Unequal social metabolism and environmental justice in the Colombian palm oil sector: MEFA-based evidence from the Caribbean region (2016–2022)

Dustin Tahisin Gómez Rodríguez[1]

Recibido: 19/07/2025 Aceptado: 01/09/2025 Actualizado: 06/04/2026

DOI: 10.17151/luaz.2025.62.4

Abstract

This study analyzes the social metabolism and ecological externalities of the palm oil agribusiness in the Colombian Caribbean between 2016 and 2022, using the MEFA (Material and Energy Flow Analysis) approach. Results show an uneven metabolic pattern characterized by water overexploitation (1,580 m³/ha annually, 42% above recharge capacity), soil degradation (0.91% annual organic matter loss), and low waste circularity (13.4% recovered). These dynamics generate socio-environmental conflicts (1.89 cases/1,000 ha) and precarious employment (71% of workers are informal). Energy efficiency (EROI 2.4:1) remains below sustainable thresholds (5:1), indicating a model of "unsustainable efficiency." The methodology integrates quantitative methods (MEFA, GIS, dynamic modeling) and qualitative methods (interviews, workshops). Five policy pillars for metabolic transition are proposed: integrated water management, soil conservation banks, circular technology parks, certification reform, and participatory observatories. The study concludes with the need for sectoral policies grounded in biophysical limits and environmental justice.

Key words: social metabolism, ecological externalities, palm oil agroindustry, MEFA, sustainability, socio-environmental conflicts, circularity, energy efficiency.

Metabolismo social desigual y justicia ambiental en el sector palmicultor colombiano: evidencia basada en MEFA para la región Caribe (2016-2022)

Resumen

Este estudio analiza el metabolismo social y las externalidades ecológicas de la agroindustria del aceite de palma en el Caribe colombiano entre 2016 y 2022, utilizando el enfoque MEFA (Análisis de Flujo de Materiales y Energía). Los resultados muestran un patrón metabólico desigual caracterizado por la sobreexplotación hídrica (1580 m³/ha anuales, 42 % por encima de la capacidad de recarga), la degradación del suelo (0,91 % de pérdida anual de materia orgánica) y la baja circularidad de los residuos (13,4 % valorizados). Estas dinámicas generan conflictos socioambientales (1,89 casos/1000 ha) y precariedad laboral (71 % de trabajadores informales). La eficiencia energética (EROI 2,4:1) se mantiene por debajo de los umbrales sostenibles (5:1), lo que indica un modelo de "eficiencia insostenible". La metodología integra métodos cuantitativos (MEFA, SIG, modelado dinámico) y cualitativos (entrevistas, talleres). Se proponen cinco pilares de política para la transición metabólica: gestión integrada del agua, bancos de conservación de suelos, parques tecnológicos circulares, reforma de la certificación y observatorios participativos. El estudio concluye con la necesidad de políticas sectoriales basadas en límites biofísicos y justicia ambiental.

Palabras clave: metabolismo social, externalidades ecológicas, agroindustria palmera, MEFA, sostenibilidad, conflictos socioambientales, circularidad, eficiencia energética.

Introduction

Social metabolism constitutes a fundamental analytical framework for understanding the socio-ecological transformations generated by industrial development models, particularly in agribusiness systems such as palm oil cultivation (Delgado, 2014; González de Molina & Toledo, 2011). The flows material and energy associated with these systems reveal profound contradictions between productive efficiency and environmental sustainability, highlighting critical externalities such as water overexploitation (1,580 m^3/ha annually, 42% above recharge capacity), accelerated loss of soil organic matter (0.91% annually), and low waste circularity (only 13.4% valorized) (Guzmán et al., 2018; Martínez-Alier, 2009). These biophysical indicators, analyzed through standardized methodologies (MEFA, ISO 14046/14067), demonstrate how current patterns of appropriation and transformation of natural resources exceed critical ecological thresholds, generating a metabolic deficit that threatens the long-term viability of palm-growing territories (Gómez, 2022; Qaim et al., 2020).

The social dimension of this unequal metabolism is manifested in employment precarity (71% of workers without formal contracts) and territorial conflicts (1.89 conflicts/1,000 ha), reflecting what the theory called "accumulation by ecological dispossession" (Gómez, 2021; ANDI, 2018; Infante et al., 2017).

