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Environmental Impact Assessment of the Bioprocesses on the Plantain Supply Chain in Mexico

Evaluación del impacto ambiental de los bioprocesos de la cadena de suministro del plátano en México

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Abstract

The waste, by-products, and rejects generated in the processing, distribution, and sale of bananas are not optimally utilized. If not properly managed, this organic waste can cause serious environmental problems. Between 24% and 40% of bananas are not marketed and end up in landfills until they decompose, mainly because they do not comply with export regulations. Although it is feasible to use this waste to produce flour and bioethanol, it is necessary to evaluate the potential environmental consequences of these processes. This study assessed the environmental viability of flour and bioethanol production from immature plantain within the plantain production chain in Mexico, using life cycle analysis (LCA). The functional unit for the agronomic stage was 1 kg of plantain produced for direct sale. In contrast, for the industrial processes, 1 kg of flour produced was used as the functional unit, with bioethanol as a co-product. A sensitivity analysis was performed by varying the allocation between mass and economic value, while holding the total product flow constant across scenarios. E-LCA was performed using SimaPro 9.6.0.1 with ReCiPe Midpoint (H) v1.13 and Ecoinvent v3.3 data. Monte Carlo simulations modeled input uncertainty using probability distributions, enabling variability/sensitivity analysis to support robust environmental results. The results showed that the transport of inputs, together with the use of machinery, fertilizers, herbicides, and insecticides, has the most significant environmental impact during cultivation. In addition, the production of flour and bioethanol has substantial implications due to the complexity of the underlying technological processes. In conclusion, this work provides reliable environmental inventories and criteria to support decisions aimed at reducing environmental impacts in the banana marketing chain, thereby contributing to its sustainability and the circular economy.

Keywords

Bioethanol, circular economy, environmental impact, life cycle analysis, sustainability.

Resumen

Los subproductos generados en la cadena productiva del plátano no se aprovechan de manera óptima. Su mala gestión genera impactos ambientales graves. Entre el 24 % y el 40 % de los plátanos no se comercializan, principalmente por no cumplir con la normativa de exportación, y terminan en vertederos, donde se descomponen. Aunque es viable aprovechar estos residuos para producir harina y bioetanol, es necesario evaluar las posibles consecuencias ambientales de dichos procesos. Este estudio tuvo como objetivo evaluar la viabilidad ambiental de la producción de harina y bioetanol a partir de plátano inmaduro en la cadena productiva del plátano en México, mediante el análisis del ciclo de vida (ACV). La unidad funcional para la etapa agronómica fue de 1 kg de plátano producido para la venta directa, mientras que, para los procesos industriales, se consideró 1 kg de harina producida, con el bioetanol como coproducto. Se realizó un análisis de sensibilidad variando la asignación entre masa y valor económico, considerando el flujo total de productos en cada escenario. La evaluación del ACV se realizó con SimaPro 9.6.0.1, el método ReCiPe Midpoint (H) v1.13 y la base de datos Ecoinvent v3.3. Las simulaciones de Monte Carlo modelaron la incertidumbre de los insumos mediante distribuciones probabilísticas, lo que permitió analizar la variabilidad y la sensibilidad para obtener resultados ambientales robustos. Los resultados mostraron que el transporte de insumos, junto con el uso de maquinaria, fertilizantes, herbicidas e insecticidas, genera el mayor impacto ambiental durante el cultivo. Además, la producción de harina y bioetanol conlleva impactos significativos debido a la complejidad de los procesos tecnológicos implicados. En conclusión, este trabajo aporta inventarios y criterios ambientales confiables para apoyar decisiones orientadas a reducir el impacto ambiental a lo largo de la cadena de comercialización del plátano, contribuyendo así a su sostenibilidad y a la economía circular.

Palabras clave

Bioetanol, economía circular, impacto ambiental, análisis de ciclo de vida, sostenibilidad.

1. INTRODUCTION

Plantains in México are grown in the coastal regions of the Pacific Ocean and the Gulf of Mexico. In 2022, production was 2 652 188 tons from an arable land area of 164 057 ha. The primary producing states are Tabasco (24%), Chiapas (19.7%), Veracruz (13.6%), and Colima (8%) [1].

In 2024, approximately 11 500 hectares of plantain were cultivated in Colima, of which 5% was exported to foreign markets, and 95% was sold locally [2]. The waste, by-products, and rejects resulting from plantain processing, distribution, and retailing are not being fully utilized. If these wastes are not disposed of properly, the final waste management of all this organic biomass involves serious environmental problems. Approximately 24–40% of plantains are not marketed and are disposed of in landfills until they decompose because they do not meet export regulations [3]. Plantain that does not meet the quality standard is rejected, but can be transformed into value-added products. For example, whole (pulp with peel) plantain flour has been used to produce a gluten-free food matrix [4]. This flour can replace wheat flour without compromising cooking quality [5]. Unripe plantain flour with the peel has the advantage of increasing fiber and antioxidant content, which are beneficial to consumer health. Based on prior research, unripe plantain flour is a viable ingredient for human consumption [6] and for producing bioethanol [7]. The potential of bioethanol to reduce greenhouse gas emissions from the transport sector is generating research interest. Bioethanol has been considered an alternative to reduce dependence on fossil fuels and meet biofuel targets in the transport sector [8]. However, when crops used to produce bioethanol require arable land, controversy arises over their social and environmental impacts, particularly their sustainability [9]. To be truly sustainable, bioethanol production should reduce its environmental impact relative to fossil-fuel gasoline.

Environmental Life Cycle Assessment (E-LCA) is a reliable method for assessing the environmental impacts of processes and products. E-LCA's method seeks to accurately identify and quantify the energy required and the flows released to the environment. E-LCA assesses which flows have the greatest impact on the environment, human health, and natural resources [10]. ISO 14040 and 14044 [11] guide the phases of the E-LCA. The definition of the aim and scope is the first phase of an E-LCA. This determines the exact approach to be followed. This includes defining the system boundaries and the functional unit and deciding whether to include or exclude stages or inputs. It also involves selecting impact indicators and characterization factors [12]. The second phase consists of the life cycle inventory (LCI). The quality and accuracy of data collection in this phase determine the depth of the study. Data collection must be specified and detailed (e.g., databases, fieldwork, interviews, journal articles, packages of practices, etc.) [13].

