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Alternatives for the Valorization of Avocado Waste Generated in the Different Links of the Value Chain Based on a Life-Cycle Analysis Approach

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Abstract: This work evaluates the sustainability of small-scale biorefineries as a potential enterprise alternative to be introduced in rural areas based on experimental and simulation data. Four scenarios were evaluated: the first scenario involves the production of guacamole, the second involves the production of animal feed, and the third and fourth scenarios involve the extraction of bioactive compounds and the production of avocado oil or animal feed, respectively. In addition, all scenarios produce biogas and fertilizer. Each of the scenarios were evaluated considering the technical, economic, environmental, and social aspects. As a main result, the first scenario showed the lowest operating and investment costs, as well as the lowest economic profitability (profit margin 35%). On the other hand, the third and fourth scenarios present the highest investment and operating expenses (OpEx USD 6.2 million per year and CapEx USD 1.0 million), but their profit margins are in the 60–70% range. Furthermore, a life-cycle assessment (LCA) was carried out and allows inferring that the transformer link presents the highest environmental impact of the entire value chain and that the carbon footprint for all scenarios ranges between 1.01–2.41 kg CO_2 eq per kg avocado. Similarly, the social impact methodology shows that the proposed scenarios do not present any social risk. Thus, the biorefinery for animal feed, bioactive compounds, biogas, and fertilizer was selected as the best option to be implemented in Caldas.

Keywords: creole avocado; biorefineries; life-cycle assessment; bioeconomy; sustainability

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1. Introduction

In recent years, due to the large increase in the demand for industrial products obtained from nonrenewable resources, different economic, environmental, and social problems have arisen [1]. In addition, the international economic model is based on noncyclical schemes. These schemes are characterized by the extraction and subsequent use of natural resources, with no opportunity for a second use. As a result, natural resources are extracted, transformed into high-value-added products, distributed, consumed, and, finally, disposed of without possible valorization [2]. This single-use model generates large amounts of waste and pollutants, harming human health due to soil and water contamination, and affecting the wellbeing of communities [3,4]. Therefore, alternative waste disposal is essential. These changes suggest implementing policies guided by sustainability and represented by circular economy models in the production processes [5]. These policies should include a model based on two perspectives: (i) production processes should promote the use of waste generated during the transformation of biomass into high-value-added products and, (ii) biomass conversion mechanisms should be improved to reduce the amount of waste generated [6,7].

The creole avocado (*Persea americana* Mill.) is considered by different authors as a nutritious fruit with a high content of unsaturated fatty acids, minerals, protein, vitamins, and fiber, as described by Rodríguez-Carpena et al. [8]. It is a fruit native to Mexico and Central America, although it is currently cultivated in almost all tropical and subtropical regions. Colombia has been ranked as one of Latin America's most important avocado producers. This country produced about 61,853.6 t of creole avocado in 2021, according to MinAgriculture, 2021 [9]. The creole avocado value chain in Colombia is mainly made up of four links: (i) the agricultural stage (cultivation, harvest, and postharvest); (ii) transport; (iii) primary processing (guacamole production), and (iv) distribution (sale as fresh fruit at a national scale or export). Throughout this value chain, different residues are generated, including rejected avocado and the peel and seed fractions [10]. During the agricultural stage and transport, 49% of the avocado is considered rejected because of the ripening time and diseases that affect plantations, such as the red spider mite, the small stone borer (*Conotrachelus perseae*), or the branch borer (*Copturus aguacatae*) [11]. Meanwhile, during the primary processing at the industrial scale, residues are generated, consisting mainly of the peel and the seed, which can comprise between 30% and 35% of the weight of the fruit (13% and 17%, respectively) [12]. Thus, the use of peels and seeds should be improved to ensure the sustainability of the avocado value chain. Numerous studies have confirmed the high potential of these fractions to produce value-added products such as avocado oil and antioxidant compounds [13] and energy carriers such as biogas [14].

Bioactive compounds are highly important in the industrial sector, mainly in the pharmaceutical and food industries. In recent years, the search for new natural antioxidant compounds derived from waste biomass has taken relevance in different research areas [15]. Extracts derived from creole avocado have demonstrated numerous biological activities, such as antimicrobial, antioxidant, anti-inflammatory, or anticancer properties [16]. On the other hand, oil derived from avocado pulp is another product of commercial interest due to its similar properties to olive oil. Some reports suggest that avocado oil presents similar properties to olive oil [17]. In Colombia, the market for avocado oil reached USD 484.6 million in 2020 [18]. However, avocado-oil production is limited in Colombia as most avocados are marketed directly or carried to guacamole production. Similarly, biogas production has been analyzed in biorefinery design since it allows for the use of biomass integrally by producing energy vectors [19]. In this sense, the use and valorization of these residues should be integrated into the avocado value chain, emphasizing the biorefinery concept to improve sustainability and promote the bioeconomic development of the region. In this way, using biomass in biorefinery schemes contributes to establishing a circular bioeconomy and meeting several of the sustainable development goals (SDGs) proposed by the 2030 agenda [20]. This work aims to analyze the sustainability of creole avocado-based biorefineries considering the value-chain approaches. This evaluation includes valorizing residual fractions to promote compliance with the sustainable development goals (SDGs), specifically those related to responsible production and consumption in Caldas (Colombia).

2. Methodology

2.1. Experimental Methodology

2.1.1. Raw Material Characterization

The characterization of the residual avocado fractions was based on the methodology reported by Poveda-Giraldo et al. [21]. First, a convective dryer using forced air was used to dry the residual fractions of the creole avocado (seed and peel). Then, a rotary knife mill (SR200 Gusseisen, Redsch GmbH, Munich, Germany) was used to reduce the particle size to a homogeneous size of 0.420 mm. The composition of creole avocado seeds and peels was estimated for starch, extractives, fat, cellulose, hemicellulose, lignin, and ash. Starch was quantified by an indirect volumetric method using barium hydroxide. The extractives were determined after Soxhlet recirculation with water and ethanol [22]. The liquors obtained from the extractives procedure were analyzed in terms of reducing sugar content using the 3,5 dinitrosalicylic acid (DNS) method. Fats were measured by applying n-hexane under reflux in a Soxhlet for 10 h [23]. Holocellulose was determined by the acetic acid chlorination method and cellulose after NaOH dosages [24]. Insoluble lignin was determined as Klason lignin [25] and ash after slow heating until 575 °C [26].

On the other hand, a proximal analysis was performed to estimate volatile matter (VM), fixed carbon content (FC), total solids (TS), and volatile solids (VS). Initially, the volatile matter was determined following the ASTM E872-82 (2013) standard method [27]. For this purpose, 0.5 g of sample (previously dried, including moisture recording) were volatilized in a DAIHAN brand 1200 °C programmable digital muffle furnace (FHPX). Total and volatile solids were then estimated using the ASTM E1756-08 standard method [28]. In determining total solids, 2.0 g of the sample were taken and introduced to the programmable digital muffle furnace at 105 °C for 6 h. Then, to determine volatile solids, the solid resulting from the above process was subjected to 550 °C for 2 h. Finally, the fixed carbon content was determined by the difference.

