

Life cycle assessment in coffee systems in Veracruz

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Abstract

Coffee production is an important economic activity worldwide, as it generates employment for more than 20 million people engaged in growing, transforming, processing and marketing the product. This research evaluated and compared the environmental performance of agricultural production in three coffee (*Coffea arabica*) production systems in La Tinaja, Veracruz -coffee with banana (*Musa paradisiaca*), coffee with mango (*Mangifera indica*), and full-sun coffee- in 2024. Using the life cycle assessment methodology and the ReCiPe 2016 method (H), the impacts per functional unit of 1 kg of cherry coffee were analyzed, considering the stages of establishment, development, and agricultural management. The results indicated that producing 1 kg of coffee generates global warming of 0.79, 1.05 and 0.44 kg of CO₂eq in the full-sun coffee, coffee-banana, and coffee-mango systems, respectively. Direct soil emissions from fertilizer application contributed to most of the categories assessed. The coffee-banana system registered the highest environmental loads, followed by the full-sun coffee system. The coffee-mango system presented the lowest environmental impacts in all categories, proving to be the system with the best environmental performance compared to the systems studied.

Keywords:

agroforestry systems, climate change, environmental impact.



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Introduction

Coffee farming represents a source of income for 25 million small producers, who generate 80% of the world's coffee production (FAO, 2025). In Mexico, coffee production reached 1 059 000 t in 2023. Chiapas, Veracruz and Puebla contributed 30, 27 and 24%, respectively, to national production (SIAP, 2024).

In Mexico, coffee production is carried out primarily in systems under shade and in full sun. Shade coffee plantations are agroforestry systems, among which traditional rustic and polyculture systems predominate (Moguel and Toledo, 2004).

Shaded coffee plantations are mainly located in high-biodiversity regions, such as Oaxaca, Chiapas and Veracruz (Moguel and Toledo, 2004). In contrast, full-sun coffee systems represent 10% of the country's farms and are found in areas such as Soconusco (Chiapas) and Xicotepec (Puebla) (Moguel and Toledo, 1999).

Full-sun coffee systems have environmental impacts, such as soil degradation and reduced carbon storage (Mengesha *et al.*, 2026). Agroforestry systems help reduce soil compaction, erosion, and biodiversity loss (Valdés-Velarde *et al.*, 2022). In addition to improving organic matter and nutrient availability, they promote water infiltration and carbon sequestration (Dollinger and Jose, 2018).

This research aimed to evaluate and compare the environmental performance of three coffee production systems with different types of shade (tree species) in Mexico using life cycle assessment (LCA), with the purpose of identifying the systems with the lowest environmental impacts and the main critical points associated with their production.

Materials and methods

Study site and production systems

The research was conducted in the town of La Tinaja, municipality of Emiliano Zapata, in the state of Veracruz, Mexico (north latitude 19° 30' 57.936" and west longitude 96° 45' 18.024"), at an altitude of 901 m (INEGI, 2021). At the study site, three systems were evaluated: two traditional polycultures-coffee with mango trees (*Mangifera indica*) (CM) and coffee with banana plants (*Musa paradisiaca*) (CB) and a monoculture coffee in full sun (CS).

Life cycle assessment methodology

Life cycle assessment (LCA) allows us to assess the environmental impacts of a product from the acquisition of raw materials, its production, use and final disposal. This methodology is accredited by the International Organization for Standardization (ISO) through the ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b) standards. The LCA consists of four stages: 1) definition of the objective; 2) life cycle inventory; 3) life cycle impact assessment; and 4) interpretation.

Definition of the objective and limits of the system

This research aimed to evaluate and compare the environmental performance in three coffee production systems using LCA. In accordance with ISO 14040, the study systems (CS, CB and CM) were defined as product systems. Each system comprises a set of unitary processes, including input entry, agronomic management operations, and associated emissions within the system limits established for analysis.

The boundaries defined were the stages of plantation establishment, plant development (years 1-3), and agricultural management (production and harvesting). The functional unit (FU) defined was 1 kg of fresh, unprocessed cherry coffee.

Data for life cycle inventory and emissions

The research work was conducted in 2024 based on agronomic information collected in coffee production systems in Veracruz in 2023. The inputs used in each stage are presented in Table 1.

Table 1. Inventory of agricultural management of full-sun coffee (CS), coffee-banana (CB), and coffee-mango (CM) production systems.