Recent LCA studies of banana and plantain supply chains reveal consistent climate-change hotspots, dominated by farm production, international transport (for plantain exports), and waste management. The environmental profile of Ecuadorian export bananas confirms this pattern, identifying synthetic fertilizers, on-farm fuel consumption, and long-distance refrigerated shipping as key hotspots of greenhouse gas emissions along the cradle-to-port system [14]. [15] report a carbon footprint of 0.805 kg CO_2-eq/kg for Costa Rican bananas consumed in Europe, with agriculture (fertilizers) at ~25%, shipping ~20%, and end-of-life ~36%. Similar findings emerge for Brazilian semiarid bananas (0.21-0.84 kg CO_2-eq/kg), where N-fertilizers and irrigation drive emissions, projected to worsen under climate scenarios [16]. Yogyakarta banana farming highlights the role of pesticides in GHG via energy use. Overall, these works underscore the need for optimized agrochemicals, improved nutrient management, energy-efficient irrigation and packing, and optimized shipping and ripening logistics to lower the product's carbon footprint substantially, thereby mitigating ~0.5-1.3 kg CO_2-eq/kg across chains [17].

There have been few studies focusing on the E-LCA of tropical, perennial agricultural products. [18] developed an approach in which the environmental indicators of plantain production in Brazil were assessed using E-LCA. In that study, E-LCA was applied from the perspective of a farm with retail sales to quantify the environmental impact of Cavendish and Prata bananas available in Brazilian retail stores. Highlights indicate that the use of nitrogen as fertilizer and carbofuran-based pesticides were the main contributors to agricultural production across all assessed impact categories. However, this study focuses on the farming and commercialization phases, without accounting for plantain losses. As plantain is the fourth most widely cultivated crop in the world, recent studies have explored ways to utilize its harvest and post-harvest losses. [8] Conducted a technical analysis of ethanol production from unripe, rejected plantains. They also conducted an economic analysis of producing ethanol and flour from unripe whole plantain (including the peel) as the raw material. However, to determine the environmental sustainability of these processes, it is necessary to assess the potential environmental impacts of plantain production and its transformation into value-added products. Furthermore, research on tropical perennial agricultural products must be expanded, given their great diversity and the paucity of primary information.

To assess the environmental impact of flour and bioethanol production, using unripe plantain with peel as raw material, this research employs the E-LCA method to analyze environmental indicators and identify hotspots for improvement. For this analysis, Mexico was selected as a case study. Unripe plantain was chosen as the main product for commercialization, while rejected plantain (24%) was used to produce flour and ethanol in four scenarios, including a base case. Across the three scenarios, 76% of the harvested product is marketed, with the remaining 24% processed. In the first scenario, 100% of the unripe plantain (UP) was used to produce flour. In the second scenario, bioethanol and plantain flour were produced using UP; in the third scenario, plantain pulp flour and bioethanol from the peel were produced. The objective of this study is to evaluate the environmental implications of bioprocesses applied to rejected unripe plantain within the Mexican plantain supply chain.

2. MATERIALS AND METHODS

The E-LCA was carried out in accordance with the methodology reported in ISO 14040:2006 [11], which comprises four steps: Goal and scope definition, Environmental Life Cycle Assessment (E-LCA), Environmental Life Cycle Evaluation (E-LCE), and Interpretation of results.

2.1 Goal scope definition

The first step describes the system boundary, functional unit, allocation, and sensitivity analysis.

2.1.1 Goal

The E-LCA aims to evaluate the environmental impact of different valorization scenarios of UP in the productive chain in Mexico (Colima, 18°56'13"N 103°57'54"O). The cradle-to-gate approach was implemented in the E-LCA, beginning with the germination of the plantain crop and ending at the UP valorization, across three process scenarios. Finally, an attributional analysis was performed by varying the allocation (sensitivity analysis).

2.1.2 Scope

The E-LCA was conducted considering the stages of the plantain production chain in Mexico. In this sense, the agronomic stage (plantain crop) and the UP valorization to produce flour and ethanol were considered. Plantain crop data were taken from bibliographic sources in the Mexican context [1], [2], [19]. To conduct the inventory, the scientific literature, technological packages, and databases provided by the Mexican entity Fideicomisos Instituidos en Relación con la Agricultura (FIRA) were used. This entity provides farmers with financial and technical support and has standardized methodologies for estimating agricultural production costs, which are available via the Agrocostos platform. The data used for this study are adapted for plantain cultivation in the Colima region and are known as Pump-Enhanced-Fertilized (BMF for its initials in Spanish) [19]. The system inputs involved machinery (such as a tractor, a semi-heavy harrow, a leveler, and a backhoe), fossil fuels, fungicides, fertilizer production, and transport. The emissions from fertilizers and the combustion of fossil fuels used in machinery, as well as organic matter generated, were considered outputs to soil, air, and water. The application of diammonium phosphate (DAP), as a fertilizer, results in emissions to air and water. According to [3], 24% of the plantain produced in one hectare is rejected due to undesirable organoleptic characteristics, such as dirty fruit, undersized fruit, friction, mutilation, mistreatment, or animal scratches.

The material and energy balances for UP valorization were taken from [8]. Figure 1 shows the scenarios considered in the E-LCA. The base case involves the agronomic stage of the plantain crop. Scenario 1 involves UP valorization for flour production from the whole plantain. Scenario 2 consists of the production of flour and bioethanol. Bioethanol production was achieved through enzymatic hydrolysis using commercial preparations of α-amylase (Licuamil™), amyloglucosidase (Glucozyme™), pectinase (Zymapect™), and cellulase (Celuzyme™), followed by fermentation with Saccharomyces cerevisiae (ATCC 20252). In this scenario, 50% of the UP is used to produce flour, and the other 50% is used to produce bioethanol. Finally, Scenario 3 involves producing bioethanol from plantain peel (31% of the whole fruit) [20] and bioethanol from pulp flour

2.1.3 Functional unit

The functional unit (FU) for the E-LCA of the agricultural stage was defined as 1 kg of plantain produced for direct sale. For the technological scenarios, the FU was defined as 1 kg of flour produced. This was selected based on the objective of the analysis (the plantain and flour production chains in Mexico).

