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ORGANIC SHADE-GROWN COFFEE: A PRODUCTION SYSTEM WITH A LOW CARBON FOOTPRINT AND HIGH SUSTAINABILITY POTENTIAL

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ABSTRACT

The production of organic coffee (*Coffea arabica* L.) under shade contributes to mitigating climate change, as it generates lower greenhouse gas (GHG) emissions than conventional cultivation, thereby reducing its carbon footprint (CF). This study estimated the CF of coffee produced by the Comon Yaj Noptic SPR de RL cooperative in the municipality of La Concordia, Chiapas, Mexico, with the aim of identifying critical emission points and opportunities for environmental improvement. Information was collected from 161 plots through visits and interviews with producers, and wet milling data was integrated using emission factors from the Intergovernmental Panel on Climate Change (IPCC). The CF was estimated per kilogram of green coffee produced, considering emissions from plot management to the packaging of the final product. In the primary stage (plot management to parchment coffee), CF was 0.401 ± 0.079 kg CO_2e, with variability associated with altitude, plantation age, and planting density. The main sources were pulp decomposition (0.262 kg) and wastewater (0.078 kg) due to methane and nitrous oxide emissions. During processing (roasting, grinding, and packaging), CF was 0.415 kg CO_2e, with roasting being the main source (0.304 kg), followed by packaging (0.086 kg) and grinding (0.009 kg). The average CF for the entire production chain was 0.816 kg CO_2e, with a range of 0.758–1.271 kg CO_2e, showing consistency and low impact compared to conventional systems. The results confirm that shade-grown organic coffee has low CF and show high sustainability potential. However, opportunities for improvement were identified, such as the use of clean energy, efficient wastewater management, and the use of pulp as a by-product.

Keywords: *Coffea arabica* L., cooperative, greenhouse gases, agroforestry systems.

INTRODUCTION

The global agri-food system is one of the main sources of greenhouse gas (GHG) emissions. In 2015, it generated approximately 18 billion Mg of carbon dioxide equivalent (CO_2e), corresponding to 34 % of total anthropogenic emissions, with an estimated range between 25 and 42 % (Crippa *et al*., 2021). This sector is a determining factor in climate change due to its intensive use of energy and land, as well as the processes associated with food production, processing, transport, and consumption.

In this context, the carbon footprint (CF) has established itself as a fundamental tool for quantifying and comparing the climate impact of products, processes, or organizations throughout their life cycle. CF is defined as the total amount of GHGs emitted, directly or indirectly, into the atmosphere by an individual, organization, or activity during a given period (Pandey *et al*., 2011). This metric provides a comprehensive estimate of a production system's contribution to global warming, ranging from direct CO_2 emissions to broader assessments based on life cycle analysis (Samaniego and Schneider, 2010).

CF is expressed in units of carbon dioxide equivalent (CO_2e) and is calculated based on the inputs used at each stage of the value chain (kilograms of fertilizers, kWh of electricity, and liters of fuel), multiplied by their respective emission factors (EF) (Noponen *et al*., 2012; Bockel and Schiettecatte, 2018). However, most of the available EFs have been developed under production, energy, and technological conditions typical of industrialized countries, which limits their applicability in traditional agroecosystems in coffee-producing regions.

Contextual differences can introduce uncertainty into CF estimates by not accurately reflecting management practices, energy efficiency, or local soil and climate conditions, which could lead to overestimates or underestimates of actual emissions (Noponen *et al*., 2012). Nevertheless, CF remains a fundamental tool for quantifying GHG emissions throughout the life cycle of products and assessing their global warming potential (Samaniego and Schneider, 2010).

The functional unit used for estimating the CF is one kilogram of green coffee or coffee cherry production. This unit allows emissions to be linked to a specific measure of the product, enabling comparisons of results across different stages of its life cycle or between various studies (Bockel and Schiettecatte, 2018). In this regard, Segura and Andrade (2012) evaluated CF according to different certification standards, considering emissions during the production of *Coffea arabica*. On the other hand, Noponen *et al*. (2012) estimated the CF in conventionally managed coffee systems (0.26–0.67 kg CO_2e kg^{-1} of coffee cherry) and organic systems (0.12–0.52 kg CO_2e kg^{-1} of coffee cherry). These results reflect a wide variability in the reported values and emphasize the necessity of local studies that integrate all stages of the production process.

In 2024, *C. arabica* was grown in 79 countries, harvested from a total area of 12 362 994 ha, with a production of 11 248 094.3 Mg of green coffee. Mexico ranked eighth in harvested area (659 699 ha) and 12th in production (194 470 Mg of green coffee), although its average yield (294.8 kg ha^{-1}) remained among the lowest worldwide (FAO, 2025). At the national level, coffee is grown in 14 states, of which Chiapas accounts for around 35.7 % of production, consolidating its position as the main coffee-growing state (SIAP, 2022).

Coffee farming in Chiapas not only provides economic sustenance to thousands of producers but also constitutes a model of sustainable agricultural practices (Folch and Planas 2019). Although conventional farming is the most common and is associated with negative effects such as biodiversity loss and chemical fertilizer pollution, interest in organic shade-grown systems as an environmentally responsible alternative has grown. However, scientific information quantifying the CF of these systems remains limited, especially in local cooperatives and with a comprehensive life cycle analysis approach.