Stage	System	Inputs	Unit	Amount
Establishment	CS, CB and CM	Nitrofoska	kg ha ⁻¹	50
		Ammonium sulfate	kg ha ⁻¹	50
Coffee plant development (years 1-3)	CS, CB and CM	Nitrofoska	kg ha ⁻¹	50
		Ammonium sulfate	kg ha ⁻¹	150
		Herbicide (glyphosate)	L ha ⁻¹	5
Agricultural management (years 4-25)	CS	NPK 18-12-6	kg ha ⁻¹	500
		Herbicide (glyphosate)	L ha ⁻¹	5
	CB	NPK 18-12-6	kg ha ⁻¹	400
		Takle (glyphosate)	L ha ⁻¹	5
	Banana plants	Urea	kg ha ⁻¹	100
		Insecticide (organophosphates)	L ha ⁻¹	1
	CM	NPK 18-12-6	kg ha ⁻¹	400
		Herbicide (glyphosate)	L ha ⁻¹	5
	Yield	Cherry coffee	t ha ⁻¹	1.5
		Cherry coffee	t ha ⁻¹	1.8
	Banana	Banana	t ha ⁻¹	0.8
		Cherry coffee	t ha ⁻¹	3
	CM	Mango	t ha ⁻¹	0.6

Romero-Fernández *et al.* (2023). The composition of Nitrofoska fertilizer is as follows: N-total: 21%; N-NO₃: 11%; N-NH₄: 10%; P₂O₅: 1%; K₂O: 21%.

Direct soil emissions

Direct emissions to air, water and soil were estimated using the methodology of Nemecek and Schnetzer (2011). The following were evaluated: ammonia, nitrous oxide (N₂O), and nitrogen oxide in air; phosphate and nitrate in groundwater; phosphate and phosphorus in surface water. Soil N₂O emissions were calculated using the same methodology (equation 1). Data were obtained from Romero-Fernández *et al.* (2023) and from the laboratory.

$$(1) \quad N_2O = \frac{44}{28} * (0.01(N_{tot} + N_{cr}) + 0.01 * \frac{14}{17} * NH_3 + 0.0075 * \frac{14}{62} * NO_3)$$

LCA environmental impact assessment

The results were analyzed using the openLCA 2.0 software and the Ecoinvent 3.2 database. Environmental impacts were assessed with the ReCiPe 2016 (H) method at the midpoint level (Huijbregts *et al.*, 2017).

Sensitivity analysis

Variations of ±25% in the NPK fertilizer dose in the study systems were evaluated.

Results and discussion

Environmental assessment of coffee production systems

LCA allows us to identify the environmental impacts and the processes that generate them most in the evaluated systems. Table 2 shows the results for the impact categories using the ReCiPe 2016 (H) method across the study systems.

Table 2. Results of the impact evaluation of the indicators characterizing the midpoint of the production systems.

Impact category	Reference unit	CS	CB	CM
Global warming (GWP)	kg CO ₂ eq	0.79336	1.05223	0.43777
Freshwater eutrophication (FEP)	kg P eq	0.00279	0.00041	0.00022
Marine eutrophication (MEP)	kg N eq	0.00349	0.0048	0.00269
Stratospheric ozone depletion (ODP)	kg CFC11 eq	0.00002	0.00002	0.00001
Mineral resource scarcity (SOP)	kg Cu eq	0.00299	0.00265	0.00125
Terrestrial acidification (TAP)	kg SO ₂ eq	0.00249	0.00274	0.00106
Fine particulate matter formation (PMFP)	kg PM _{2.5} eq	0.00096	0.00102	0.00041
Fossil resource scarcity (FFP)	kg oil eq	0.14209	0.17209	0.0594
Freshwater ecotoxicity (FETP)	kg 1 4-DCB	0.01519	0.01491	0.00647
Cancer human toxicity (HTPc)	kg 1 4-DCB	0.01312	0.01331	0.0056
Non-cancer human toxicity (HTPnc)	kg 1 4-DCB	0.50495	0.49182	0.21449
Ionizing radiation (IRP)	kBq Co-60 eq	0.01397	0.01389	0.00592
Marine ecotoxicity (METP)	kg 1 4-DCB	0.02219	0.02202	0.00943
Ozone formation and human health (HOFP)	kg NO _x eq	0.00107	0.00123	0.00053
Ozone formation, terrestrial ecosystems (EOFP)	kg NO _x eq	0.00109	0.00126	0.00054
Terrestrial ecotoxicity (TETP)	kg 1 4-DCB	2.20295	2.52701	0.92237
Water consumption (WCP)	m ³	0.01715	0.02196	0.00696
Land occupation (LOP)	m ² a crop eq	0.01553	0.0108	0.00626

CS= full-sun coffee; CB= coffee-banana and CM= coffee-mango.