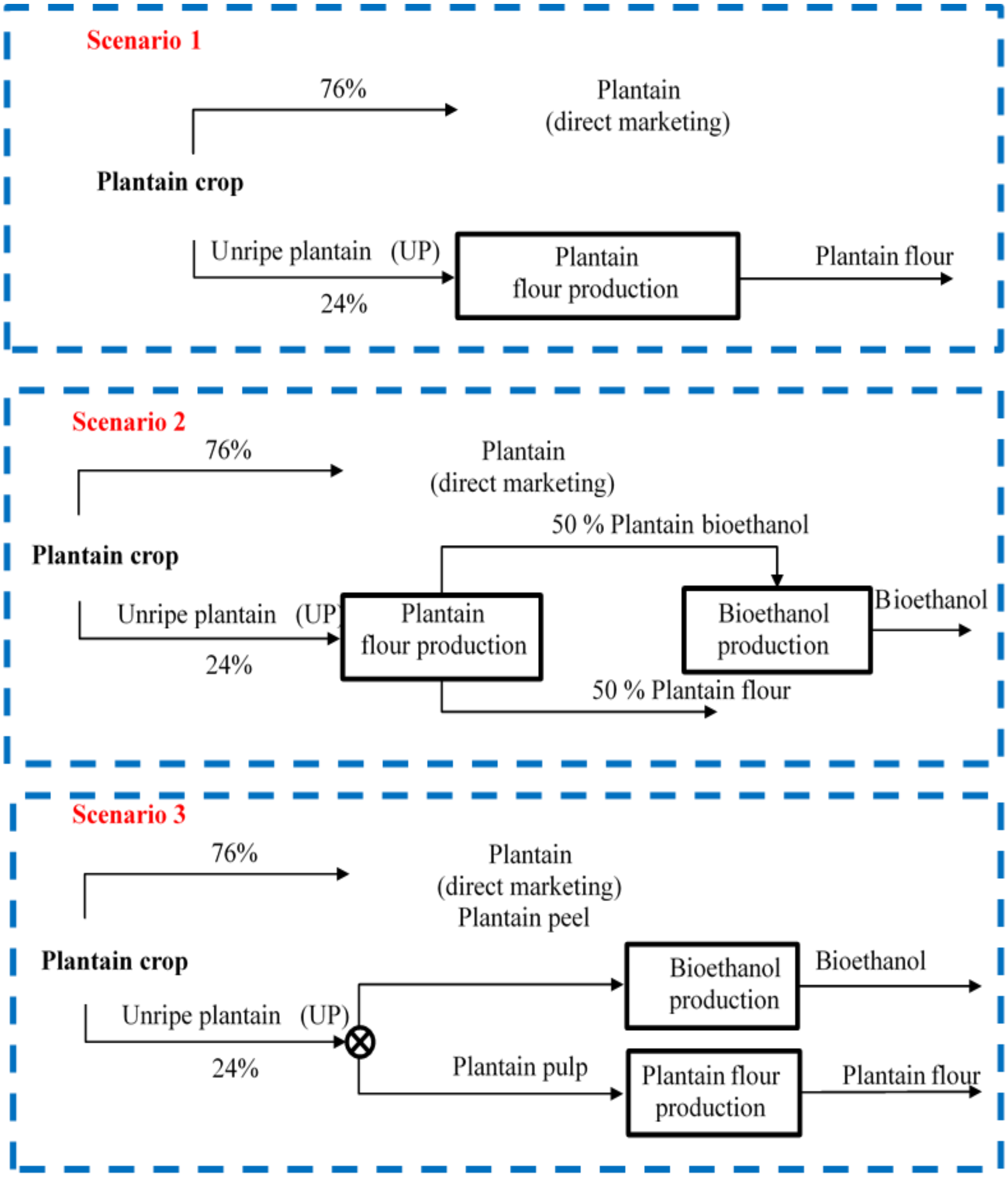

Figure 1. The scenarios considered in the E-LCA. Source: own elaboration.

2.2 Sensitivity analysis

The sensitivity analysis was performed by varying the allocation type (mass and economic). In the mass allocation, the flow of all products across all scenarios was taken into account. On the other hand, the estimated sale prices of the products were used in the economic allocation: 0.152 USD kg-1 for plantain, 3.09 USD kg-1 for flour, and 1.13 USD kg-1 for ethanol [8].

2.3 System boundaries

Figure 2 shows the system boundaries for the E-LCA of the plantain production chain, considering the valorization of UP. The plantain crop is based on 1 ha, with a density of 2000 plants and a 10-month cycle. Plantain production encompasses all activities from corm multiplication to harvest and bunch packaging. System 1 comprises four subsystems: (i) germination and the nursery stage; (ii) land preparation and planting; (iii) cultural work on the plantation; and (iv) harvesting.

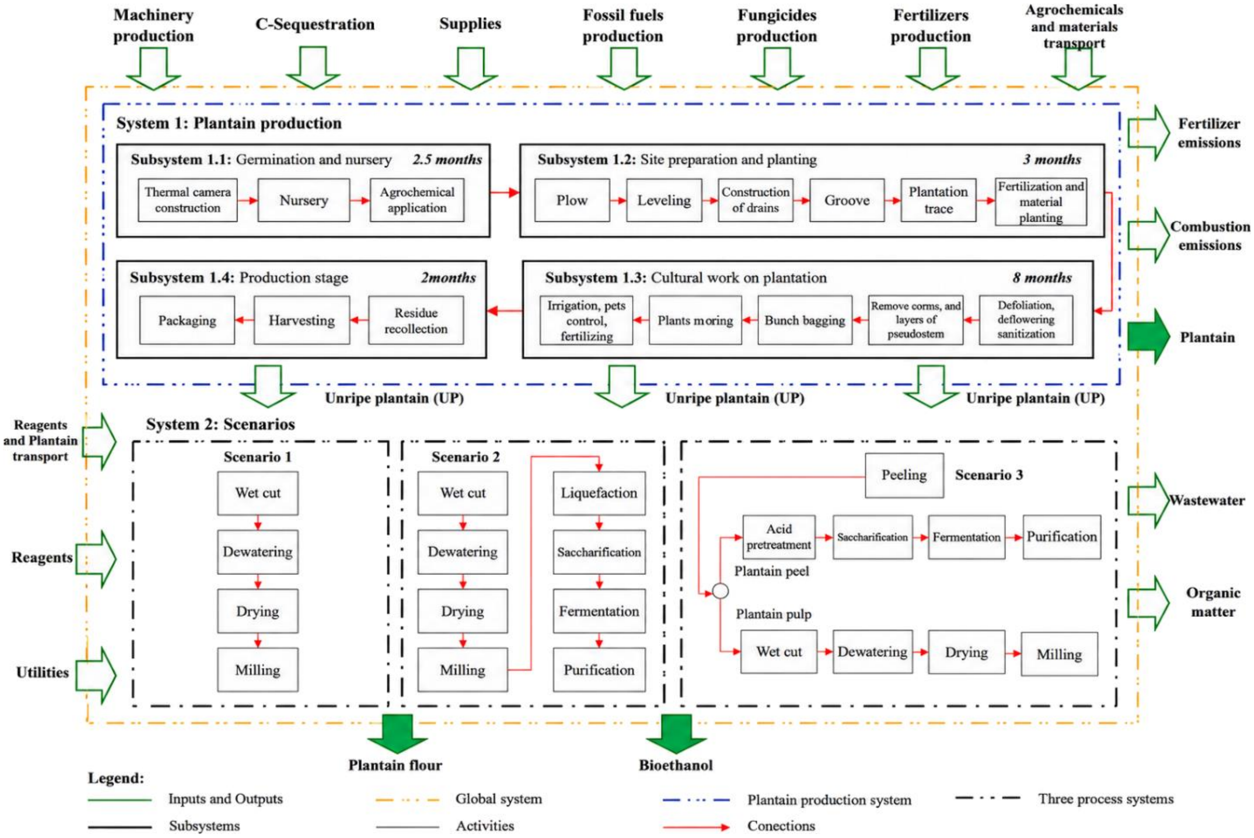

Figure 2. The system boundaries for the E-LCA of the plantain production chain, considering UP valorization. Source: own elaboration.