The territorialization of the palm oil agribusiness exemplifies the tensions between productivist logics and strong sustainability, where the appropriation of natural resources for industrial purposes reconfigures not only material flows but also power relations in the territory (López & Toledo, 2018; Infante et al., 2017). This process, analyzed from a political ecology perspective, demonstrates how metabolic asymmetries translate into recurrent socio-environmental conflicts, particularly in areas with water stress and accelerated soil degradation (Rendón and Gómez, 2022; Martínez Alier & Walter, 2015). Resolving these contradictions requires interdisciplinary approaches that integrate quantitative flow analysis (e.g., energy balances, nutrient cycles) with qualitative perspectives on environmental justice and territorial governance, overcoming the limitations of conventional agribusiness management models (Rodríguez, 2024; Gómez and Barbosa, 2021). In this sense, social metabolism emerges as a key tool for designing sectoral policies based on rigorous scientific evidence, capable of measuring both hidden ecological costs and real opportunities for transitioning toward more equitable and resilient agri-food systems (Fischer-Kowalski, 2011; 2003).

In fact, the palm oil agribusiness in Colombia has experienced exponential growth over the past two decades, particularly in the Caribbean region, where the department of Magdalena concentrates 12.4% of the national cultivated area (Fedepalma, 2022a; 2022b). However, this development has generated deep contradictions between economic benefits and socio-environmental costs, evidencing what various authors have called "unequal social metabolism" (Gudynas, 2014; Fischer-Kowalski, 2020).

While the MEFA approach provides a robust metric for quantifying biophysical flows, its application in Global South contexts requires critical interaction with Latin American epistemologies that challenge hegemonic frameworks of sustainability (Leff, 2004; Escobar, 2015). Concepts such as "colonial metabolism" (Gudynas, 2021) or "environmental rationality" (Leff, 2004) make it possible to interpret externalities not only as market failures, but also as expressions of a deeply rooted epistemic and political asymmetry. This research adopts MEFA as an analytical tool but is framed within a critical perspective that problematizes the notion of "unsustainable efficiency" beyond the operational, understanding it as a political category inherent to extractivist development models (Gudynas, 2021; Martínez Alier, 2009).

This study identifies this problem through an innovative approach that combines material and energy flow analysis (MEFA) with environmental justice indicators, quantifying both productive efficiency and the externalities generated in the Magdalena oil palm corridor (Magdalena is a Department located in the northern Caribbean region of Colombia) (Fedepalma, 2023; 2016). The research is based on the hypothesis that the current production model operates under a regime of "unsustainable efficiency," characterized by high yields per unit area (3.8 ± 0.4 tons of oil per hectare) but with uninternalized socio-ecological costs averaging USD 1,820 per hectare annually (Girón & Mahecha, 2015; Fedepalma, 2014).

Similarly, the secondary hypothesis proposes that soil degradation (0.91% annual loss of organic matter) is significantly correlated with job precarity (71% of workers are informal), mediated by long-term productivity decline and reduced investment in labor conditions. This relationship will be validated through structural equation modeling (SmartPLS 4.0), integrating biophysical and socioeconomic data (Caixeta et al., 2018; Albarracín, 2015).

This study aims to evaluate the asymmetric social metabolism and its socio-ecological implications in the Colombian palm oil agribusiness, focusing on the Department of Magdalena. Specifically, it aims to quantify metabolic indicators using the MEFA framework, and analyze the relationship between biophysical degradation and socio-economic vulnerability using structural equation modeling.

Material and methods

The methodological design implemented in this study represents a significant advance in the analysis of complex agribusiness systems by integrating three connected components that capture both the biophysical and social dimensions of palm oil metabolism (Arrazola and Pertuz, 2025; Barrios et al., 2020). First, the quantitative component incorporated a standardized MEFA analysis following the protocols of the International Resource Panel, quantifying material flows in 42 sample farms representing 78% of the cultivated area in the study region (Gómez, 2020; Lodice, 2015). Measurements included critical variables such as water footprint (following ISO 14046), greenhouse gas emissions (ISO 14067), and energy balances, with data collected over six consecutive production cycles (2016-2022) to capture interannual variability. Dynamic modeling was performed using the STELLA Architect v3.0.1 tool, incorporating IDEAM climate parameters from and soil characteristics documented by IGAC (IDEAM, 2024; 2015).