This study aimed to estimate the carbon footprint of organic shade-grown coffee produced by the Comon Yaj Noptic cooperative in La Concordia, Chiapas, considering emissions from plot management to ground coffee packaging. The results provide quantitative evidence on the climate impact and sustainability potential of this system, contributing to the strengthening of replicable low-carbon production strategies in Mexican coffee farming. Understanding emissions throughout the production cycle is essential for optimizing agricultural practices, improving environmental management, and promoting low-carbon production models.

MATERIALS AND METHODS

Study area

The study was conducted at the Comon Yaj Noptic SPR de RL organic coffee cooperative, based in the community of Nuevo Paraíso, in the municipality of La Concordia, Chiapas. Founded on May 19, 1995, this cooperative comprises 141 producers who manage 161 plots across 12 communities (Figure 1). According to data from weather

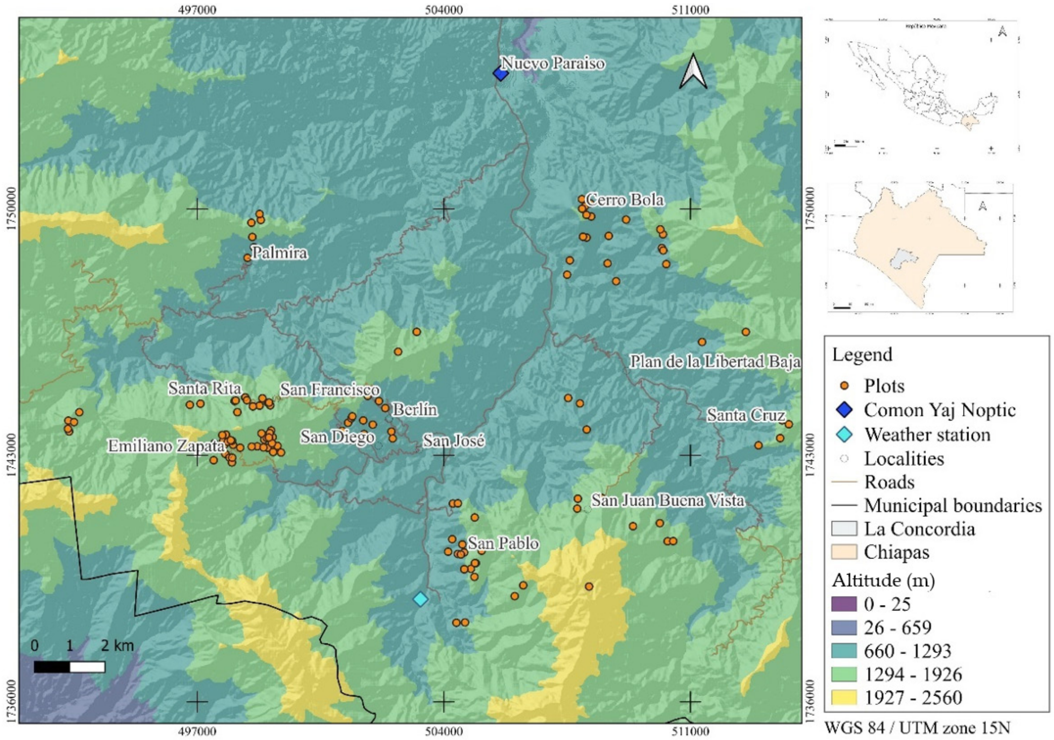

Figure 1. Location of the plots and main communities in the study area in the municipality of La Concordia, Chiapas, Mexico.

station 00007037 Finca Cuxtepeques (SMN, 2025), located at 15° 43’ 43“ N, 92° 58’ 08” W, and an altitude of 1550 m, the average temperature in the area is 22.3 °C, with an average annual precipitation of 2110.2 mm.

The sampling period corresponded to the 2022–2023 production cycle. The survey of production units and the first stage of crop data collection took place between July and October 2022. Subsequently, in February 2023, during the harvest and post-harvest phase, a second stage of data collection was carried out, focusing on practices associated with harvesting, wet processing, and parchment coffee processing.

In both stages, structured interviews were conducted with producers, supplemented by an analysis of technical data sheets for each production unit. This made it possible to identify the specific management practices used on the coffee plots, including planting densities, age of plantations, shade species, yields, doses, and frequencies of input application, as well as the routes and types of transport used. The survey was designed based on the methodological recommendations of the IPCC (2006) and Noponen *et al*. (2012) for the collection of primary data in studies on GHG and CF emissions and was adapted to the cooperative’s production context.

Stages considered in the CF estimate

Similar to the procedure followed by Noponen *et al*. (2012), GHG emissions associated with land use change were not considered, given that more than 20 years had elapsed since the land was converted for the establishment of coffee plantations. Carbon storage in vegetation and soil was also not considered, as the objective of the study was to estimate emissions associated with production operations. The analysis was structured into two main stages: 1) the primary stage, covering activities from plot management to the production of dry parchment coffee, including wet processing and transport to the cooperative; and 2) the processing stage, covering operations from threshing to packaging the final product.

In the primary stage, emissions were considered from several sources: plantation renewal, transportation, application of inputs (such as compost and PSD dihydro solubilizing enhancer), pulping, pulp decomposition, and the wastewater generated during the wet processing stage. These emissions are associated with the agronomic management phase and the immediate post-harvest phase. The processing stage included the industrial operations carried out at the cooperative, comprising the threshing of parchment coffee to obtain green coffee, roasting, grinding, weighing, and packaging of the final product (Figure 2).