(i) The subsystem involves three key steps: constructing a thermal chamber and storage room and applying agrochemicals. In the chamber, healthy corms (1–1.5 kg) are selected, cleaned of roots, and disinfected using a solution of sodium hypochlorite (1%), cypermethrin (2.2 g per corm), and thiabendazole (0.125 cm^3 per corm). The corms are then placed in 25–30 cm of rice husk, spaced 10 × 20 cm apart, and exposed to a temperature of 50–70 °C and humidity of 30–100% [21]. After 18 days, each corm yields 20–30 pest-free suckers. Those with two to four leaves are separated using sanitized tools (2.5% hypochlorite solution) and planted in 17 × 23 cm polystyrene bags containing a soil-organic matter-rice husk mix in a 3:1:1 ratio. By weeks 6–10, the suckers are ready for field planting. This method produces 3–4 times as many suckers as other in vivo techniques [22].

ii) The land preparation and planting subsystem has seven activities: plowing, leveling, drainage construction, furrowing, plantation layout, fertilization, and planting. The plantain cycle in the central-western region of Mexico requires 355 days of spray irrigation. In Colima, irrigation is necessary during dry months and late production stages. Plowing is carried out to a depth of 30-60 cm, with a minimum depth of 30 cm. The depth of plowing is proportional to the consumption of diesel. Approximately 10 days after passing the plow, two transverse passes of a sea mi-heavy harrow are made to reduce the particle size of the soil. When the soil contains more than 60% clay, it is necessary to incorporate organic matter to improve soil structure, aeration, and nutrient exchange [22]. If irrigation is caused by flooding, the soil should be leveled to prevent ponding and promote uniform plant growth. Therefore, it is necessary to establish an effective drainage system.

Working at hand requires a backhoe. The accumulated soil from the drainage construction can be used for leveling [23]. In this subsystem, fertilization is necessary for proper growth and development of fruits and other plant tissues, as well as for the availability of nutrients such as nitrogen (N) and potassium (K). Although a certain amount of these macronutrients is recycled into the pseudostem and leaves left in the plantation, a large amount is extracted from the harvested fruit and must be replaced. However, excessive fertilizer application can lead to soil acidification [24]. Therefore, a fertilization program should be carried out during the 355-day cycle, incorporating phosphonitrate (200 kg ha^{-1} every four months), DAP (diammonium phosphate, containing 18% nitrogen, 46% phosphorus, and 0% potassium) (180 kg ha^{-1}), potassium sulfate (100 kg ha^{-1}), and compost + humus (3 600 kg ha^{-1}) [19].

iii) The cultural work subsystem on the plantation includes irrigation, pest control, fertilization, plant mooring, bunch bagging, corm removal, deflowering, shoring, and leaf removal. Weed infestation is one of the most serious problems on the plantation and requires significant labor and capital investment. However, as most activities are manual, the environmental impact is reduced. When considering environmental impact, the use of fertilizers and materials such as bags and raffia is commonly discussed. Manual control (traditional) is one alternative for weed control and consists of hoeing around the plant. The disadvantage of this method is that weeds quickly recover during the rainy season, increasing labor costs [25]. The application of herbicides offers the advantages of greater effectiveness and lower price, but it is a soil-polluting method [26]. Another more sustainable method is the use of legume crops, which suppress weeds and enrich the soil [27]. However, the usual method in Colima is the use of herbicides (mainly glyphosate) during the rainy season, with manual methods in the dry season [28]. Other cultural practices that have the potential to impact the environment and generate solid waste include pest control by removing corms, the outer layer of the corms, flowers, and leaves (which is fundamental to reducing the inoculum of black Sigatoka), mooring plants to prevent them from falling over, and bunch bagging [29].

iv) The production stage subsystem includes waste collection, harvesting, and packaging. Around 80% of plantations are harvested by creating an open space (*patio*) within the plantation. In this system, the transport vehicle (truck) is moved to the plantation and loaded on site. This manual work involves a cutter, a packer, a stevedore, and two packers and helpers to remove the rachis. Additionally, a vehicle transports water, and a washing tank is used to disinfect the bunch crown by adding iodine. Finally, the fruit is removed from the plantation by conveyors [30]. This manipulation results in 24%-30% of the fruit being wasted. These wasted plantains will be used in this project to produce flour and ethanol.

System 2 comprises the UP valorization and is divided into three scenarios (Figures 1 and 2). In scenario 1, unit operations are wet cutting, dewatering, drying, and milling. After the plantain chips cutter machine was used, the UP slices were dewatered and dried at 45°C in an electric forced-air oven. The dried slices were crushed in an industrial hammer mill to produce the flour. Scenario 2 comprises the production of bioethanol and flour using UP. In this scenario, 50% of the UP flour was used to produce bioethanol. The most used method in the industry for producing ethanol from raw materials with high starch content is dry grinding [31]. This study outlines the process of producing bioethanol, which involves liquefaction, saccharification, fermentation, and purification by distillation and dehydration. Bioethanol was produced using starch and cellulose present in plantain flour. Sugar release during liquefaction and saccharification was achieved using a combination of amylase, glucoamylase, cellulase, and pectinase, as described by [7], with fermentation improvements as described by [7]. At the end of fermentation, the resulting wort, containing water, ethanol, and non-fermentable components, was processed in distillation columns. The bioethanol production process was simulated using two distillation towers and a molecular sieve system [8]. The distillation columns were simulated using MESH equations, which utilize material, energy, and balance ratios. The initial concentration is 50% v/v in the first tower, with a subsequent distillation stage that reaches the azeotropic limit. Anhydrous ethanol is then obtained by dehydrating the rectified product with molecular sieves [8].

Scenario 3 involves producing flour and bioethanol separately from the pulp and peel (pulp flour and peel bioethanol). The bioethanol production process consists of acid pretreatment, saccharification, fermentation, and purification (distillation and dehydration). The bioethanol production process was simulated using only the cellulose content in the peel.