2.1.2. Avocado-Oil Extraction and Production of Animal Feed

The pulp of the creole avocado was subjected to a dehydration process at 60 °C for 24 h. Then, a 50 g sample was placed in a Soxhlet thimble with 250 mL of ethyl ether at a constant temperature for 6 h, following the process described by Solarte-Toro et al. [10]. The extraction yield was assessed as the ratio between the oil extracted on a dry basis and the initial amount of avocado pulp. Gas chromatography and mass spectrometry (GC/MS) were used to characterize the avocado oil. For chemical analysis, an Agilent 6890N GC with an Agilent 5973N mass detector was used. The column used was DB-1MS, using helium as the carried gas. With a temperature of 250 °C, an injection volume of 3.0 μL was applied. The detector temperature was maintained at 320 °C. Before sample injection, the initial temperature was set at 70 °C and was increased at a rate of 8 °C/min to 320 °C for 30 min. Therefore, the total time required to process a sample was 60 min.

Animal feed was produced using the solid residues (exhaust pulp) generated during the other processing steps (guacamole and avocado oil) [29]. The residual materials were dried, homogeneously mixed, and then subjected to milling processes for subsequent palletization [30].

2.1.3. Bioactive Compounds Extraction and Characterization

The methodology used to extract bioactive compounds involved a conventional extraction method with solvent (ethanol). For this, 4.0 g of avocado seed or peel was taken, previously ground, and dried. The controlled variables were time, temperature, ethanol concentration, and solid:liquid ratio, set at 30 min, 60 °C, 70 %w/w, and 1:15 respectively, according to conditions reported by Trujillo-Mayol et al. [31]. Initially, the extracted samples were vacuum filtered and centrifuged for subsequent characterization. Total polyphenol content (TPC) and antioxidant capacity (DPPH and ABTS) assays were performed. TPC was measured following the Folin–Ciocalteu colorimetric method of Singleton [32]. In this method, samples were diluted using 15 μL of extract with 240 μL of distilled water. Quickly, the solutions were mixed with 15 μL of Folin–Ciocalteu solution (1N) and 30 μL of sodium carbonate at a concentration of 20 %w/w. The resulting solutions were taken to a dark place and left for 2 h of reaction. Finally, the absorbance was measured at a wavelength of 765 nm (UV/Visible Model 6405, Jenway, Felsted, UK). Thus, TPC was expressed as mg gallic acid equivalents per 100 g dry sample (mg GAE/100 g fruit). TPC was calculated based on the calibration curve for gallic acid (5–150 μg/mL).

The second methodology corresponds to the determination of antioxidant activity by DPPH (2,2-diphenyl-1-picrylhydrazyl) radical inhibition. It was carried out employing the methodology described by Morinova et al. and others [33–35]. First, 10 μL of extract and 200 μL of 60 μM solution of DPPH (dissolved in 96% ethanol) were prepared in microplates. The solutions were allowed to react for 1 h without light. Then, using a spectrophotometer (UV/Visible Model 6405, Jenway, Felsted, UK) adjusted to 517 nm, the absorbance was measured using ethanol as a blank. The radical inhibition was calculated using Equation (1), where A_o is the absorbance of the black and A_f is the absorbance of the sample solution. A standardization curve was prepared with Trolox standard solution diluted in ethanol. The percentage inhibition data were expressed as μmol of Trolox/100 g of dry sample (TAA—μmol of Trolox/100 g of fruit).

$$\text{Radical Inhibition}(\%) = \left(1 - \frac{\text{A}_\text{f}\text{ sample solution}}{\text{A}_\text{o}\text{ blank}}\right)\cdot(100) \tag{1}$$

Finally, the third methodology corresponds to the antioxidant activity by decolorization of the ABTS+ radical cation. This methodology was performed by applying the steps described by Re et al. [36], and Ozgen et al. [37]. Initially, an ABTS solution had to be prepared, which required a 7 mM solution of 2,2-azino-bis-(3-ethylbenzothiazolin)-6-sulfontium acid (ABTS+) with a 2.45 nM solution of potassium persulfate. The assays were carried out by mixing 231 uL of ABST+ cation-radical solution with 10 ul of the extracted sample. Finally, the resulting solutions were left in an unlit place for 30 min. After the reaction time, the absorbance was measured at 734 nm with a spectrophotometer (UV/Visible Model 6405, Jenway, Felsted, UK) and using type I water as a blank. The mixture was vortexed for 2 min and left in an ultrasonic bath at room temperature (25 ± 2 °C) for 20 min and, finally, stored for 24 h without light at 4 °C to reach a steady oxidative state. Then, the solution was diluted with 20 mM acetate buffer solution (pH 4.5) to an absorbance of 0.700 ± 0.01 at 734 nm. A calibration curve was prepared with Trolox standard solution diluted in ethanol. The percentage inhibition of the ABTS+ radical cation was calculated using the same equation used in the DPPH- radical inhibition method (Equation (1)).

2.1.4. Biogas Production

Biogas production was performed by anaerobic digestion. The anaerobic digestion conditions were 20 days at 37 °C and both the seeds and the peels of the creole avocado, resulting from the extraction process, were used as a substrate. The standard method VDI 4630 was used for the biogas assays [38]. The experiments were performed in glass flasks of 90 mL of digestion volume, which involved adding micro- and macronutrient solutions [39]. The medium was bubbled with nitrogen for 10 min and then hermetically closed to ensure an anaerobic atmosphere. The inoculum was obtained from an anaerobic reactor company of a soluble coffee-producing industry (Buencafe Liofilizado de Colombia, located in Chinchiná, Caldas). The volatile solids ratio of substrate to sludge was set at 0.4 for digestion. The biogas productivity was measured by volume displacement, whereas the gas composition was by a portable gas analyzer (Gasboard—3100P), following the methodology described by Ortiz-Sanchez et al. [40].

2.2. Valorization Schemes: Simulation Procedure

The biorefinery schemes for using creole avocado were developed within the socioeconomic context of Caldas, Colombia. For this purpose, small-scale transformation schemes were proposed, considering the production scale of the zone. The production of creole avocado in Caldas was 12,939.3 t in 2021, according to MinAgriculture, 2021 [9]. However, phenomena associated with pests and plant diseases cause fruit losses of about 49%, as reported by Perez et al. [41]. Thus, a rejected avocado creole rate of approximately 6340 t/year was produced. For this reason, it was considered to use 33% of this production to avoid supply problems. Thus, the processing scale for the small-scale biorefinery scenarios was 5.7 t/day. The creole avocado processing was simulated using Aspen Plus v9.0 (Aspen Technology Inc.) software using the experimental results as input data. All simulations were completed considering the nonrandom two liquid (NRTL) and Peng–Robinson equation of state (PR EoS) to estimate activity coefficients and fugacity.