The activities considered included the renewal of plantations by transporting plants from the cooperative’s nursery to the plots to maintain productivity, as well as the transport of inputs, specifically compost and PSD, from the cooperative to the communities. PSD was applied at a dose of 50–100 g per plant to improve the health and productivity of the coffee trees. Pulping consisted of separating the beans from the pulp using pulpers, mainly electric (109 units) and, to a lesser extent, gasoline-powered (11 units).

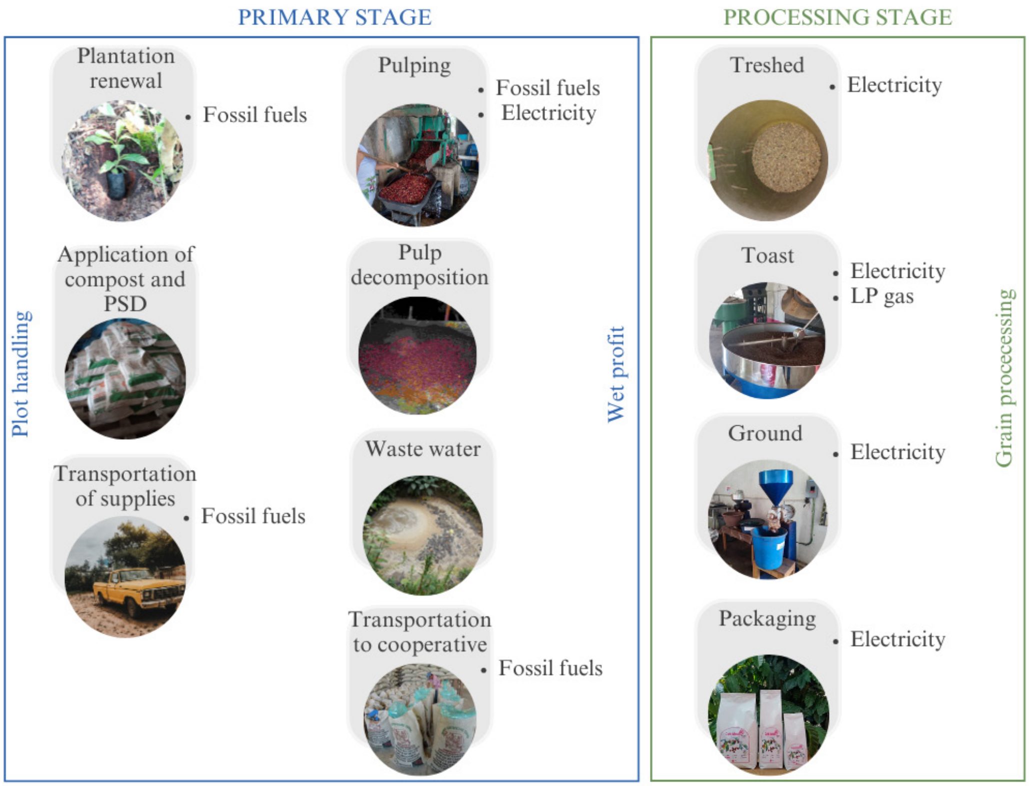

Figure 2. Stages and inputs in the coffee production process.

Emissions from the fermentation and decomposition of pulp and wastewater from washing were also considered, as these processes generate methane (CH_4) and nitrous oxide (N_2O). Threshing involved removing the parchment coffee husk to obtain green coffee, using a five-horsepower (HP) electric machine. Roasting was carried out at controlled temperatures, using LP gas and electricity to power a two-HP motor that ensures the homogeneity of the process. Subsequently, the roasted beans were ground with a three-HP electric grinder to produce ground coffee. Finally, packaging was carried out using an electric packaging machine and an electronic weighing scale (model BAR-8) for distribution and sale.

All GHG emissions were normalized to the defined functional unit, following the methodology proposed by Noponen *et al*. (2012). Specific conversions for the production system were calculated in the field through direct measurements taken during the second sampling phase in the wet and dry mills. It was established that 4.7 kg of coffee cherry is required to obtain 1 kg of parchment coffee and 1.28 kg of parchment coffee are required to obtain 1 kg of green coffee. These values reflect the actual processing conditions of the Comon Yaj Noptic cooperative and were used to normalize emissions throughout the production chain. This relationship was fundamental for distributing emissions among the different stages of the process and calculating the CF of each emission source, in accordance with the approach of Segura and Andrade (2012).

The CF results for each activity were expressed in kilograms of CO_2e per kilogram of green coffee produced. To improve understanding of the text, the reported values are presented only in kg of CO_2e. The classification of activities by stage made it possible to identify the processes with the highest emissions and provided a solid basis for proposing GHG mitigation strategies in the coffee production chain.

Procedure for calculating CF

GHG emissions were calculated by multiplying specific EFs by the amount corresponding to the activity data (liters of gasoline, kWh of electricity, or kilograms of PSD). The EFs used were obtained from scientific literature and reports from the Intergovernmental Panel on Climate Change (IPCC, 2006). To calculate emissions from fertilization and liming, an EF of 0.01 kg N2O kg^{-1} N was applied for nitrogen. In the case of calcium carbonate and magnesium carbonate, 0.12 kg C kg^{-1} $CaCO_3$ and 0.122 kg C kg^{-1} $MgCO_3$ were used, respectively (IPCC, 2006).