2.4 Environmental life cycle inventory

The inventory data for the plantain production, including all stages, is presented in Supplementary Material 1. The diesel emissions from tractor use are determined by the combustion factors reported in [32]. The application of diammonium phosphate as fertilizer considers emissions to air and water. Air emissions are determined by the amount of NH_3, N_2O, and NO_x released into the atmosphere. Emissions to water are calculated as the deposition of PO_4^{3-} and NO^{3-}. Phosphate emissions to water sources are quantified with emission factors reported by [33]. Nitrogen emissions to the air are quantified using the emission factor proposed by [34]. The use of pesticides results in the emission of heavy metals, including cadmium, copper, zinc, lead, nickel, and chromium. [35] and [36] reported information on mg ha^{-1} y^{-1} for each component. [37] reported the calculation procedure for these emissions, considering the distance between agrochemical production plants and crop locations. An estimated distance of 13 km was used for materials such as wood, soil, plastic bags, compost, etc. It is assumed that the plant will be located in Armería, given its proximity to Manzanillo and Tecomán. It is also close to compost and manure production facilities in Coalatilla. Plantain cultivation is prevalent in the rural areas of Armería. In this sense, the average distance between crop locations and process scenarios is 10 km. Reagents (e.g., enzymes and sulphuric acid) for the production plants are procured in Mexico City, approximately 700 km away. All distances were determined using Google Maps®. Two trips were necessary to transport all materials. A EURO 3 truck with a capacity of 7.5–16 metric tons was chosen for this purpose.

The mass and energy balances used to calculate the scenarios were derived from the process design in Aspen Plus® v8.0. Properties and kinetic expressions were taken from [8]. The process requirements for utilities were evaluated using the Aspen Energy Analyzer® software. Emissions resulting from bioprocesses using plantain waste were calculated using rejected plantain as a raw material, as well as considering wastewater, cooling water, steam, and reagents, among others. Figure 3 shows the mass and energy balances for the scenarios involved in producing flour and bioethanol.

2.5 Environmental life cycle evaluation

E-LCA was conducted using SimaPro 9.6.0.1 PhD© [38] (license registration name ITC 002), applying the ReCiPe Midpoint (hierarchic v1.13) method with data from the Ecoinvent v3.3 database [39]. The Monte Carlo method was used in SimaPro to model the uncertainty of the input data. This was achieved by assigning probability distributions to the uncertain parameters and by running simulations to analyze the variability and sensitivity of the results, thereby improving the quality and robustness of the environmental analysis.

3. RESULTS AND DISCUSSION

Table 1 shows the yields (kg kg^{-1} of feedstock) of various products reported in the literature for biorefinery schemes. [40] analyzed a biorefinery to produce bioethanol, fertilizer, and electricity from bread waste. The authors reported a bioethanol yield of 0.242 kg kg^{-1} of raw material. In comparison, scenario 3 yields 0.055 kg kg^{-1} of feedstock, significantly lower than that reported by [40]. This may be due to the level of technology and the type of organic waste managed. Scenario 3 uses UP peels, a raw material that requires pretreatment before fermentation to break down its cellulosic structures, due to its high content of cellulose, hemicellulose, pectin, and starch [41]. On the other hand, bread waste is characterized by its starch composition. This polysaccharide is relatively easy to convert into fermentable sugars, which are then transformed into bioethanol by yeast [42]. The generation of byproducts also affects bioethanol yield. In this study, UP pulp was used to produce flour.

Table 1. Bioethanol and co-product yields in biorefineries are reported in the literature.
Source: own elaboration.

Feedstock	Yields (kg kg-1 of feedstock)					Reference
	Bioethanol	Flour	Fertilizer	Electricity*	Xylooligo-saccharides	
Bread waste	0.242		0.050	0.045		[40]
Potatoes	0.167					[43]
Sugarcane	0.167					[43]
Citrus waste	0.124					[44]
Barley Straw and brewer's spent grain	0.123				0.094	[45]
Rice straw	0.078					[43]
Unripe plantain	0.055	0.145				This study (scenario3)
Cattle manure	0.036					[43]
Unripe plantain	0.025	0.125				This study (scenario 2)

*kWh kg^{-1} of feedstock

The selected impact categories are climate change (CC—kg CO_2 eq), fossil depletion (FD—kg oil eq), human toxicity (HT—kg 1.4-DCB eq), ionizing radiation (IR— Bq U_{235} eq), metal depletion (MD—kg Fe eq), urban land occupation (ULO—m^2 y^{-1}), agricultural land occupation (ALO—m^2 y^{-1}), photochemical oxidant formation (POF—kg NMVOC eq), terrestrial acidification (TA—kg SO_2 eq), marine ecotoxicity (ME—kg N eq) and water depletion (WD—m^3).

The environmental impact categories were classified by relevance, and the most relevant factors are shown in Figure 4 and Table 2. The most affected impact categories in the cultivation stage are CC, FD, HT, and IR. During cultivation, transportation is the activity that most affects CC, FD, HT, and IR (53%, 56%, 69%, and 58%, respectively). Followed by plantation equipment that affects CC, FD, and IR (29%, 30%, and 30%, respectively); fertilizer, herbicide, and insecticide activities affect HT in third place (22%).

The cultivation stage has the greatest impact on the productive chain proposed in this study. The hotspots with the greatest contribution to climate change at this stage are the transportation of 0.86 kg CO_2-eq kg^{-1} of plantain produced for direct marketing, accounting for 53% of CC. This is followed by plantation equipment (29%) and fertilizers, herbicides, and insecticides (9%). Plantation equipment (tractors, excavators, and skid-steer loaders) can have environmental impacts. Benzothiazole is used as an inducer of plant immune systems. Additionally, phosphate fertilizer (DAP) and polyethylene, used in plastic bags covering bunches, have significant pollution potential.

The results for the three proposed agro-industrial transformation scenarios are presented in Figure 5. In this figure, only the categories that offered the most significant impact in all scenarios (CC, FD, HT, and ALO) are shown. Scenario 1 (milling for flour production) involves the least complex use of machinery, equipment, and inputs, resulting in lower environmental impact in terms of both mass and economic allocation. Conversely, scenario 2, in which banana flour and ethanol are produced, shows the most significant environmental impact. Scenario 3 exhibits an intermediate impact compared to scenarios 1 and 2. The sensitivity analysis with allocation variations yielded different results. For example, CC in Scenario 2 has the greatest impact, generating 18.73 kg CO_2 eq for economic allocation, compared to 11.56 kg CO_2 eq for mass allocation. This ratio is consistent across most of the four major impact categories, except for ALO. In this category, ALO are matched in scenario 1 in 0.03 m^2 y^{-1}.