Secondly, the qualitative evaluation comprised 13 semi-structured interviews (with a Kappa coefficient of inter-rater agreement of 0.87) and five participatory workshops with palm oil farming communities, designed to capture local perceptions of socio-environmental impacts (Maldonado, 2018; González de Molina, 2016). The qualitative assessment was designed to biophysically contextualize the metabolic results and capture perceptions of local actors involved in the socio-ecological conflict (Aguilera et al., 2020; Leff, 2010). The study area, located in the Department of Magdalena, is characterized by a historical concentration of land ownership and water vulnerability exacerbated by agribusiness expansion (Gómez, 2020b; Martínez-Alier, J. (2011b). Thirteen semi-structured interviews were conducted with key stakeholders: 5 informal palm workers (to capture the perspective of precarious employment), 4 community leaders from villages neighboring the plantations (to understand conflicts over water and land), 2 plant engineers (to obtain the technical-operational perspective), and 2 representatives of regional environmental entities (to understand governance challenges). The testimonies not only served to triangulate data but also revealed narratives about the perceived deterioration of aquifers and precarity as a structural condition, enriching the interpretation of quantitative indicators with deep social meanings (Gómez, 2020; Martínez-Alier, 2011). These data were analyzed using grounded theory with support from MAXQDA 2022 software, identifying recurrent discursive patterns and territorial tensions. Finally, for analytical integration advanced methodological triangulation techniques were used (Barbosa et al., 2020; Denzin, 2017), including spatial analysis with geographic information systems (ArcGIS Pro 3.1.3) and structural equation modeling (SmartPLS 4.0) to validate the causal relationships between metabolic variables and socio-ecological indicators. This multidimensional approach enabled the development of 10 statistically validated indicators (Cronbach's $\alpha > 0.85$), organized into four analytical axes: biophysical efficiency, resource circularity, distributive equity, and institutional resilience (Carrillo, 2015; Obidzinski et al., 2012).

Results and discussion

The findings reveal critical metabolic patterns that question the sustainability of the current palm oil production model in three fundamental dimensions (Costa, 2020; Delgadillo, 2014). In the biophysical realm, data demonstrate an average water extraction of 1,580 ± 60 m^3 per hectare annually (95% CI: 1,520-1,640; $t(41) = 8.37$, $p < 0.001$), exceeding the recharge capacity of the studied micro-basins by 42% ($t = 8.37$, $p < 0.001$), with direct consequences for water availability in local communities. Soils showed an accelerated loss of organic matter (0.91% annually, $r^2 = 0.85$ from linear regression of organic matter vs. years of cultivation, $F(1,40) = 226.7$, $p < 0.001$) in 68% of the sampled plots, particularly in plantations with over 10 years of continuous use. In terms of energy, the EROI (Energy Return on Investment) was only 2.4:1, significantly below the sustainability threshold of 5:1 established in the specialized literature (Crespo & Pérez, 2018; Fischer-Kowalski & Haberl, 2007), with 71% of total energy associated with transporting inputs from distant production centers (Fedepalma, 2022c).

The socioeconomic results revealed structural employment insecurity, with 71% of workers lacking formal contracts and gender pay gaps of 29%, contradicting the official discourse on creating decent jobs (Giraldo, 2018; Kalmanovitz, 2019). The documented socio-environmental conflicts showed a concerning spatial density of 1.89 cases per 1,000 hectares (SD ±0.31), with average resolution times of 3.7 years (95% CI: 3.2-4.1), indicating inefficient territorial governance (Guerrero et al., 2020; Junquera, 2020).

Similarly, spatial analysis (ArcGIS Pro 3.1.3) revealed that 62% of water conflicts occur in micro-basins with annual aquifer declines >1.2 m (Pearson's $r(40) = 0.78$, $p < 0.001$, $n=42$; Cohen's $f^2 = 1.52$ indicating a large effect size), validating the metabolic asymmetry hypothesis. This correlation is supported by geospatial layer overlays and logistic regressions, confirming that water overexploitation operates as a predictor of territorial conflict (Pérez, 2021; Mendoza et al., 2020).

Table 3 summarizes the key metabolic indicators compared to international standards, highlighting that only 13.4% of waste is recovered in the current production system, compared to 51% reported in certified plantations in Malaysia (MPOB, 2022). This circularity gap represents not only a waste of valuable resources but also a missed opportunity to reduce environmental impacts and generate local added value (Rodríguez and Martinez, 2019; Reina, 2013).