Furthermore, CH_4 and N_2O emissions from pulp decomposition were estimated in terms of CO_2e using a global warming potential of 28 g CO_2e g^{-1} for CH_4 and 298 g CO_2e g^{-1} for N_2O (IPCC, 2006). To quantify the amount of pulp generated, a conversion factor of 0.4 was applied, representing the percentage of pulp relative to the weight of the cherry (Rodríguez-Durán *et al*., 2019). In addition, an EF of 0.12 was used for the combined emissions of CO_2, CH_4, and N_2O associated with the process, in accordance with the value reported by Villa-Herrera *et al*. (2025), who adopt it as a technical reference.

Regarding CH_4 emissions from wastewater, water consumption during pulping was considered to be 7 L kg^{-1} of coffee cherry, determined from measurements at wet mills. In addition, the biochemical oxygen demand of the effluent (0.00025 kg L^{-1}) was considered, together with a CH_4 EF of 0.3 kg CO_2e kg^{-1} of green coffee, in accordance with the IPCC Good Practice Guidance (IPCC, 2006).

Water samples were collected at five wet mills (out of a total of 120) at representative points in the process (the supply source, pulping, washing, and wastewater reception pits). The number of mills sampled was limited due to access restrictions resulting from high insecurity in the area. However, the selected subset is representative of the local processing system, since in all cases wet processing is used, the same basic operations are performed, and waste management follows a consistent pattern. Most of the pulp is deposited in nearby sites without treatment, and wastewater is discharged into pits. This similarity in management practices allowed validly inferring the results for the cooperative's processing facilities as a whole.

Biochemical oxygen demand analyses were performed at the Environmental Sciences Laboratory of the Postgraduate College, using the modified Winkler method with the addition of sodium acid (APHA, 2005). CO_2e emissions from transport were estimated based on gasoline consumption for the transport of inputs and parchment coffee. The distance traveled from the producer communities to the cooperative was determined using the QGIS software, version 3.16.9, with the EPSG:6370 reference system, Mexico ITRF2008/UTM, zone 15N, and an average vehicle fuel efficiency of 8 km L^{-1}. The calculation considered the route usually used by producers, which in most cases is the only one available due to the geographical isolation of the study area. An EF of 2.33 kg CO_2e L^{-1} of gasoline was used (IPCC, 2006).

During the threshing, roasting, grinding, and packaging stages, energy consumption was estimated based on the capacity and power of the machines. An EF of 1.595 kg CO_2e L^{-1} was considered for LP gas and 0.3 kg CO_2e kWh^{-1} for electricity, the latter corresponding to the national value reported for Mexico in the 2022 Climate Transparency Report (Climate Transparency, 2022). Additionally, for the packaging process, an EF of 1.99 kg CO_2e kg^{-1} of plastic bags used was considered (Castaño-Peláez and Botero-Agudelo, 2017).

Data analysis

A database was constructed with information from 161 plots, and yields were standardized in kilograms of green coffee per hectare. Data management was performed using Microsoft Excel worksheets. Statistical analysis was performed using the R program (version 4.3.1) and its RStudio interface (version 2023.6.0.421) (R Core Team, 2023). Descriptive statistics were calculated using the *pastecs* library and the *stat.desc* function. Graphs were created using the *ggplot2* library and the *ggplot* function.

RESULTS AND DISCUSSION

Production system

Descriptive statistics for the variables associated with the plots provided a detailed overview of the coffee production conditions (Table 1). Plot size ranged from 0.5 to 6 ha, while altitude ranged from 769 to 1846 m. Similarly, planting density showed a wide range (1050–9800 plants ha^{-1}) and a coefficient of variation of 0.372 (Table 1),

Table 1. Descriptive statistics of the variables analyzed in the coffee plots studied in La Concordia, Chiapas, Mexico.

Variables	Units	Mínimum	Maximum	Median	Mean	Standard deviation	Coefficient of variation
Surface	ha	0.5	6	1.5	1.95	1.276	0.656
Altitude	m	769	1846	1429	1369.2	225.93	0.165
Planting density	Plants ha^{-1}	1050	9800	4090	4316.7	1606	0.372
Age	Years	1.7	26	9.3	10.1	5.465	0.542
Shade species	Quantity	1	50	12	13.2	5.754	0.436
Performance (cherry)	kg ha^{-1}	216.2	8648	2162	2767.4	1829.05	0.663
Distance	km	12.43	32.5	22.04	21.96	5.915	0.269

confirming a high relative dispersion and reflecting the adoption of different agronomic practices among producers. The coffee plantations were between 1.7 and 26 years old, which could have direct implications for yield. The coefficient of variation for yield was 0.663, reflecting high variability attributable to differences in management practices implemented by producers. The distance between the communities where wet processing was carried out and the cooperative's facilities ranged from 12.43 to 32.5 km.

The number of shade trees per plot ranged from 1 to 50, with a median of 12. Species of the genus *Inga* (*I. oerstediana* Benth., *I. vera* Willd.), *Alchornea latifolia* Sw., *Tabebuia rosea* (Bertol.) DC., *Cecropia obtusifolia* Bertol., and *Liquidambar styraciflua* L. predominated, as did fruit species of economic value such as *Mangifera indica* L. and *Persea americana* Mill. According to the classification of agroforestry systems used by Chéron-Bessou *et al*. (2024), most of the systems were classified as complex. The high number of shade species not only benefits biodiversity but also influences CO_2 capture (van Rikxoort *et al*., 2014; Casanova-Lugo *et al*., 2016) and the provision of other regulatory ecosystem services, such as climate adjustment, erosion, humidity, soil fertility, and biological control of pests and diseases (Altieri and Nicholls, 2020).