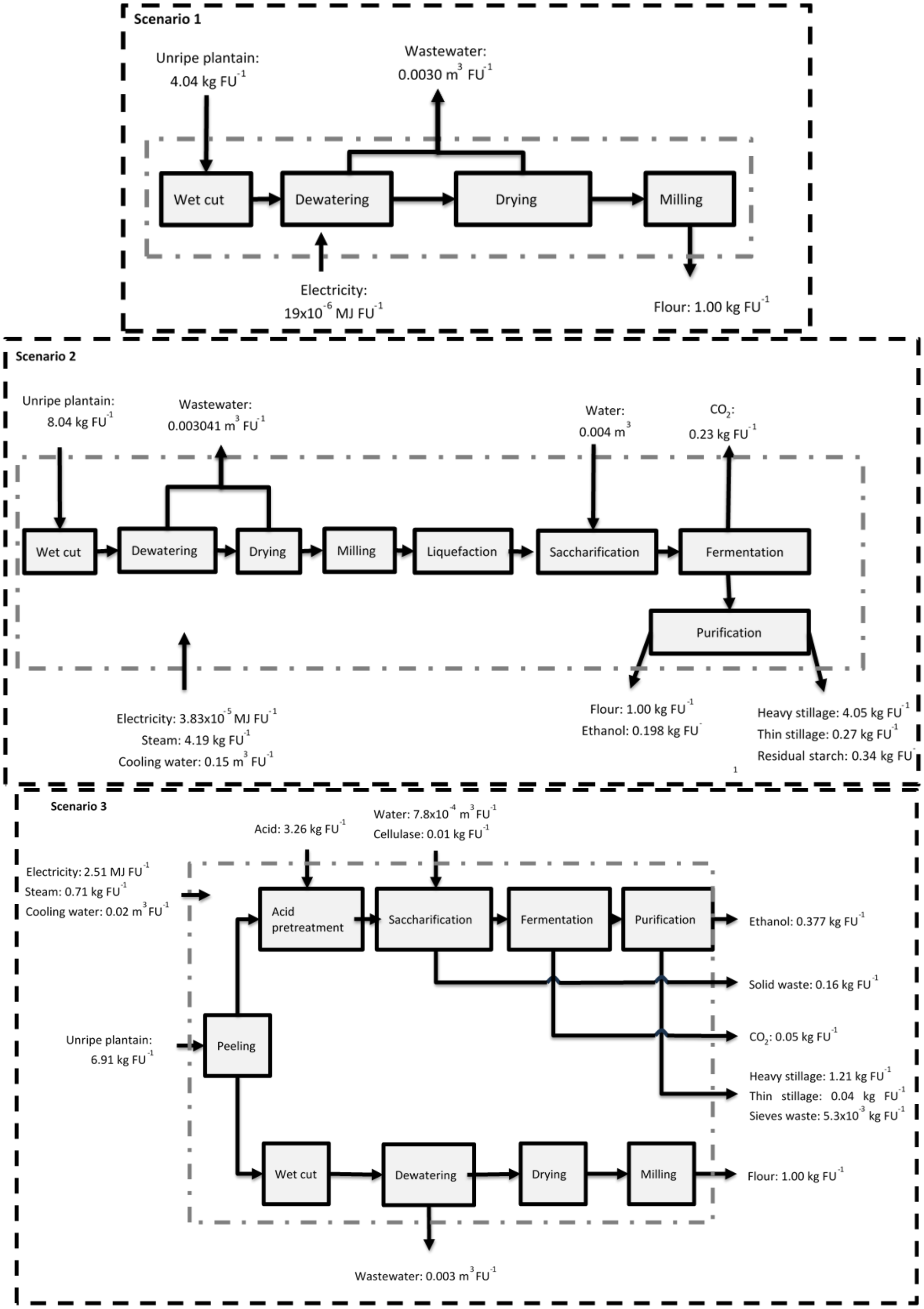

Figure 3. Mass and energy balance for scenarios 1, 2, and 3. Source: own elaboration.

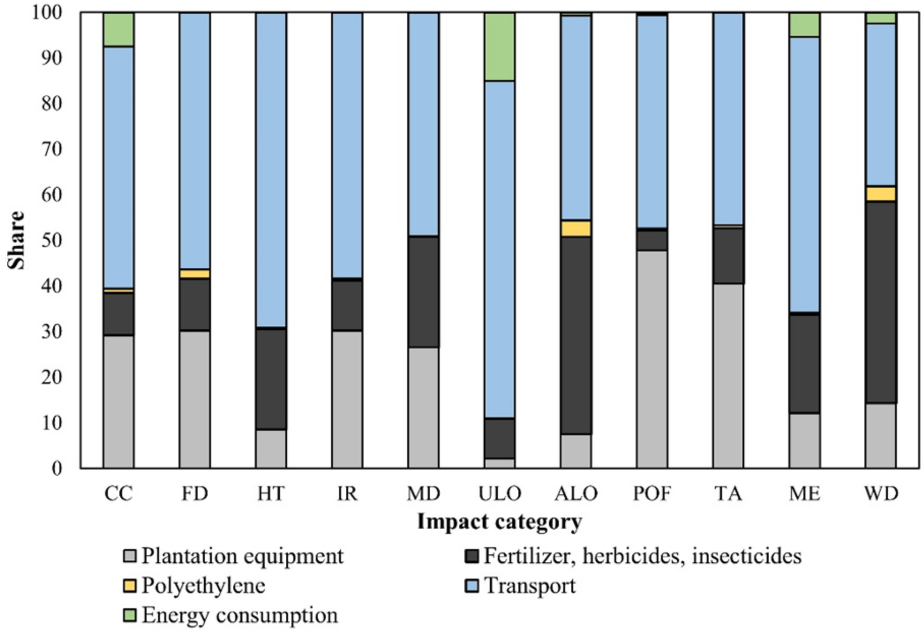

Figure 4. Distribution of environmental impacts by plantain cultivation stage. Climate change (CC), Fossil depletion (FD), Human toxicity (HT), Ionizing radiation (IR), Metal depletion (MD), Urban land occupation (ULO), Agricultural land occupation (ALO), Photochemical oxidant formation (POF), Terrestrial acidification (TA), Marine ecotoxicity (ME), Water depletion (WD). Source: own elaboration.

Table 2. Results on the environmental impact of the plantain cultivation stage. Source: own elaboration.