Small-Scale Biorefineries

Four small-scale biorefineries were proposed in the region of Caldas, Colombia. Avocado oil was produced by cold pressing [42]. The animal feed was obtained by drying and granulating the spent avocado pulp, as described by Serna-Loaiza et al. [43]. Biogas was produced by codigesting seeds and peels in an anaerobic digester using the model reported by Rashama et al. [44]. Finally, the bioactive compounds were simulated using the methodology reported by Restrepo-Serna et al. [45]. The simulation schemes are described in Table 1 and the flow diagram (Figures S1–S4) can be found in Supplementary Materials.

Table 1. Simulation schemes.

Scenario	Raw Material	Product and Subproducts
Small-B1	Rejected avocado	Guacamole Biogas Fertilizer
Small-B2	Rejected avocado	Animal feed Biogas Fertilizer
Small-B3	Rejected avocado Seeds and peels from industrial processing	Avocado oil Bioactive compounds Biogas Fertilizer
Small-B4	Rejected avocado Seeds and peels from industrial processing	Animal feed Bioactive compounds Biogas Fertilizer

Different mass and energy indicators were proposed to evaluate the technical performance of the processes. The mass indicators are the product yield (γ_P), the mass intensity of the processes (PMI), and the mass loss index (MLI). γ_P correlates the product flows and the main feedstock (i.e., creole avocado). On the other hand, the PMI is calculated as the ratio between input flows and the desired product. Finally, the MLI index relates the flow of waste and unused materials to the flow of products. The energy indicators were specific energy consumption (SEC), self-generation (SGI), and energy efficiency resources (η_E). SEC is estimated as the ratio between the heat and energy needs of the process and the initial raw material flow. The SGI was considered the onsite energy production potential of the process, considering that one of the products present in all the schemes is biogas, considered an energy vector. Finally, the η_E relates the energy provided by the energy products to the energy derived from feedstock use. The equations used to calculate the mass and energy indicators were reported by Alonso-Gómez et al. [46] and by Ruiz-Mercado et al. [47], summarized in Table 2 (Equations (2)–(7)).

Table 2. Mass and energy index used to evaluate small-scale biorefineries.

Index	Equation	Units	Equation
Mass			
Product yield	$Y_P = \frac{\sum \dot{m}_{product,i}}{\dot{m}_{Rawmaterials}}$	kg P/t RM	(2)
Process mass intensity	$PMI = \frac{\sum_{i=1}^{N} \dot{m}^{in}}{\sum \dot{m}_{product,i}}$	kg RM/kg P	(3)
Mass loss index	$MLI = \frac{\sum_{i=1}^{N} \dot{m}^{in} - \sum \dot{m}_{product,i}}{\sum \dot{m}_{product,i}}$	kg WS/kg P	(4)
Energetics			
Specific energy consumption	$SEC = \frac{\dot{Q}+\dot{W}}{\dot{m}_{Rawmaterials}}$	kW/kg RM	(5)
Self-generation	$SGI = \frac{\left(\dot{m}_{Product,i} LHV_{Product,i}\right)}{\dot{Q}+\dot{W}}$	N.A.	(6)
Resources energy efficiency	$\eta_E = \frac{\dot{m}_{Product} \Delta H_{Product}}{\sum_{i=1}^{N} \dot{m}_j^{in} \Delta H_j} x100$	%	(7)

RM: Raw materials, P: Products, WS: Waste streams. N.A: Not Applicable

2.3. *Sustainability Analysis of Valorization Schemes*

2.3.1. Economic Assessment

The economic assessment was carried out in Aspen Process Economic Analyzer v9.0 software. By analyzing the mass and energy balances, it was possible to design, size, and calculate the total capital cost. The methodology used was described by Peters et al. [48] and Rueda-Durán et al. [49]. In addition, the economic parameters (indicators, prices, rates, etc.) were considered based on the Colombian context and the study region and can be found in Supplementary Materials, in Table S1. Continuous-type processing is assumed for each scenario, with 2800 working hours per year, an interest rate of 9.34%, and an internal rate of return of 35%. The above was selected considering the regulations regarding work in rural areas of Colombia (8 h/day) [50]. The equipment depreciation method was a straight line and the economic viability of each scenario was evaluated considering the net present value (NPV) for ten years.

2.3.2. Social Assessment

Social analysis is considered one of the three pillars in evaluating sustainability. In this paper, an analysis was carried out to establish the social impact generated by using creole avocado as the raw material for different small-scale biorefinery schemes. For this purpose, indicators related to workers and local communities were evaluated, considering the people who may be affected by the implementation of these production processes. An analysis and identification of all the indicators associated is required to consider other categories. For this reason, the categories of value chain agents, society, and consumers were not evaluated in this study. Table 3 summarizes the stakeholders, subcategories, and indicators used to assess the social impact of small-scale creole avocado biorefineries. Each indicator was evaluated considering the equations reported by Aristizábal-Marulanda et al. [51] and Poveda-Giraldo et al. [52]. All indicators were normalized using statistics and information derived from the industrial sector in the Colombian context. In addition, they were identified following the Product Social Life Cycle Assessment (PSILCA) database developed by Greendelta [53].

Table 3. Social indicators used to evaluate the social impact of small-scale biorefineries.

Stakeholders	Subcategory	Indicator	Equation
Workers	Fair wages	Living wage per month	$LW = \frac{\text{Living wage in Colombia}}{\text{Living was in Latin America}}$
		Minimum wage per month	$MW = \frac{\text{Minimum wage in Colombia}}{\text{Minimum was in Latin America.}}$
	Working time	Hours of work per employee	$WH_{total} + WH_{extra\ time} - WH_{resting\ time}$
Local community	Local employment	Employment generation	N.A
	Access to material resources	Industrial water use	$FWU_{sector} = \frac{W_{process} + W_{cooling}}{W_{withdrawal} \text{by Industry sector}}$
		Energy demand	$ED = \frac{\text{Energy demand in process}}{\text{Energy demand in Caldas}}$

(i) Stakeholder: Workers

The social impact calculated for the category of workers was evaluated by considering fair wages and working time as subcategories. The first subcategory, i.e., fair wage, involved calculating the living and minimum wage in Colombia and comparing them with average wages in Latin American countries [54]. The second subcategory, i.e., working time, involves the number of working hours per employee. The indicator was estimated considering that the facilities have a working time of eight hours per shift.

(ii) Stakeholders: Local community

The social impact related to the subcategory local communities was evaluated considering two indicators related to employment generation and the use of natural resources.