CF during the primary phase

The CF of transporting inputs averaged 0.0133 kg CO_2e and had a median of 0 kg CO_2e, indicating that more than half of the plots did not record emissions associated with this activity (Table 2). Of the 161 plots analyzed, only 73 carried out individual transport of inputs; of these, PSD was applied in 58, while the rest did not report any travel because they did not apply inputs during the period evaluated. Zero values were assigned in cases with no evidence of travel or with collective distribution, which explains the asymmetry observed in the data. The standard deviation of 0.0248 kg CO_2e reflects moderate variability, mainly attributable to differences in distances traveled and frequency of trips.

The transportation of inputs contributed, on average, to 1.6 % of total CF. However, its wide variability and high emissions in some plots indicate room for improvement. Strategies such as optimizing transportation or reducing the frequency of trips could reduce emissions in this phase of the process (Pramulya *et al*., 2022). GHG emissions associated with PSD application ranged from 0 to 0.272 kg CO_2e, with an average of 0.027 kg CO_2e and a median of 0 kg CO_2e, representing 3.3 % of total CF. This low contribution is due to the fact that PSD is applied in small doses and in a localized manner.

With regard to activities related to plot management, GHG emissions were recorded in 74 of the 161 plots evaluated. The values ranged from 0 to 0.465 kg CO_2e, with an average of 0.04 kg CO_2e and a standard deviation of 0.072 kg CO_2e, reflecting high variability among production units. This suggests that there are opportunities to optimize management practices to reduce emissions on certain plots.

Table 2. Carbon footprint (CF) of activities in the primary and processing stages of shade-grown organic coffee on the coffee plots studied in La Concordia, Chiapas, Mexico.

Activity	Number of plots	Minimum	Average	Maximum	Median	Standard deviation	% Total CF
	kg CO_2e kg^{-1} of green coffee						%
Transportation of supplies	161	0	0.013	0.193	0	0.022	1.6
Application of PSD	161	0	0.027	0.272	0	0.052	3.3
Pulping	161	0.001	0.002	0.012	0.001	0.002	0.2
Pulp decomposition	161	ND	0.262	ND	ND	ND	32.1
Wastewater	161	ND	0.078	ND	ND	ND	9.5
Transportation of parchment	161	0.003	0.017	0.113	0.013	0.016	2.5
Threshing	NA	NA	0.013	NA	NA	NA	1.6
Roasting	NA	NA	0.304	NA	NA	NA	37.2
Grinding	NA	NA	0.009	NA	NA	NA	1.1
Packaging (bags)	NA	NA	0.086	NA	NA	NA	10.5
Weighing	NA	NA	0.001	NA	NA	NA	0.1
Sealing	NA	NA	0.002	NA	NA	NA	0.2
CF of the primary phase	161	0.343	0.401	0.856	0.372	0.079	49.2
CF of the processing stage	ND	ND	0.415	ND	ND	ND	50.8

NA corresponds to activities that do not apply at the plot level, as they were carried out centrally at the cooperative's facilities (threshing, roasting, grinding, packaging, weighing, and sealing). ND indicates that it was not possible to obtain disaggregated information by plot, as no individual measurements were taken; in these cases, emissions were estimated from representative averages derived from measurements taken at the wet mills sampled.

The average estimated emissions per plot (0.04 kg CO_2e kg^{-1} of green coffee) were lower than those reported in Brazil and Vietnam (0.05 and 0.08 kg CO_2e kg^{-1} of green coffee in sustainable systems) (Nab and Maslin, 2020); Veracruz, Mexico (1.41 kg CO_2e kg^{-1} of green coffee in a conventional production system) (Giraldi-Díaz *et al*., 2018), and Costa Rica (1.02 kg CO_2e kg^{-1} of green coffee in traditional production systems) (Killian *et al*., 2013). However, the highest value found in this study (0.465 kg CO_2e) was higher than the averages for some of these systems. This highlights the importance of taking into account the variability of agricultural practices and the specific conditions of each plot. The highest emissions were mainly associated with the use of nitrogen fertilizers, in line with the findings of Arellano and Hernández (2023) and Trinh *et al*. (2020).

GHG emissions from wet processing

The CF associated with the use of gasoline-powered pulpers was 0.012 kg CO_2e, while for electric pulpers it was 0.001 kg CO_2e, with an overall average of 0.002 kg CO_2e. The predominance of electric equipment (90.83 %) explains the low average emissions at this stage, given that these are more energy efficient and reduce dependence on fossil fuels, which is an environmentally friendly alternative.

Emissions from pulp decomposition and methane (CH_4) from wastewater were the main sources of wet processing, with 0.262 and 0.078 kg CO_2e, equivalent to 32.1 and

9.5 % of total CF, respectively. According to van Rikxoort *et al*. (2014), the variability in CF in this process reflects differences in water management during fermentation and washing, as well as in the efficiency of the inputs applied. Likewise, Chéron-Bessou *et al*. (2024) highlight that the initial DBO conditions of the wastewater directly influence the magnitude of GHG emissions.