Impact categories	Unit	Plantation equipment	Fertilizer, herbicides, insecticides	Polyethylene	Transport	Energy consumption	Total
CC	kg CO_2 eq	4.76×10^{-1}	1.51×10^{-1}	1.58×10^{-2}	8.65×10^{-1}	1.22×10^{-1}	1.630
FD	kg oil eq	1.65×10^{-1}	6.25×10^{-2}	1.10×10^{-2}	3.08×10^{-1}	5.06×10^{-9}	0.547
HT	kg 1.4-DCB eq	2.93×10^{-2}	7.54×10^{-2}	1.06×10^{-3}	2.37×10^{-1}	3.36×10^{-4}	0.343
IR	kg Bq U_{235} eq	3.26×10^{-2}	1.17×10^{-2}	5.52×10^{-4}	6.29×10^{-2}	1.86×10^{-6}	0.108
MD	kg Fe eq	1.85×10^{-2}	1.69×10^{-2}	9.98×10^{-5}	3.42×10^{-2}	4.55×10^{-6}	0.070
ULO	$m^2 y^{-1}$	1.10×10^{-3}	4.46×10^{-3}	4.62×10^{-5}	3.76×10^{-2}	7.66×10^{-3}	0.051
ALO	$m^2 y^{-1}$	1.86×10^{-3}	1.07×10^{-2}	8.89×10^{-4}	1.11×10^{-2}	1.75×10^{-4}	0.025
POF	kg NMVOC	6.53×10^{-3}	5.86×10^{-4}	6.49×10^{-5}	6.38×10^{-3}	8.41×10^{-5}	0.014
TA	kg SO eq	3.83×10^{-3}	1.15×10^{-3}	5.49×10^{-5}	4.41×10^{-3}	5.68×10^{-6}	0.009
ME	kg N eq	9.51×10^{-4}	1.68×10^{-3}	3.81×10^{-5}	4.73×10^{-3}	4.24×10^{-4}	0.008
WD	m^3	9.81×10^{-4}	3.02×10^{-3}	2.30×10^{-4}	2.44×10^{-3}	1.68×10^{-4}	0.007

Climate change (CC), Fossil depletion (FD), Human toxicity (HT), Ionizing radiation (IR), Metal depletion (MD), Urban land occupation (ULO), Agricultural land occupation (ALO), Photochemical oxidant formation (POF), Terrestrial acidification (TA), Marine ecotoxicity (ME), Water depletion (WD)

Research consistently identifies agricultural production as the most impactful stage in the plantain life cycle [18], [46]. At this stage of cultivation, transportation is the primary contributor to environmental impact. All materials, supplies, and products were transported by trucks with a capacity ranging from 7.5 to 16 metric tons. These trucks have EURO 3 engines. It is also important to note that GHG emissions data vary by country, as each has different fuel qualities. In Mexico, for example, there is no mixture of biofuels and fossil fuels [47], which would improve the carbon balance and therefore reduce the high contribution of transport to GHG emissions.

The second factor with the greatest impact on the environment during cultivation is the use of machinery. In this region of Mexico, soil mechanization is commonplace, and the land in question was not constructed with irrigation drains. A backhoe loader is required for the construction of the drains, and a semi-heavy harrow maquila is used to mechanize site preparation. Therefore, it is reasonable to conclude that the use of machinery for cultivation has a significant environmental impact, given that this analysis considers the construction of this machinery and all the industrial processes involved.

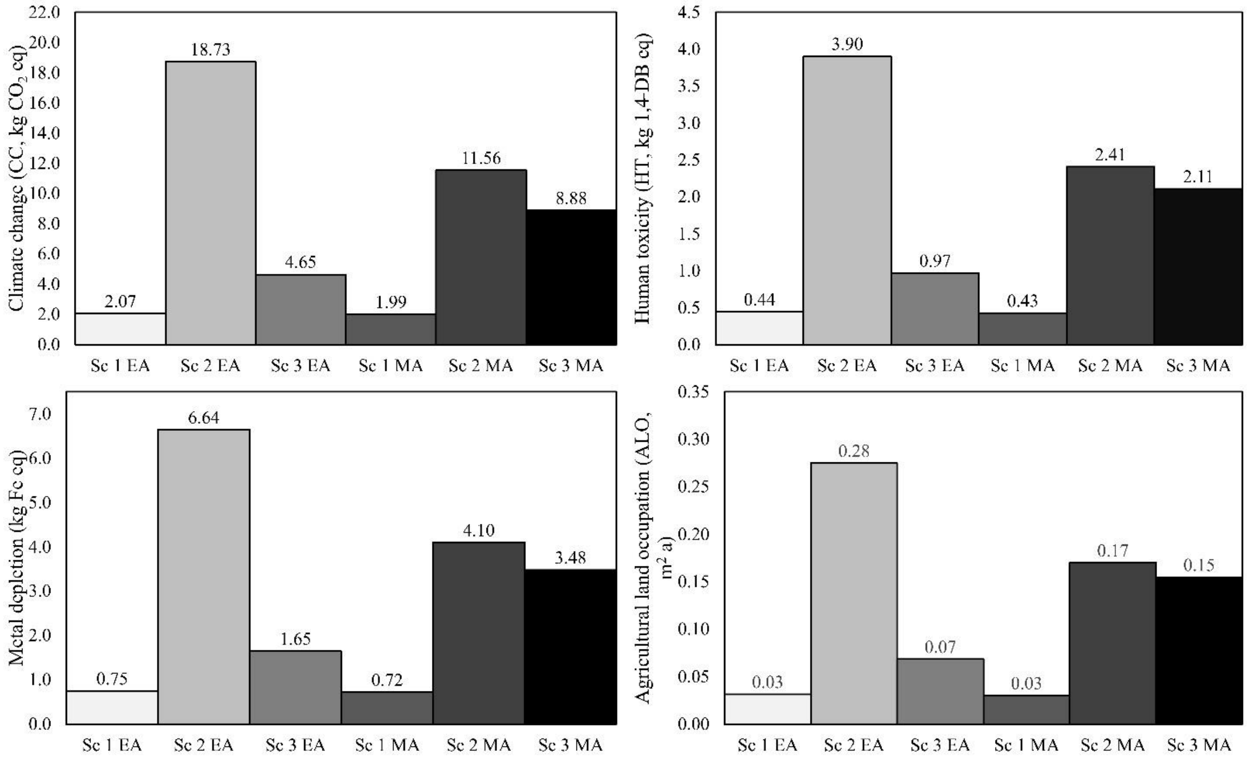

Figure 5. Analysis of the E-LCA of three scenarios considering economic allocation (EA) and mass allocation (MA). Source: own elaboration.