The first subcategory was calculated considering the labor required by the facilities according to the methodology reported by Peters et al. considering only the workers needed in the production plant (without the workers of other productive links) [48]. The second subcategory included the analysis of water use and energy demand. Industrial water use was calculated as the ratio between the water used during the process (process water and cooling water) and the national water flow used in the industry. The AQUASTAT database of the Food and Agriculture Organization of the United Nations (FAO) was used for this analysis. Finally, the last indicator relates each scenario's energy demand to the industrial sector's national energy demand.

2.3.3. Life-Cycle Assessment

The environmental assessment was carried out according to the environmental life-cycle analysis (LCA) approach considering the method proposed by ISO 14040:2006 [55]. This methodology comprises four steps: (i) definition of the objective and scope; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation of the results. The SimaPro v9.1 software (PRé Sustainability, The Netherlands) and the Ecoinvent V.9 database were used for the LCA. In addition, it was carried out quantitatively through the estimation of midpoint indicators using the ReCiPe Midpoint (H) V1.05/World (2010) H method. As a result, the most representative of the 18 indicators generated by this method is reported. In addition, carbon dioxide (CO_2) sequestration by Caldas's avocado crop was determined by considering aerial biomass, root system, and soil organic carbon to determine its environmental contribution in the value chain.

(i) Definition of scope and objective

The objective of the LCA was to determine the environmental impact of the creole avocado value chain (VC) in the department of Caldas and establish the bottlenecks in the chain, considering the following specific objectives: (i) to compare environmentally the transformation scenarios of the residues generated in the VC and identify the stages of the process with the greatest contribution to environmental impact; (ii) to determine the environmental impact of the creole avocado crop in the department of Caldas

(ii) System boundaries

The geographical limits of the study involved the production of creole avocado in the department of Caldas. Considering the time limits, the primary information for this study was collected in the third quarter of 2022 and the first quarter of 2023. Likewise, the VC showed low technological complexity in the different links of the value chain. Thus, the agricultural processes described in the first links are carried out manually (pruning, weeding, harvesting, etc.) and the transformation of avocados into commercial products is carried out by means of low-tech processes.

(iii) System studied

The creole avocado VC is mainly comprised of four links: (i) input suppliers, (ii) producers categorized as small producers, (iii) commercialization is responsible for distributing the avocado to processors or directly to the local market, and (iv) processors. This study did not consider the distribution of creole avocados to the national market due to the wide national supply. Figure 1 shows the limits of the system analyzed, the set of activities, and the processes involved and considered for this study.

(iv) Functional unit

The functional unit (FU) was selected based on the productivity of creole avocado in the department of Caldas and to compare different links of the VC and the transformation processes analyzed. In this sense, 1 kg of creole avocado was selected as the FU.

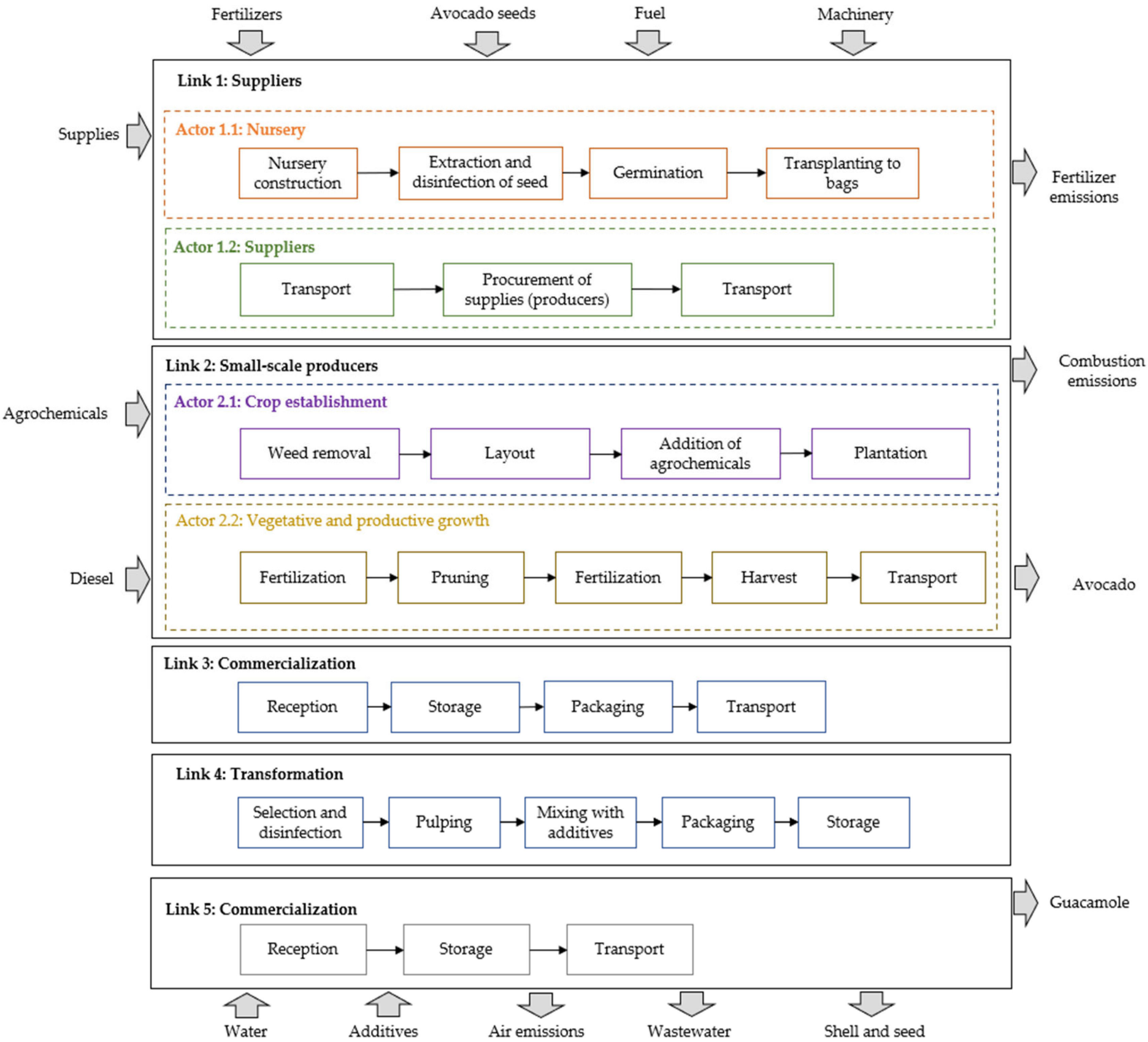


Figure 1. System boundaries of the VC of the creole avocado in Caldas.

(v) Life-Cycle Inventory (LCI)

Data collection was obtained mainly from secondary sources through an open literature search. Additionally, some interviews were conducted with avocado producers in the region to validate the information. Unfortunately, information on creole avocado production in the department of Caldas is very limited. The creole avocado has a share of 9.15% of the cultivated area and 9.09% of the production in the department of Caldas. Therefore, a reduction of supplies at the input and output of the first links of the VC was considered to provide greater veracity to the data (see Table 4). The information, considerations, and limitations of the information considered in the LCI for the study region can be found in Tables S2 and S3 in Supplementary Materials.