In the present study, the largest contribution came from pulp decomposition, while Pramulya *et al*. (2019) reported the opposite pattern: 0.125 kg CO_2e kg^{-1} for wastewater and 0.015 kg CO_2e kg^{-1} for pulp. This difference is attributed to the fact that, in the study region, pulping is carried out dry, leaving the pulp exposed to the environment for decomposition, while water is mainly used for washing, which concentrates organic matter in the pulp and increases CH_4 and N_2O emissions. Together, these processes contributed about 85 % of wet mill emissions, compared to 65 % reported by Pramulya *et al*. (2019).

Similarly, van Rikxoort *et al*. (2014) recorded much higher emissions (4.7 ± 2.8 kg CO_2e kg^{-1} of parchment coffee), attributable to intensive water use (80 L kg^{-1}) compared to the 7 L kg^{-1} used in this study. These differences confirm that water management is a determining factor in the magnitude of emissions during wet processing. The average CF of wet processing was 0.359 ± 0.016 kg CO_2e, indicating consistency and low dispersion among producers, as homogeneous water volumes, DBO values, and emission factors were used. This value was lower than that reported by Killian *et al*. (2013) (0.48 kg CO_2e kg^{-1}) and much lower than that of van Rikxoort *et al*. (2014) (3.0 ± 2.1 kg CO_2e kg^{-1} of parchment coffee), but higher than the values reported by Nab and Maslin (2020) (0.08–0.1 kg CO_2e kg^{-1}), who did not consider emissions from pulp decomposition or wastewater.

The transport of parchment coffee contributed 0.017 kg CO_2e, equivalent to 2.5 % of total CF. This result is lower than that reported by Maina *et al*. (2016) (0.036 kg CO_2e kg^{-1} of parchment coffee), which is attributed to the lower conversion factor applied (1.28). Overall, the primary stage, from plantation management to the production of parchment coffee, recorded values between 0.343 and 0.856 kg CO_2e, with an average of 0.401 kg CO_2e and a coefficient of variation of 19.6 %, reflecting moderate variability in production practices. This value was higher than that estimated by Pramulya *et al*. (2019) (0.341 kg CO_2e kg^{-1} of green coffee) but lower than the range reported by Arias-Hernández *et al*. (2018) (1.05–3.56 kg CO_2e kg^{-1} of parchment coffee), confirming the low climate impact of the organic shade-grown system analyzed in this study (Table 2).

CF grain processing

The total CF of the processing stage was 0.415 kg CO_2e (Figure 3). Threshing contributed 0.013 kg CO_2e, roasting 0.304 kg CO_2e, grinding 0.009 kg CO_2e, plastic bags 0.086 kg CO_2e, weighing 0.001 kg CO_2e, and sealing 0.002 kg CO_2e. Roasting had a higher CF than the 0.19 kg CO_2e kg^{-1} of green coffee reported by Killian *et al*. (2013). However, post-roasting emissions were lower (0.098 kg CO_2e) than the 0.13 kg CO_2e kg^{-1} of green coffee reported by Killian *et al*. (2013). In contrast, these results were lower than those

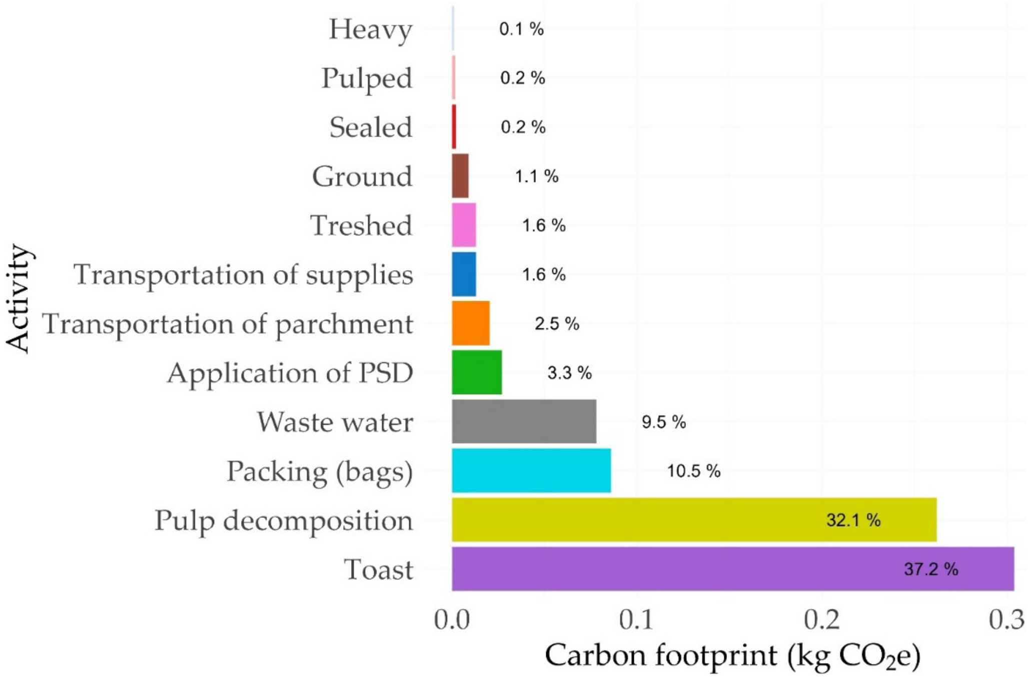

Figure 3. Relative contribution of production chain activities to the carbon footprint (CF) of shade-grown organic coffee on the coffee plots studied in La Concordia, Chiapas, Mexico.

of Giraldi-Díaz *et al*. (2018), who obtained CF values of 1.5 and 2.82 g CO_2e kg^{-1} of ground coffee.