Table 3. Comparative metabolic indicators: Colombian Caribbean vs. international standards (Averages 2016-2022)

Indicator	**Colombian Caribbean**	**Malaysia (MPOB, 2022)**	**Sustainable threshold (RSPO)**	**Calculation method**
Waste recovery (%)	13.4 ± 2.1	51.2 ± 3.8	≥45	(Ton. waste used / total Ton.) × 100
Water intensity (m^3/Ton)	315 ± 28	210 ± 15	≤250	Water balances (ISO 14046)
Energy efficiency (EROI)	2.4:1	4.7:1	≥5:1	Useful energy/Invested energy
Conflicts/1,000 ha	1.89 ± 0.31	0.75 ± 0.12	≤1.0	GIS records of documented conflicts
Gender wage gap (%)	29 ± 4	18 ± 3	≤15	-

Source: Prepared by the authors based on (Román et al., 2025; FEDEPALMA, 2022a; 2022b; MPOB, 2022; National Interpretation Working Group for Mexico, 2019; SISPA, 2017).

All values are reported as mean ± standard deviation (n=42 for Colombia, n=115 for Malaysia).

EROI calculated as EROIst (standard) according to the methodology of Murphy et al. (2011).

Confidence intervals calculated using the t-distribution for small samples.

Chi-square tests include Yates' correction for 2x2 tables.

The results of this research confirm the hypothesis of an asymmetric social metabolism in the Colombian palm oil sector, revealing four structural issues that demand urgent intervention (Fedepalma, 2021; Millán, 2018). First, the identified pattern of ecological externalization aligns with the theory of accumulation by dispossession, where non-internalized environmental costs represent 34.7% of gross value of production, including water resource degradation, the loss of soil fertility, and carbon emissions (Gómez, 2024b; López et al., 2017). Secondly, the low circularity of the system (13.4% waste recovery) reflects both technological failures such as the absence of anaerobic digesters in 62% of the farms studied and institutional gaps in the regional bioeconomy policies, a situation that contrast markedly with the progress documented in countries such as Malaysia (Fedepalma, 2020; Kalmanovitz & López, 2006).

Low circularity (13.4%) and unsustainable EROI (2.4:1) are not mere technological failures. They are symptoms of a colonial metabolism (Gudynas, 2021) that prioritizes export efficiency over local ecological regeneration (Martínez et al., 2024) The proposed technical solutions (technology parks, certification) are necessary but insufficient if they are not accompanied by a political transformation that addresses inequality in access to land and water, and that recognizes values beyond purely metric ones (Gómez, 2025; Maldonado, 2023). Qualitative data reveal that communities demand not only greater efficiency but also water sovereignty and territorial autonomy, which challenges the very notion of top-down "governance" (Escobar, 2018; Rendón, 2017).

Spatial analyses revealed that 62% of water conflicts are concentrated in areas with overexploitation of aquifers (>1.2 meters of annual decline), validating the environmental justice framework (CORPAMAG, 2020; Blanco, 2016), and demonstrating how inequality in access to natural resources generates persistent social tensions. Projections made using the STELLA model are particularly alarming, indicating that, if current trends persist, linear projection shows that soil organic matter will reach critical levels (<2%) in 11.3 years (95% prediction interval: 8.9-13.7 years; RSE = 0.24%), which compromises the very viability of the production system in the medium term (Fedepalma, 2024; Correa, 2020).

Systematic comparison with the Malaysian model suggests that Colombia could increase its energy efficiency by 38% by adopting second-generation waste management technologies, although this would require substantial initial investments (USD 18,500 per hectare) with payback periods of 6 to 8 years, which poses significant financing and technical assistance challenges (FAO, 2019; Eurostat, 2018).

Similarly, low circularity of waste (13.4%) directly impacts EROI (2.4:1) by neglecting potential energy sources (e.g., biogas from anaerobic digesters), as demonstrated by the STELLA Architect simulation models (Castro et al., 2017; Rushforth, 2016). However, extrapolating these findings requires caution due to underestimation of non-certified farms (22% of area excluded), whose metabolic patterns may differ significantly (confidence interval not calculated) (Fedepalma, 2021; Barbosa et al., 2021).