Table 4. Information, considerations, and limitations of the life-cycle inventory in the region.

Link	Criteria	Commentary/Consideration/Limitation
Input suppliers	Construction of the nursery	The inputs and outputs considered in the producer's link were adjusted according to the contribution of the area planted with creole avocados to the total avocados planted
	Hectares of creole avocado in Caldas	The creole avocado crop represents 9.15% of the total avocado in the department
	Germination	Germination was carried out in germinators and the seedlings were grown in plastic bags
	Average distance between nursery and grower	Average distance 35 km. Distances were modeled with EURO 1 type engines (SimaPro)
Producers	Crop establishment	The inputs and outputs considered in the producers' link were adjusted according to the percentage contribution of the area planted with creole avocado to the total avocado planted
	Crop type	Monoculture
	Genetic material	Creole avocado (*P. americana* var. *Drymifolia*)
	Seeding density	142 avocado trees/ha
	Productivity	400 kg of dry avocado per hectare per year
	Labors	The environmental impact associated with the transportation of workers was not considered
Commercialization	Marketing	Plastic baskets were considered for avocado transportation
	Transporter	The average distance was 20 km. Distances were modeled with EURO 1 type engines (SimaPro).
Process	Raw Materials/Utilities	The mass and energy balances compiled from the simulation of the processes or scenarios evaluated using the Aspen Plus v9 software were considered for avocado processing. Likewise, electricity consumption and the consumption of low- or high-pressure steam (thermal consumption) were also considered for the process
Commercialization	Transporter	The environmental impacts associated with the transportation of creole avocado and processed products were not considered for the study due to the diversity of routes that must be involved

(a) Input suppliers

The LCI considered all the materials and inputs of the nursery (i.e., sunshade greenhouse, wood, bricks, and rope), substrate preparation, and the dosages of fertilizers and agrochemicals. Moreover, the environmental impact of manufacturing and transporting materials, such as hand pumps and water pumps, was not considered. The LCI also involves the transport of seedlings to the crop, assuming a general average based on the location of the nurseries and producers. The contributions of the supplier were defined as the transport of supplies to the growers. This distance was also taken as a general average for each region. The activities carried out in the first link are shown in Figure 1.

Seed handling and selection: seeds must be selected from healthy and vigorous avocados. Once the avocados have been selected, the pulp should be removed. Removing the tegument (peel that covers the seed) is also advisable, as this inhibits germination. The seed must be extracted from the fruit in a hygienic place where there is no probability of contamination. The seeds should be disinfected by immersion in water at a temperature of 49–50 °C for 30 min and then dried in a shaded and ventilated place. The seed is then treated with Vitavax at 10 g per kg per seed.

Seed sowing in the germinator: A germinator is a structure that promotes the seed germination process. The germinator is constructed from boards and is 40 cm above the ground. Generally, a germinator of 1 m^2 can hold between 70 to 100 seeds. The substrate is based on sand and organic matter (e.g., worm humus and hen manure), representing 30% of the substrate mixture. The substrate must be sterilized with hot water. The seeds are sown in the germinator by placing them in separate rows (1 to 5 cm apart) and at a 2–3 cm depth.

Transplanting to bags: After 30 to 45 days, the seeds begin to sprout and must be transplanted 45 to 60 days later. The plastic bags have dimensions of 26 × 48 cm and a caliber of 5 in. The substrate used is soil and organic matter (rice peels and chicken manure) in the same ratio as in the nursery and must be disinfected with hot water. The seeds are placed 2–3 cm deep. This process lasts approximately 4 to 6 months, during which adequate irrigation, fertilization, shade, and pest control should be provided.

(b) Small producers

In the case of small producers, the inputs were taken according to the crop establishment and the vegetative and productive stages. Planting is carried out after the tree-growing process in the nursery bags. The soil requires adequate weed control performed with an axe or machete. The soil is laid out in a square shape with a spacing of 9 m per tree. The following is done manually with a shovel, and the average size of the hole is 40 × 40 × 40 cm. To improve the pH and soil structure, dolomite lime is added to the hole at a dose of 500 g per hole. Pruning is done manually with pruning shears.

Fertilization: granulated fertilizers with a high nitrogen content (e.g., 15–30–15) are generally used. During the first year, the quantities per tree per month added vary from 50 to 150 g. Applying fertilizers can be less frequent from the second year onwards, approximately every 2 months. For subsequent years, it is recommended to apply between 700 g to 1 kg of fertilizer each year to the tree, distributed in three applications throughout the year.

(c) Commercialization

The activities carried out in this link are the reception of the fruit, storage, and transportation. In this link, 70% of the avocado is directed to the local market for direct consumption and the rest is directed to the transformer's link.

(d) Transformation

The inputs and outputs of the transformation of avocado into guacamole and other byproducts (raw material consumption, utilities, products, and waste) were taken from the simulation schemes proposed above.

(e) Commercialization

The activities in this link are the reception of the fruit, storage, and transportation. In addition, the distribution of the processed avocado is considered in this link.

3. Results

3.1. Experimental Results

3.1.1. Raw Material Characterization

The results obtained in the chemical characterization are summarized in Table 5. The seeds of the creole avocado showed high concentrations of extractives (26.4%) and starch (24.6%); meanwhile, the peel is rich in extractives (30.8%) and carbohydrates (36.7%) such as cellulose and hemicellulose. The high content of extractives represents an opportunity to extract bioactive compounds such as flavonoids, alkaloids, and oxalates [56], representing an opportunity to produce marketable products. However, these processes should involve low technology complexity to avoid incurring complex technification that makes their application impossible in areas with low investment at the industrial level. On the other hand, the high starch content in seeds is also a fraction that can be used for flour production, as reported by Solarte-Toro et al. [19]. Regarding proximate analysis and high calorific value, their values agree with other authors and are similar to other agroindustrial wastes used for energy purposes [57]. Thus, the VM/FC ratio allows for the use of these residues in combustion processes, such as gasification, considering that the VM/FC ratio recommended by All Power Labs is 3–4 and the slight variation of the study data may imply a higher volatilization rate during thermal decomposition [58].

Table 5. Chemical characterization of the seed and peel of creole avocado.