CF of the entire production chain

The average CF for the entire production chain was 0.816 kg CO_2e, ranging from 0.758 to 1.271 kg CO_2e. The activities with the highest contribution were roasting, pulp decomposition, packaging bags, and wastewater (Figure 3). These results are within the range reported for organic coffee systems, although they are slightly higher than the values of 0.64–0.647 kg CO_2e kg^{-1} of green coffee obtained by Trinh *et al*. (2020), who did not consider emissions from pulp decomposition or wastewater management. In contrast, Maina *et al*. (2016) documented a considerably higher CF (4 kg CO_2e kg^{-1} of parchment coffee) in conventional systems. Similarly, Pramulya *et al*. (2022) reported intermediate values, from 1.48 to 1.93 kg CO_2e kg^{-1} of green coffee, considering the stages from harvest to packaging.

According to Maina *et al*. (2016), the differences observed in CF values between studies can be attributed mainly to variations in production methods, especially in the type and management of fertilization. Similarly, Pramulya *et al*. (2019) highlight that discrepancies in CF estimates may also be due to differences in calculation methods, DBO values used, or EFs considered.

The main sources of GHG emissions identified in this study corresponded to wet processing, in particular pulp decomposition and wastewater management, which together accounted for 41.6 % of total CF. Similarly, Killian *et al*. (2013) identified wastewater as a significant source of emissions and demonstrated that the use of biodigesters can reduce CH_4 emissions from 0.374 to 0.340 kg CO_2e kg^{-1} of green coffee. For their part, van Rikxoort *et al*. (2014) proposed that mitigation strategies in Latin American coffee production should focus on: 1) conserving carbon stocks in biomass and preventing deforestation; 2) reducing emissions from fertilizer use through efficient management practices; and 3) reducing wastewater emissions through dry processing or the implementation of improved wet processing methods.

CONCLUSIONS

The analysis of organic shade-grown coffee production at the Comon Yaj Noptic cooperative revealed high variability in management conditions and production characteristics across plots, which is reflected in differences in the estimated carbon footprint for each production unit. Overall, the results confirm the low climate impact and environmental efficiency of this system compared to conventional models, showing the potential of organic agroforestry systems to contribute to mitigating greenhouse gas emissions in Mexican coffee farming.

Areas for improvement were also identified with a view to increasing the sustainability of the process, particularly through the incorporation of clean energy in the processing and packaging stages, the optimization of water use and treatment during wet processing, and the recovery of coffee pulp as an agricultural by-product. The case study indicates that shade-grown organic coffee is a viable alternative for moving toward low-emission coffee farming with greater environmental resilience. Although the results correspond to a specific context, they offer a useful reference for promoting sustainable practices that can be replicated in other producing regions of the country.

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REFERENCES

Altieri MA, Nicholls CI. 2020. Agroecology: Challenges and opportunities for farming in the Anthropocene. International Journal of Agriculture and Natural Resources 47 (3): 204–215. https://doi.org/10.7764/ijanr.v47i3.2281

APHA (American Public Health Association). 2005. Standard methods for the examination of water and wastewater (21st edition). Washington, DC, USA. 1368 p.

Arellano C, Hernández C. 2023. Carbon footprint and carbon storing capacity of Arabica coffee plantations of Central America: A review. Coffee Science 18: e182072. https://doi.org/10.25186/.v18i.2072

Arias-Hernández JJ, Riaño-Herrera NM, Riaño-Becerra AM, Ariza-Camacho W, Posada-Suarez HJ, Valenzuela-Andrade J, Vega-Cano MA, Murgueitio-Cortes YP, Castro-Chavez JF. 2018. Determinación de la huella de carbono en el sistema de producción de café pergamino seco de cuatro municipios del sur del departamento del Huila (Colombia). Revista de Investigación Agraria y Ambiental 9 (2): 109–120.

Bockel L, Schiettecatte LS. 2018. Life cycle analysis and the carbon footprint of coffee value chains. *In* Lashermes P. (ed.), Achieving Sustainable Cultivation of Coffee. Burleigh Dodds Science Publishing: Sawston, UK, pp: 359–382. https://doi.org/10.19103/as.2017.0022.20

Casanova-Lugo F, Ramírez-Avilés L, Parsons D, Caamal-Maldonado A, Piñeiro-Vázquez AT, Díaz-Echeverría V. 2016. Environmental services from tropical agroforestry systems. Revista Chapingo Serie Ciencias Forestales y del Ambiente 22 (3): 269–284. https://doi.org/10.5154/r.rchscfa.2015.06.029

Castaño-Peláez HI, Botero-Agudelo JL. 2017. Evaluación ambiental del proceso de elaboración de bolsas plásticas en Colombia utilizando la metodología de análisis de ciclo de vida. Revista Politécnica 13 (24): 9–18.

Chéron-Bessou C, Acosta-Alba I, Boissy J, Payen S, Rigal C, Setiawan AAR, Sevenster M, Tran T, Azapagic A. 2024. Unravelling life cycle impacts of coffee: Why do results differ so much among studies? Sustainable Production and Consumption 47: 251–266. https://doi.org/10.1016/j.spc.2024.04.005

Climate Transparency. 2022. Climate transparency report. G20 response to the energy crisis: critical for 1.5 °C. Bali Nusa Dua, Indonesia. 59 p.