The results showed that the CB system had the highest environmental loads, followed by CS, whereas CM had the lowest values in all categories.

Similarly, Acosta-Alba *et al.* (2020) evaluated the environmental impact on three coffee production systems and reported that crop diversification and shade type may be influencing the environmental assessment of coffee.

Factors such as yield and fertilization contribute to environmental impacts. Alishah *et al.* (2019) observed that environmental impacts per unit of product decreased as yield increased. In coffee crops, NPK fertilizer use and nitrogen fertilization were the primary contributors to the environmental categories (Rahmah *et al.*, 2022; Pazmiño *et al.*, 2024).

In this research, the CM system had the lowest environmental impacts, which may be related to yield, fertilization doses and its positive performance on soil fertility. This is consistent with reports by Romero-Fernández *et al.* (2023), who observed that the CM system favored soil fertility, improved soil properties, increased nutrient concentrations in leaves and fruits, and promoted higher yields than CS and CB (Table 1).

In contrast, the CB system exhibited the greatest environmental damage in most of the categories measured by LCA (Table 2). In agroforestry systems, Parra-Paitan and Verburg (2022) linked negative results to lower yields. In this study, the CB system outperformed the CS system in productivity at the same fertilization dose.

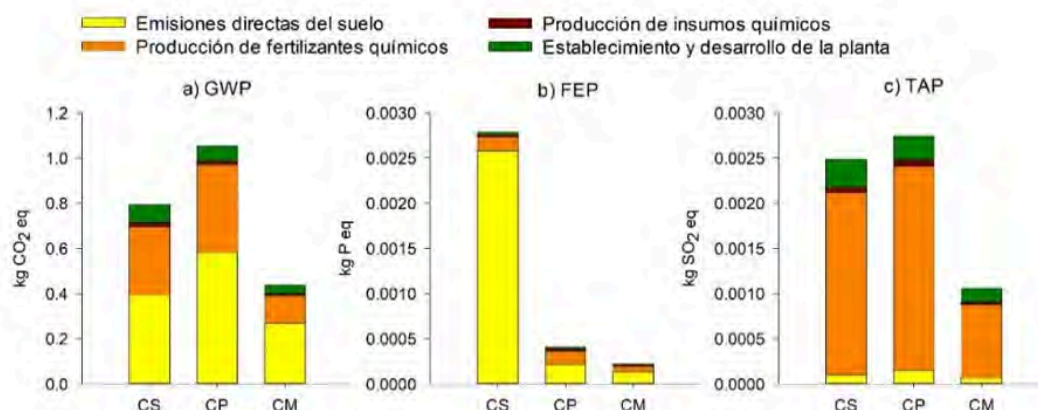
The difference between the CB system and the other study systems was likely due to the nitrogen source: the CB system was the only one that applied urea for banana cultivation. The use of chemical fertilizers, particularly urea and other nitrogenous compounds, constitutes the main source of GHG emissions in coffee crops (Ratchawat *et al.*, 2020; Cornelius *et al.*, 2025).

Impact contribution in LCA categories

In this study, the categories of global warming (GWP), freshwater eutrophication (FEP), and terrestrial acidification (TAP) were analyzed due to their relevance to agriculture.

Figure 1 shows the results for the GWP, FEP and TAP impact categories and their contributions to environmental impacts (direct soil emissions, production of chemical inputs and fertilizers and crop establishment and development) in the study systems.

Figure 1. Total environmental damage and impact contributions by category in the full-sun coffee (CS), coffee-banana (CP) and coffee-mango (CM) systems. In the categories of GWP= global warming, FEP= freshwater eutrophication, and TAP= terrestrial acidification.



Global warming (GWP)

The emission of GHGs into the atmosphere is the main cause of global warming (Guineé, 2002). The results showed that producing 1 kg of cherry coffee results in global warming between 0.44 and 1.05 kg CO₂ eq kg⁻¹ in the analysis systems (Figure 1a). These values are consistent with reports on coffee crops (Noponen *et al.*, 2012; Ratchawat *et al.*, 2020; Basavalingaiah *et al.*, 2022).

Direct soil emissions from chemical fertilizer applications were the primary cause of this category, contributing 50, 55 and 61% in the CS, CB and CM systems, respectively (Figure 1a), followed by fertilizer production, which contributed between 28 and 38% (Figure 1a). Similarly, Noponen *et al.* (2012); Van der Feen *et al.* (2025) reported that direct and indirect soil emissions, mainly associated with fertilizer use, accounted for 67 and 52%, respectively, in the global warming category.