Item	Seed		Peel	
Chemical Characterization (%w/w Dry Basis)				
Extractives	26.45	± 0.55	30.78	±0.57
Reducing sugars (g/L)	3.01	±0.57	2.09	±0.40
Fats	9.81	±0.40	13.89	±1.58
Cellulose	13.38	±0.43	21.64	±0.98
Hemicellulose	9.30	±0.59	15.04	±0.27
Total lignin	7.78	±0.82	9.95	±0.81
Insoluble acid lignin	7.59	±0.67	9.71	±0.65
Soluble acid lignin	0.19	±0.01	0.24	±0.02
Starch	24.58	±1.12	1.60	±1.33
Proximate analysis				
Moisture	13.17	±0.11	11.09	±0.10
Ash	2.86	±0.10	3.27	±0.13
Volatile matter	79.91	±0.54	80.26	±0.23
Fixed carbon	17.22	±0.13	16.48	±0.11
VM/FC	4.64	±0.81	4.87	±0.58
Higher calorific value (MJ/kg)	18.37	±1.11	18.05	±1.02
Solids content				
Total solids	87.61	±0.20	89.51	±0.27
Volatile solids	3.33	±0.03	6.44	± 0.05

3.1.2. Avocado-Oil Extraction and Characterization

The yield of creole avocado oil obtained through the Soxhlet extraction methodology was 11%. This value is similar to previous reports by Solarte-Toro et al. [19]. Avocado oil is rich in oleic, palmitic, linoleic, and palmitoleic acids, while stearic acid is in smaller composition [59]. The oil extracted from creole avocado pulp had a high lipid content. Among these lipids, oleic and palmitic acids were identified in amounts of approximately 62.9% and 28.7%, respectively. These results are similar to other avocado oils. Oleic acid was found to be 45.9% to 54.5%, followed by palmitic acid, with values between 19.84% and 15.63% [60].

3.1.3. Bioactive Compounds Extraction and Determination of DPPH, ABTS, and TPC

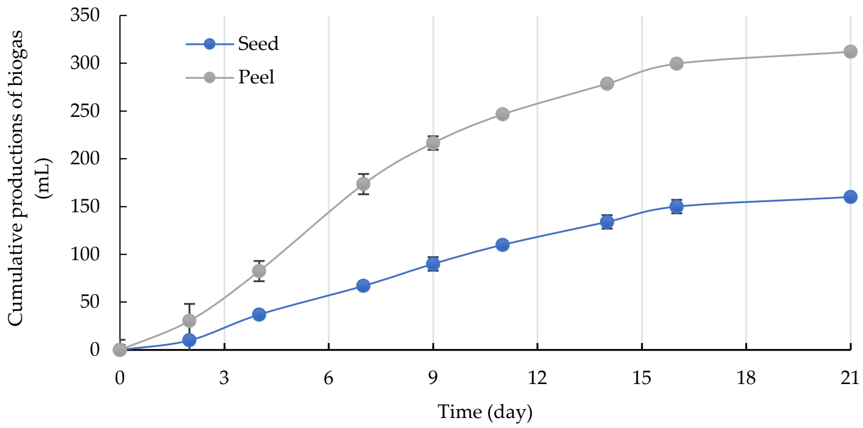
During the extraction processes carried out on both the seeds and peels of creole avocado, it was found that these residues contain a wide range of bioactive compounds extractable using polar solvents, such as water and ethanol. Table 6 shows the main results of the analysis of avocado extractives. As previously reported, avocado peels and seeds are rich in organic acids, such as gallic acid, in concentrations varying from 0.2–0.4 mg/kg of raw materials [61]. On the other hand, phenolic acids and their derivatives include 4-hydroxybenzoic acid in concentrations ranging from 14.8 to 40 mg/kg raw materials. As for flavonoids, it was possible to identify catechin, epicatechin, and epicatechin gallate with higher concentration levels ranging from 100 mg/kg to 280 mg/kg of raw materials. These concentrations are reflected in the high levels of polyphenols and the high level of antioxidant activity reflected in the avocado seeds and peels. Thus, the extraction of these high-value-added bioactive compounds is established as a potential alternative to produce various pharmaceutical and nutritional products from biomass. Therefore, the extraction processes allow the valorization of creole avocado residues [62].

Table 6. Extractive analysis of seed and peels of creole avocado.

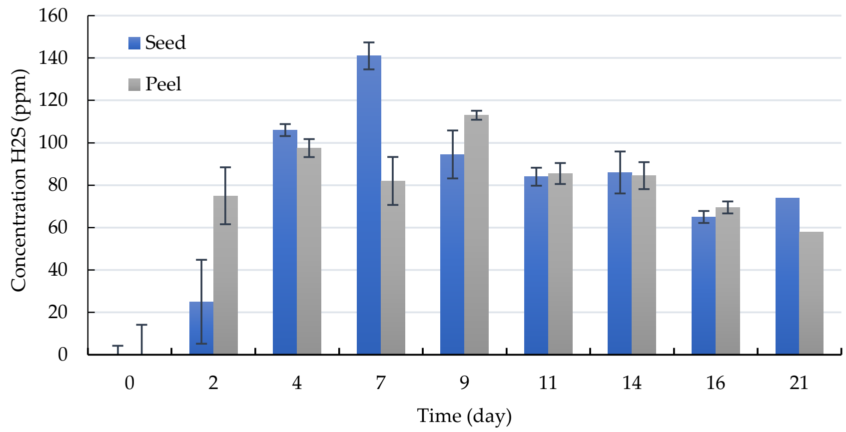
Item	DPPH (µmol Trolox/100 g MP)	TPC (mg GAE/g MP)	ABTS + (µmol Trolox/100 g MP)
Seed	718.94	559.14	613.60
Peel	773.05	388.04	245.35

3.1.4. Biogas Production

The potential for biogas production from the residues generated during the processing of creole avocado was evaluated by applying the biochemical methane potential (BMP) test. The results obtained are shown in Figure 2a. The results suggest that the peel was presented as a better substrate since it generated approximately twice as much biogas as the seed. These results may be because the C/N ratio was 40 for the peels and less than 24 for the seed. In biogas assays, the C/N ratio must be in the range of 25–30 for optimum performance. An excess of nitrogen could lead to an accumulation of ammonia, inhibiting the biomethane-producing microorganisms. After 21 days of digestion, there were no differences in the accumulated methane yield for both samples, being 8.08 and 8.49 L/gVS for seed and peel, respectively. These values are similar to the results reported for avocado residues by Girmaye, et al. [14]. Finally, Figure 2b shows the hydrogen sulfide content produced daily by each residual fraction. Bücher or diesel engines running on heavy fuel can only operate at a maximum of 600 ppm H_2S [63]. Thus, biogas production never exceeds this concentration for seed and peel, suggesting that the use of a biological filter prior to biogas combustion for electric power generation is not necessary.



(**a**) Biogas production for creole avocado seed and peel



(**b**) Concentration of hydrogen sulfide (H_2S) in biogas per day.

Figure 2. Biogas production from creole avocado seed and peel. (**a**) Biogas production and (**b**) Concentration of (H_2S) in biogas.