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A. 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2 (3): 198–209. https://doi.org/10.1038/s43016-021-00225-9

FAO (Food and Agriculture Organization of the United Nations). 2025. FAOSTAT. Crops and livestock products. Rome, Italy. https://www.fao.org/faostat/en/#data/QCL (Retrieved: December 2025).

Folch A, Planas J. 2019. Cooperation, fair trade, and the development of organic coffee growing in Chiapas (1980–2015). Sustainability 11 (2): 357. https://doi.org/10.3390/su11020357

Giraldi-Díaz MR, de Medina-Salas L, Castillo-González E, León-Lira R. 2018. Environmental impact associated with the supply chain and production of grounding and roasting coffee through life cycle analysis. Sustainability 10 (12): 4598. https://doi.org/10.3390/su10124598

IPCC (Intergovernmental Panel on Climate Change). 2006. 2006 IPCC guidelines for national greenhouse gas inventories, Volumen 4. Agriculture, forestry and other land use. Kanagawa, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (Retrieved: November 2025).

Killian B, Rivera L, Soto M, Navichoc D. 2013. Carbon footprint across the coffee supply chain: the case of Costa Rican coffee. Journal of Agricultural Science and Technology B3: 151–170.

Maina J, Mutwiwa UN, Kituu GM, Githiru M. 2016. Evaluation of greenhouse gas emissions along the small-holder coffee supply chain in Kenya. Journal of Sustainable Research in Engineering 2 (4): 111–120.

Nab C, Maslin M. 2020. Life cycle assessment synthesis of the carbon footprint of Arabica coffee: Case study of Brazil and Vietnam conventional and sustainable coffee production and export to the United Kingdom. Geography and Environment 7 (2). https://doi.org/10.1002/geo2.96

Noponen MRA, Edwards-Jones G, Haggar JP, Soto G, Attarzadeh N, Healey JR, 2012. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. Agriculture, Ecosystems and Environment, 151: 6–15. https://doi.org/10.1016/j.agee.2012.01.019

Pandey D, Agrawal M, Pandey JS. 2011. Carbon footprint: Current methods of estimation. Environmental Monitoring and Assessment 178 (1–4): 135–160. https://doi.org/10.1007/s10661-010-1678-y

Pramulya R, Bantacut T, Noor E, Yani M, Romli M. 2022. Life cycle assessment of Gayo Arabica coffee green bean at Aceh Province. Habitat 33 (3): 308–319. https://doi.org/10.21776/ub.habitat.2022.033.3.29

Pramulya R, Bantacut T, Noor E, Yani M. 2019. Carbon footprint calculation for Gayo Arabica coffee primer processing. International Journal of Scientific and Technology Research 8 (12): 2934–2938.

R Core Team. 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/ (Retrieved: November 2024).

Rodríguez-Durán L, Favela-Torres E, Aguilar C, Saucedo-Castañeda G. 2019. Coffee pulp as potential source of phenolic bioactive compounds. *In* Chavez-Gonzalez M, Buenrostro-Figueroa JJ, Aguilar CN. (eds.), Handbook of Research on Food Science and Technology: Volume 1: Food Technology and Chemistry. Apple Academic Press: New York, NY, USA, pp: 107–132. https://doi.org/10.1201/9780429487859-5

Samaniego J, Schneider H. 2010. La huella del carbono en la producción, distribución y consumo de bienes y servicios. Comisión Económica para América Latina y el Caribe. Comisión Económica para América Latina y el Caribe: Santiago de Chile, Chile. 46 p.

Segura MA, Andrade HJ. 2012. Huella de carbono en cadenas productivas de café (*Coffea arabica* L.) con diferentes estándares de certificación en Costa Rica. Luna Azul 35: 60–77.

SIAP (Sistema de Información Agroalimentaria y Pesca). 2022. Anuario estadístico de la producción agrícola. Cierre de la producción agrícola por estado. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Sistema de Información Agroalimentaria y Pesca. Ciudad de México, México. https://nube.siap.gob.mx/cierreagricola/ (Retrieved: December 2025).

SMN (Servicio Meteorológico Nacional). 2025. Normales climatológicas. Gobierno de México. Comisión Nacional del Agua. Ciudad de México, México. https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Normales9120/chis/nor9120_07037.txt (Retrieved: October 2025).

Trinh LTK, Hu AH, Lan YC, Chen ZH. 2020. Comparative life cycle assessment for conventional and organic coffee cultivation in Vietnam. International Journal of Environmental Science and Technology 17 (3): 1307–1324. https://doi.org/10.1007/s13762-019-02539-5

van Rikxoort H, Schroth G, Läderach P, Rodríguez-Sánchez B. 2014. Carbon footprints and carbon stocks reveal climate-friendly coffee production. Agronomy for Sustainable Development 34 (4): 887–897. https://doi.org/10.1007/s13593-014-0223-8

Villa-Herrera A, Bolaños-González MA, Paz-Pellat F, Salvador-Castillo JM, Ramírez-Armas LM, Villagómez-Jiménez C. 2025. Evaluation of the carbon footprint of the coffee production chain: Case study of the Finca Triunfo Verde, Chiapas, México. Tropical and Subtropical Agroecosystems 28 (1): 1–14. https://doi.org/10.56369/tsaes.6043