022b;2022c; 2021[a]; Rendon y Gómez, 2022; Ordway et al., 2017).

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The analysis of water footprint and hydric balance across palm-growing zones shows that the greatest pressures occur in the Eastern region : Meta–Casanare, where plantations depend on surface and groundwater resources during prolonged dry seasons. This region recorded higher blue-water footprint values compared to the Northern and Southwestern zones, indicating greater competition over water between agricultural systems and domestic consumption (IDEAM, 2024; Rodríguez et al., 2021).

In contrast, the Southwestern region Tumaco, demonstrated more favorable hydric availability due to abundant rainfall; however, challenges were identified related to drainage management, soil salinity, and slope stability (Bustillo, 2025; Sharafi et al., 2024).

Participatory social mapping and interview data reveal that community perceptions of water availability serve as a critical indicator of territorial sustainability. In water-stressed zones, communities report reductions in both access to and quality of water, a situation that has generated disputes, the establishment of negotiated water-use agreements, and, in some areas, the formation of shared governance arrangements. These findings demonstrate that water flows associated with the palm oil sector's metabolic dynamics carry environmental, political, and social implications, particularly in territories where peasant livelihoods intersect with agro-industrial economies (López, 2025; Urrego et al., 2019).

Landscape transformation, biodiversity, and socio-ecological conflict

Table 3. Socio-ecological signals in palm-growing territories

Dimension	**Observed evidence**	**Implication**
Landscape	Reduction of ecological heterogeneity and riparian corridors	Loss of functional biodiversity

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Water	Competing priorities for water access in key watersheds	Socio-environmental conflicts
Governance	Emergence of local agreements and negotiation arenas	Potential for sustainable governance
Community	Shifts in land-use perception and resource practices	Transformation of local identities and economies

Source: Authors' elaboration based on (Fedepalma–SISPA, 2024; Rodríguez, 2024; Gómez & Barreto, 2024; Fedepalma, 2024a;2024b; 2023a;2023b; 2022a;2022b;2022c; 2021[a]; Rodríguez et al.,2021; Rendón y Gómez, 2022; Universidad Nacional de Colombia, 2020; Crespo & Pérez, 2018; Ordway et al., 2017).

Spatial and temporal analyses of landscape composition identified a clear trend toward agricultural homogenization, reflected in reduced ecological heterogeneity and weakened riparian corridors, particularly in the Magdalena and Meta sub-watersheds. The resulting loss of agroecological mosaics correlates with declines in functional biodiversity, especially among insectivorous birds, pollinators, and other species that serve as indicators of habitat quality (Kalmanovitz, 2019; Larson et al., 2016). A detailed interpretation of these landscape patterns is developed in the Discussion section to maintain analytical coherence and avoid redundancy.

Even so, the study also documented territorial initiatives aimed at mitigation and ecological restoration. These include the establishment of agroforestry corridors, the recovery of riparian buffer zones, and the application of controlled fertigation systems based on treated

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effluents. Such experiences show that sustainability is not inherently incompatible with oil palm cultivation; rather, it depends on the strength of governance frameworks, the quality of community-based territorial management, and the negotiation capacity among local actors (Rodríguez, 2025b; Gómez, 2021).

The results indicate that the social metabolism of the Colombian oil palm agroindustry between 2020 and 2024 exhibits a high intensity of biophysical flows, particularly in relation to water, residual biomass, fertilizers, and thermal energy (Barros, 2019). This metabolic configuration is neither neutral nor exclusively technical; instead, it functions as a structuring mechanism that reshapes territories, social relations, and ecological dynamics. This interpretation aligns with the contributions of Mogollón (2024) and Martínez Alier (2011), whose perspectives in political ecology and socio-ecological systems in Latin America emphasize the territorial and distributive dimensions of metabolic processes.

The productive expansion and subsequent stabilization documented during this period cannot be interpreted merely as agronomic trends. Rather, they reflect a broader process of territorial reorganization that redistributes environmental burdens and benefits across regions, communities, and ecosystems (Castro, 2024; Maldonado, 2014). This pattern underscores the extent to which socio-metabolic pressures shape both ecological integrity and social structures within palm-growing territories. The results confirm that metabolic intensification is the structural driver of socio-hydric tensions, particularly in the Meta–Casanare region, where water availability exhibits strong seasonal variability

Discussion

This discussion is organized into three analytical dimensions: agroindustrial metabolism and territorial reorganization; society–nature relations mediated by water flows; and governance dynamics, conflict, and sustainable transitions.