3.2. Small Scale Biorefineries

The mass and energy indicators estimated for the production schemes are presented in Table 7. The mass indicators for the biorefineries show that the MLI and PMI decrease as the product portfolio increases. MLI decreases because the waste streams were valorized by extracting various byproducts (e.g., avocado oil or bioactive compounds). Additionally, the MLI decreases because the product stream increases relative to the feedstock fed. In general, the mass indicators ensure that the product portfolio diversification strengthens the utilization of the fractions of the creole avocado fruit. From an energy perspective, the SEC and SGI indicators show that, as the flow of products increases, the energy requirement of the process decreases. The SEC decreases in proportion to the increase in biogas production. Therefore, the SEC is lower in the Small-B3 and Small-B4 schemes, with higher biogas production flow. This trend also holds for the on site energy production of the process. The SGI demonstrates that the energy flow derived from biogas production can supply, in some proportion, the energy needs of the different stages of the process. For this, it would be necessary to perform the combustion of the biogas produced and evaluate how much energy it can supply in the process. Finally, regarding energy efficiency, the schemes present similar values since the relationship between the flows of energy products and the raw material is maintained. Thus, it can be assured that the schemes that present better performances at the mass and energy levels are the Small-B3 and Small-B4 schemes. However, despite presenting higher productivity performance, it is necessary to carry out an economic analysis of these schemes to consider the best alternative to be implemented in the department of Caldas.

Table 7. Techno-energetic assessment for small-scale biorefinery.

Item	Units	Small-B1	Small-B2	Small-B3	Small-B4
Mass indicators					
Product yield (Yp)					
Guacamole	t/t RM	0.46	-	0.23	0.23
Avocado oil	t/t RM	-	-	0.25	-
Bioactive compounds	t/t RM	-	-	0.77	0.77
Animal feed	t/t RM	-	1.13	-	0.64
Biogas	kg/t RM	0.079	0.072	0.072	0.072
Fertilizer	t/t RM	1.18	1.18	0.78	0.78
Process Mass Intensity (PMI)	kg RM/kg P	18.54	13.65	10.74	9.16
Mass loss index (MLI)	kg WS/kg P	5.26	3.80	5.16	5.13
Energy indicators					
Specific Energy Consumption (SEC)	kWh/kg RM	20.37	20.38	12.54	12.53
Self-generation—Biogas (SGI)	N.A.	0.058	0.057	0.089	0.090
Energy efficiency resources (nE)	%	0.0060	0.0059	0.0057	0.0057

RM: Raw materials, P: Products, WS: Waste streams. N.A: Not Applicable

3.3. Sustainability Assessment

3.3.1. Economic Assessment

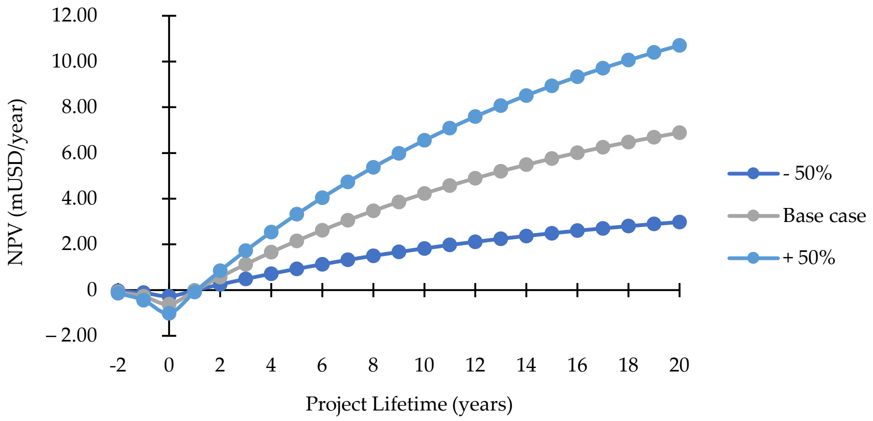
The economic assessment of the small-scale scenarios was carried out considering key aspects mentioned in the methodology. In each scenario, the capital cost involved the direct costs of equipment, instrumentation, piping, civil works before plant assembly, and other costs associated with electrical installations and firefighting. However, as seen in Table 8, the capital costs of the Small-B1 and Small-B2 scenarios are approximately half the investment costs of the Small-B3 and Small-B4 scenarios. This is mainly because the processing lines for extracting and separating the bioactive compounds and the avocado oil are expensive and require equipment with higher complexity and energy expenditure.

Table 8. Economic assessment of simulation schemes.

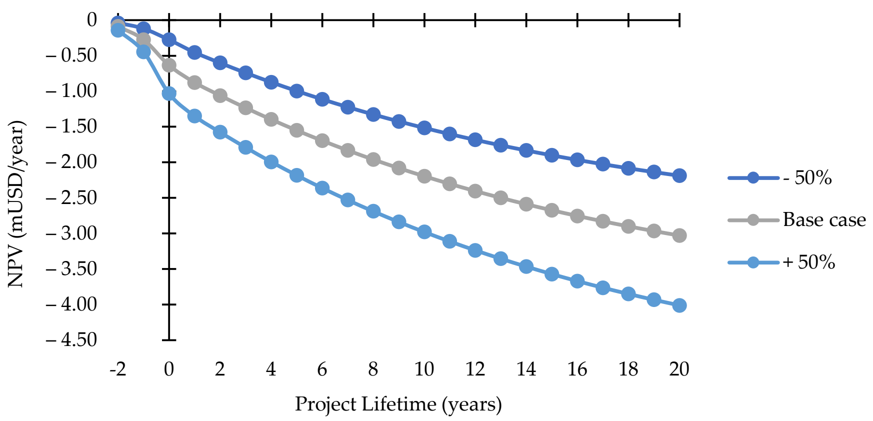
Economic Evaluation Results	Units	Small-B1	Small-B2	Small-B3	Small-B4
CapEx	mUSD	0.48	0.48	1.00	0.97
OpEx	mUSD	1.28	1.37	6.28	6.29
Payback period	year	1.04		0.16	0.17
Minimum Processing Scale for Economic Feasibility (MPSEF)	kg/h	31.59		5.94	5.23

CapEx: Capital expenditures OpEx: Operating expenditures.

Similarly, the costs associated with the operating costs are raw materials, reagents, and services required during the process, such as cooling water, low-pressure steam, and electricity. Raw material costs were the highest, varying from 58% to 84%. Similarly, capital depreciation was one of the highest costs, varying from 15% to 21%, due to the use of different equipment in the processing lines. Thus, the Small-B4 scenario, despite not being the most economical scheme, is the scheme with the lowest investment and operating costs compared to the scenarios with the highest mass productivity (Small-B3 and Small-B4). In addition, the MPSEF is lower for Small-B4 than Small-B1 and Small-B3. Finally, the NPV trend based on the processing scale was estimated for all scenarios and is presented in Figure 3. Three scales were considered, one larger and one smaller than the defined scale. Considering a proportional relationship, the NPV strongly depends on the raw material flow. The Small-B2 MPSEF is not presented since this scenario does not show economic profitability, as shown in Figure 3c.