Freshwater eutrophication (FEP)

Eutrophication includes the impacts of excessive levels of macronutrients in the environment, primarily nitrogen (N) and phosphorus (Guinée, 2002). FEP values ranged from 0.00022 to 0.0028 kg P eq kg⁻¹ (Figure 1b). Values that contrast with those of this study were observed in coffee production systems (Basavalingaiah *et al.*, 2022; Rahmah *et al.*, 2022).

Direct soil emissions from chemical fertilizer applications were the main cause in this category, contributing 92, 54 and 60% in the CS, CB and CM systems, respectively (Figure 1b). This is consistent with reports on coffee crops (Pazmiño *et al.*, 2024; Van der Feen *et al.*, 2025).

The research by Hasan *et al.* (2024) reported that chemical fertilizers applied in agricultural fields can leach into reservoirs and lakes, where nitrogenous nutrients cause eutrophication.

Terrestrial acidification (TAP)

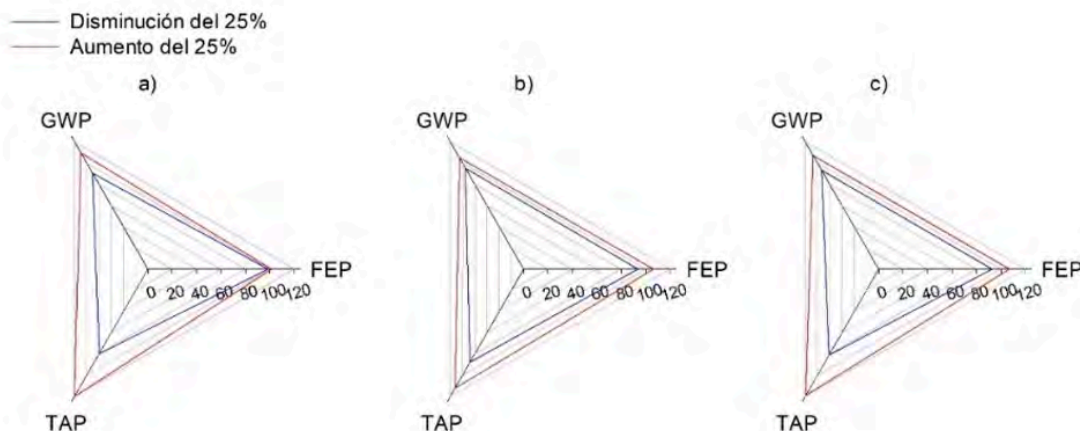
Terrestrial acidification refers to the impact caused by the deposition of acidifying compounds, mainly N and sulfur (Guinée, 2002). TAP values ranged from 0.0011 to 0.0027 kg SO₂ eq (Figure 1c). This range is consistent with that reported by Rahmah *et al.* (2022).

The production of chemical fertilizers significantly influenced this category, contributing 81, 82 and 76% in the CS, CB and CM systems, respectively. The deposition of N in terrestrial ecosystems causes effects such as loss of essential cations in the soil, nutritional imbalances in plants, and acidification (Clark *et al.*, 2013).

Sensitivity analysis

Sensitivity analysis (Figure 2) showed that a 25% reduction in dose reduced the impact by 9 to 19% in the three systems in the GWP category (Figure 2a, 2b and 2c), whereas an increase in dose raised emissions by similar amounts.

Figure 2. Sensitivity analysis of the fertilization dose of full-sun coffee (a), coffee-banana (b), and coffee-mango (c) production systems. GWP= global warming, FEP= freshwater eutrophication and TAP= terrestrial acidification.



The TAP category showed a 13-21% reduction when fertilization decreased, with equivalent increases when the dose increased (Figures 2a, 2b and 2c). Similarly, Hasler *et al.* (2015) observed that the N dose significantly affects LCA results.

Conclusions

The life cycle assessment showed clear differences in the environmental performance of the coffee production systems evaluated. The coffee-mango (CM) system had the lowest environmental impacts across all categories. This better performance is associated with higher yields and greater efficiency in the use of inputs.

In all three systems, nitrogen fertilization was the primary critical point in the categories of global warming and eutrophication. Likewise, the sensitivity analysis showed that a 25% reduction in the fertilization dose can decrease environmental impacts.

Overall, the results show that the environmental performance of coffee systems depends not only on the type of production system but also on the efficiency in input management; therefore, optimizing fertilization and adopting diversified agroforestry systems represent key strategies for reducing environmental impacts without compromising productivity.

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