The third factor most affecting the environment during cultivation is the use of fertilizers, herbicides, and insecticides. It is important to note that Black Sigatoka is caused by the fungus *Mycosphaerella fijiensis* [45], and the persistent losses from this disease in banana crops lead farmers to adopt extreme measures to control it. In this study, Aminopyridine (a fungicide) has the greatest environmental impact because fungicide production, in addition to consuming large amounts of natural resources, also consumes substantial energy [48]. The active ingredient in the fungicide Aminopyridine, Carbendazim, is used to prevent fungal infections by damaging fungal cell membranes. Still, it also causes damage to non-target organisms. Carbendazim is among the most frequently detected fungicides in sweet and saline surface waters worldwide [49]. This justifies the impact of Aminopyridine. Besides, in Colima, there are many coastal and continental lagoons. The body of water closest to Armería is the lagoon of Cuyutlán, and more than 60% of the agrochemicals used on crops are discharged into the coastal lagoons, which become sinks for pesticides and herbicides that cause ME and modify the natural productivity of coastal ecosystems [50]. This affects various productive sectors, particularly the fishing sector. Once fungicides reach bodies of water, they can affect the entire ecological food chain. This includes other animals, such as humans, that feed on contaminated aquatic animals.

Benzothiazole is a plant defense inducer that mimics the function of salicylic acid, a plant's immune hormone. It is therefore widely used to protect crops against disease by inducing plant defense responses. However, benzothiazole also has a high environmental impact.

Please note that the Colima method uses a pump to spray water, which can create puddles that promote pathogen growth. Drip irrigation is therefore recommended. This reduces the need for irrigation water and avoids the formation of inoculum sources for black Sigatoka. It is also advisable to use innovative methods, such as conditional pesticide application based on spore detection (i.e., fungicide application contingent on pest pressure), as recommended by [51]. To avoid inoculum sources of the disease, it is also recommended that manual stripping be increased and that leaves and knobs be removed from the crop. This could reduce the need for fungicides.

As shown in Table 3, producing 1 ton of plantain in Mexico has a high CO_2 equivalent contribution, greater than that of any other raw material compared. This can be attributed to the long distances traveled by the chosen transport system in moving inputs and supplies from Mexico City, which is 700 km from the crop. Similarly, the contribution of heavy machinery must be considered, given that the assessed farms are highly mechanized.

Table 3. CO_2 eq emissions per ton of crops in Latin America. Source: own elaboration. Source: own elaboration.

Feedstock	kg CO_2 eq t^{-1} of crop	Type of crop	Country	Reference
Plantain crop	1 630	Plantain	Mexico	This study
Orange production	128	Orange	Mexico	[52]
Sugar	719	Sugar	Mexico	[53]
Plantain losses and waste	1 370	Plantain	Mexico	[54]
Avocado losses and waste	1 300	Avocado	Mexico	[54]
Orange peel waste	1 420	Orange	Colombia	[55]
Creole avocado	593	Avocado	Colombia	[56]

In scenario 1, the most significant residual flux is water vapor, produced by the dehydration of flour. Therefore, the highest degree of pollution is attributable to electricity consumption and the Mexican energy matrix, which derives over 80% of its energy from hydrocarbons [57]. This result was expected because this is the least technologically complex scenario. In other words, there are no advanced technological processes that generate waste or outlet currents other than the steam generated by the drying process. According to the EDGAR database, in 2019, Mexico ranked as the top polluter in Latin America and 13th globally, with its energy production heavily reliant on fossil fuels, primarily natural gas, followed by diesel, oil, coal, and coke [58].

Furthermore, the scenarios presented in this work can handle 5.5 t h^{-1} of unripe plantain, with the sanitary landfill serving as the final disposal site. The Mexican Biogas Model [59] was used to estimate the environmental impact of managing these residues in a sanitary landfill, yielding 9 878 t CO2-eq y^{-1}. Converting these residues into flour and bioethanol instead of disposing of them would considerably reduce greenhouse gas emissions, extend the useful life of sanitary landfills, and reduce the need for new sites.

The proposed scenarios for flour and bioethanol production present considerable environmental impacts due to the incorporation of complex technological processes in the plantain marketing chain. The cradle-to-gate E-LCA implemented for this study did not consider the possibility of using rejected plantain-based bioethanol in place of commercial sugarcane-based ethanol in scenarios 2 and 3, which could have a positive environmental impact. Using bioethanol in combination with conventional fuel for vehicles could reduce the environmental impact of the evaluated scenarios. Further studies are needed to determine the environmental viability of plantain-based bioethanol. However, the results of this study and the inventories generated during the agricultural and technological phases will provide insight into this type of process.

4. CONCLUSIONS

This study evaluated the environmental viability of biorefinery schemes for producing flour and bioethanol by managing unripe plantain (UP) within the Mexican marketing chain. Mathematical models were applied alongside a cradle-to-gate life cycle assessment methodology, considering three technological scenarios: exclusive flour production (scenario 1), joint flour and bioethanol production (scenario 2), and bioethanol production from UP peel combined with flour produced from pulp (scenario 3). Scenario 2 achieved a bioethanol yield of 0.055 kg kg^{-1} of feedstock, while scenario 3 registered significantly lower values (0.025 kg kg^{-1} of feedstock), attributable to the absence of UP pulp in the bioethanol production process. The environmental impact analysis identified that, during the agricultural phase, the most relevant categories were climate change, fossil fuel depletion, human toxicity, and ionizing radiation. At this stage, transportation was the primary source of environmental impact, followed by planting activities, agricultural machinery use, and the application of fertilizers, herbicides, and insecticides.

The climate change potential was estimated at 1 630 kg of CO_2 eq per ton of plantain cultivated, primarily due to long transport distances and high mechanization in agricultural areas. Scenarios that integrate the simultaneous production of flour and bioethanol impose greater environmental burdens, as they involve incorporating more complex technological processes into the production system.

This work defines robust environmental and technological criteria to support decision-making to mitigate environmental impacts in the plantain supply chain. Its results offer tools to promote sustainable development and innovation in the agricultural and bioenergy sectors, particularly in the Mexican context. Likewise, agribusinesses can use these findings to increase flour and bioethanol production while reducing their environmental footprint by adopting efficient, low-impact technologies.

Among the main limitations of the study is the use of generic inventories, such as ECOINVENT, which may increase the uncertainty of the results. Future research could focus on developing specific regional inventories, incorporating additional impact categories, such as eutrophication, and expanding the system's boundaries to evaluate the substitution of conventional sugarcane-derived ethanol with bioethanol obtained from UP. These strategies could further reduce the environmental burdens of the scenarios being assessed.

Finally, technological advancement in this area could be strengthened by designing integrated biorefineries that generate a diverse range of bioproducts from UP, with an emphasis on improving energy efficiency, incorporating renewable energy sources, and integrating the banana production chain with other value chains.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORSHIP CONTRIBUTION

Leonardo Alexis Alonso-Gomez: Conceptualization, Scenario design, Calculations and Analysis of results, Fund management, Research development, Drafting, and Final revision of the manuscript.

Alejandro Estrada-Baltazar: Drafting and Final revision of the manuscript.

Luis Ramiro Miramontes-Martínez: Calculations and Analysis of results, Drafting and final revision of the manuscript.