Limitations

This study faces several methodological and conceptual limitations. First, the sample comprises 42 farms (78% of the cultivated area) excluding the 22% of non-certified or small-scale farms whose metabolic behavior could differ (Rodríguez, 2025; Rendón and Gómez, 2020). Second, the projections (e.g., soil degradation reaching critical thresholds in 11.3 years) assume linearity, omitting potential nonlinear dynamics or climate-induced shocks. Third, the qualitative inputs—though rigorously coded (Kappa = 0.87) are limited to 13 interviews and five workshops, which may not capture the full diversity of local perspectives (Laverde et al., 2020; González de Molina, 2013). Furthermore, transnational comparisons (e.g., with Malaysia) do not fully account for contextual differences in policy, scale, and ecology. Future research should expand the sample to include underrepresented production systems, employ nonlinear predictive models, and develop context-sensitive comparisons to strengthen policy relevance (Pérez and Rodríguez, 2026).

Beyond the methodological and sampling and limitations mentioned, it is crucial to recognize an epistemic limitation: MEFA indicators, although they are effective in quantifying flows, can operate under a logic of instrumental rationality that obscures qualitative dimensions of environmental injustice (Leff, 2004; Martínez Alier, 2004). Quantifying the conflict (1.89 cases/1000 ha), for instance, fails to fully capture the lived experience of ecological dispossession or the cultural resistance of communities (Gómez, 2026; Escobar, 2011). Future research should incorporate participatory and narrative methodologies that, from a cognitive justice perspective, complement biophysical accounting with the ontologies and territorial values of local actors (Soussa Santos, 2011; Useche, 2008).

Conclusions

This study makes three fundamental contributions to the understanding of sustainability in tropical agribusiness contexts. First, from a theoretical perspective, it confirms the relevance of the MEFA framework for diagnosing socio-metabolic imbalances in agricultural systems. The analysis validates the use of this methodology to assess both ecological externalities such as water overexploitation and soil degradation and social asymmetries like job insecurity and distributive inequity. These findings position MEFA as a robust analytical tool for understanding the contradictions inherent in agribusiness expansion models in the Global South, especially when critically framed within Latin American political ecology and decolonial thought.

Secondly, the methodological innovation of integrating GIS-based spatial analysis, dynamic modeling (STELLA), and life cycle assessment provides a comprehensive approach to studying socio-ecological transitions. This triangulation allows for the validation of causality between metabolic indicators and socio-political variables, offering high reliability (Cronbach's $\alpha > 0.85$) and predictive consistency. The integration of qualitative narratives further enriches this analysis by grounding the quantitative data in the lived experiences and conflicts of local communities. This integrated approach serves as a methodological reference for future studies addressing metabolic conflicts in rural development and sustainability planning.

Third, the study has concrete political and practical implications. The results show that palm oil production in the Colombian Caribbean operates under conditions that exceed ecological limits and exacerbate territorial conflicts. Water extraction exceeds recharge capacity by 42%, and the loss of organic matter threatens soil fertility in the medium term. To address these challenges, the study proposes a five-pillar metabolic transition strategy: watershed-based governance with enforceable water use limits; establishment of soil conservation banks with fiscal and technical incentives; investment in circular technology parks to improve waste and energy recovery; reform of certification systems to incorporate measurable indicators of sustainable agriculture and environmental justice criteria; and creation of participatory territorial observatories to ensure inclusive governance and cognitive justice.

Simulations suggest that, if these measures are implemented, externalities could be reduced by up to 40% over the next decade, requiring investments equivalent to 15 to18% of the regional GDP of the palm oil sector. This multidimensional roadmap offers policymakers and stakeholders a science-based pathway to robust sustainability, emphasizing the need to align production systems with environmental justice and biophysical constraints, and the territorial autonomy demanded by local communities.

Acknowledgments

I am profoundly grateful to all interviewees for their invaluable contributions to this research effort.

Conflict of interest: The authors declare that there is no conflict of interest.

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1 Economist, specialist in educational psychology and Master in development studies and management. Doctor en Agrociencias. Corporación Universitaria De Asturias. Dustin.gomez@asturias.edu.co. https://orcid.org/0000-0001-5359-2300.

To cite this article: Gómez Rodríguez, D., (2026). Unequal social metabolism and environmental justice in the Colombian palm oil sector: MEFA-based evidence from the Caribbean region (2016–2022). *Revista Luna Azul*, (62), 48-63, DOI: https://doi.org/10.17151/luaz.2026.62.4

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