Consistent with literature on agro-industrial sectors characterized by high water demand (Martínez et al., 2024; Gómez, 2020), the findings reveal that pressure on water sources

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varies markedly across regions, indicating that the sector's sustainability is territorially differentiated. The Eastern zone exhibits the highest levels of water stress, especially during dry seasons, a pattern that corresponds to the expansion of agricultural production in areas where water availability fluctuates significantly (Gómez, 2024a; Laverde et al., 2020).

This pattern underscores the role of water management as a central axis of socio-ecological vulnerability. Addressing this challenge requires a transition from management models based on "statistical" or average availability toward adaptive governance frameworks that incorporate community-led agreements and participatory watershed management plans (Albarracín et al., 2024; Rodríguez et al., 2021).

The landscape transformations and the reduction of ecological heterogeneity documented in the Northern and Eastern zones align with studies that highlight the consequences of monocrop expansion, including losses in functional biodiversity, declines in pollinator populations, and the simplification of trophic interactions (Gutiérrez et al., 2024). Nevertheless, the presence of territorial initiatives focused on riparian restoration, fertigation using treated effluents, and agroforestry systems demonstrates that ecological degradation does not constitute an inherent or unavoidable outcome of oil palm cultivation. Rather, environmental performance depends on the institutional and governance frameworks that shape the sector's metabolic configuration (Murphy, 2021; Maldonado, 2017).

This leads to a central point: the conflict is not inherent to oil palm, but to the territorial management regime and water access structures. Where watershed committees, community agreements, and oversight mechanisms exist, conflicts tend to decrease and cooperation increases (Novoa, 2024). In contrast, where water distribution is unilateral or lacks transparency, conflict intensifies and becomes territorialized, shaping perceptions of the crop and generating narratives of dispute (Rosero & Gómez, 2025; Otálora & Vivas, 2017).

Therefore, this study reframes the debate from asking whether oil palm can be considered sustainable to analyzing how, where, and under which institutional arrangements sustainability becomes feasible. This perspective offers a methodological and political

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contribution to territorial planning and environmental management in Colombia's palm-growing regions (Rodríguez, 2025a; Maldonado, 2023).

The finding of sustained metabolic intensification is consistent with research on agroindustrial economies in the Global South, where power relations shape the distribution of environmental burdens (Shiva, 2021; Pérez-Rincón et al., 2019). This indicates that hydric pressure is not merely a biophysical phenomenon but also a political and distributive issue."

Conclusions

The findings of this study show that the social metabolism of the Colombian oil palm agroindustry (2020–2024) is defined by a high intensity of material and energy flows, particularly in relation to water consumption, fertilizer use, and the production of residual biomass throughout the cultivation and extraction stages. This metabolic configuration functions not only as a productive mechanism but also as a territorial force that reorganizes rural landscapes, redistributes water resources, and reshapes the interactions among local communities, the business sector, and surrounding ecosystems. Consequently, the sustainability of the crop cannot be assessed solely through yield or productivity metrics; instead, it requires a socio-ecological perspective capable of integrating biophysical flows with their associated socio-environmental impacts.

Regarding water, the study confirms that hydric pressure varies among palm-growing zones, with the Eastern region exhibiting the greatest vulnerability due to the combination of climatic variability, concentration of production, and competition for surface and groundwater sources. This finding is key for addressing the research question, as it shows that water flows derived from the palm sector's metabolism directly influence society–nature relations, generating territorial tensions and negotiation processes that may escalate into conflict or, conversely, evolve into shared governance arrangements when participatory mechanisms and management agreements are present.

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With respect to landscape and biodiversity, the results reveal a trend toward the homogenization of land use associated with monocrop expansion and the reduction of ecological corridors, leading to declines in functional biodiversity and the simplification of local ecosystems. However, the study also shows that ecological degradation is not an inevitable outcome of palm cultivation, but depends on the model of territorial implementation and management. Experiences such as riparian restoration, agroforestry production, and circular biomass management demonstrate that productivity and conservation can be reconciled when there is institutional commitment and community participation. These patterns reinforce the empirical trends analyzed in the Discussion, confirming the multidimensional nature of socio-metabolic pressures.

First, the intensification of the palm oil metabolic system reorganizes the main ecological structure of territories, contributing to landscape homogenization and declines in functional biodiversity.

Second, the long-term sustainability of the sector depends on water governance systems based on community participation and territorial agreements, rather than conventional productivity indicators.

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Conflicto de intereses:

Los autores declaran que no existe conflicto de interés