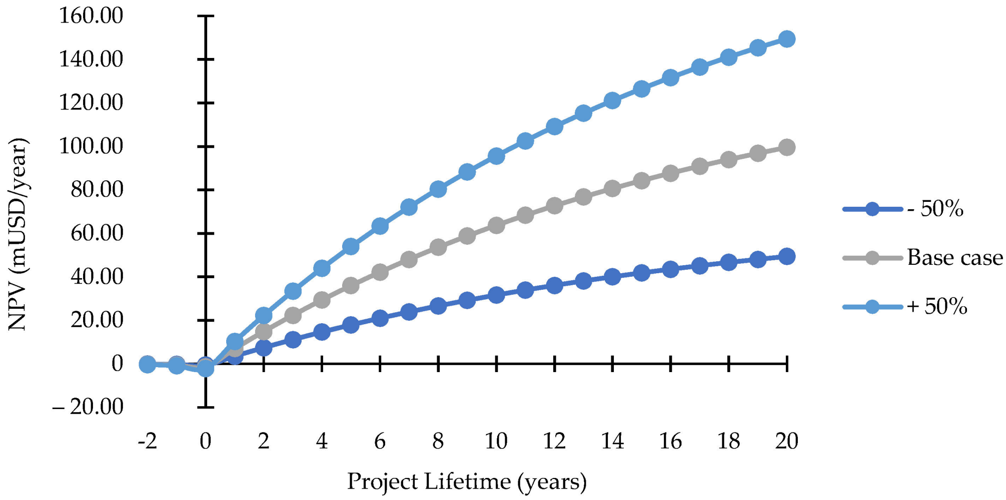


(**a**)



(**b**)

Figure 3. *Cont.*



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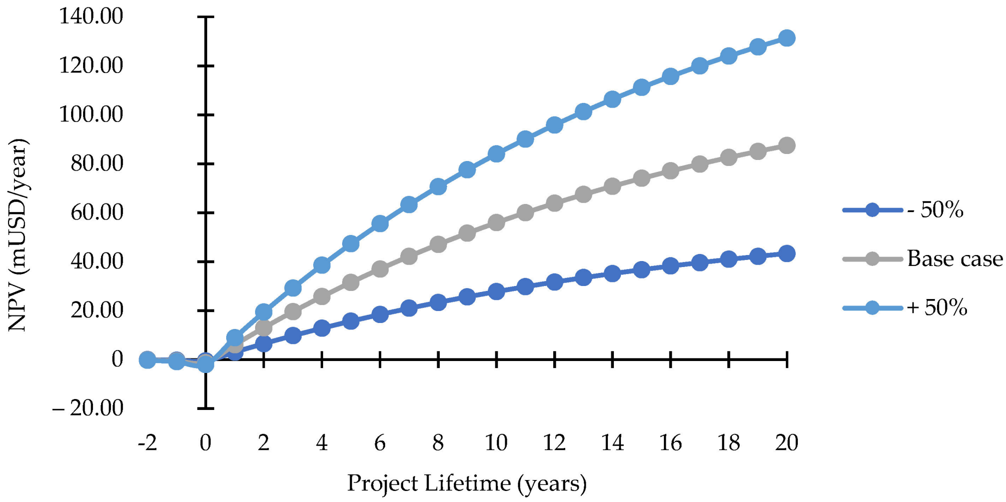

(**d**)

Figure 3. Net present value over the project lifetime with different processing scales of raw material. (**a**) Small-B_1; (**b**) Small-B_2; (**c**) Small-B_3; (**d**) Small-B_4.

3.3.2. Social Assessment

The results of the social analysis for the different scenarios are directly related to the data obtained from the simulation (Table 7). From the workers stakeholders, the indicators evaluated were the monthly living wage and the minimum wage, as well as hours of work. The results in Table 9 show the social impact based on a risk scale. Regarding the subcategory of the fair wage, it is sufficient to guarantee an income that allows a dignified life, applicable for a single person. However, many Colombian families are composed of four or more people and a higher wage is necessary to guarantee the minimum economic resources. For this reason, the minimum monthly salary is in the medium-risk category. For the employee working time indicator, it should be considered that, in Colombia, working hours per week have been reduced according to Law 2101 of 15 July 2021, from 48 h/week to 42 h/week, placing the indicator in a low-risk category.

Table 9. Social analysis of simulation schemes in the Colombian context.

Stakeholders	Indicator	Base Case for Colombia		Value	Risk
Workers	Living wage per month	238.5 USD		0.9100	Low risk
	Minimum wage per month	256.0 USD		1.3600	Medium risk
	Hours of work per employee *	42		40	Low risk
Local community	Employment generation	6–7 workers/day			Jobs
	Level of industrial water use (withdrawal) **	$3.73 \times 10^9 m^3$/year	S-B1	m^3/year 0.0003	Very low risk
			S-B2	0.0003	
			S-B3	0.0004	
			S-B4	0.0004	
	Energy demand ***	72.824 GWh	S-B1	GWh 0.0069	Very low risk
			S-B2	0.0069	
			S-B3	0.0087	
			S-B4	0.0088	

* Operator and supervisor ** 2019 *** 2021. S-B1: Small-B1, S-B2: Small-B2, S-BE: Small-B3, S-B4: Small-B4.

Six employees are needed for the local community stakeholders, in which the indicator of locally hired labor and employment generation is considered for the Small-B1 and Small-B2 schemes. While for the Small-B3 and Small-B4 schemes, seven workers are needed. Thus, the increase in the product portfolio also implies an increase in the personnel required for the production lines. Finally, the proposed production schemes open the possibility of hiring unskilled people as operators, generating employment for the rural population. Finally, regarding the consumption of industrial water used and energy demand in the process, the results allow for the conclusion that the implementation of the avocado valorization schemes does not present a risk to the country's natural resources and their installation would not significantly increase the demand for water and energy for the industrial sector.

3.3.3. Life-Cycle Assessment

(i) Detailed description of the creole avocado VC in Caldas

The evaluation of the environmental impact of the creole avocado VC in the department of Caldas began with the identification of the chain, involving different details of the links and actors in the region. The flows of raw materials, supplies, waste, and products generated within the chain were also established. Figure 4 shows the VC of creole avocado in the department of Caldas. The first link (input suppliers) considers two actors. The first actor, "nursery", covers the activities of nursery construction and seedling production. In general terms, the variety of avocados grown in the department of Caldas is the Hass avocado. The creole variety is present in smaller quantities. Therefore, the number of nurseries that favor the production of this variety is limited. For this reason, total entries are reduced, as detailed in Methodology Section 2 (see Table S2 in Supplementary Material).

The second link (producers) considers only one actor. The representative actor in this link is the creole avocado producer classified as a small producer, where the average area of avocado cultivation is less than three ha. In fact, as mentioned above, the area of creole avocado cultivated in the department is at most 10% of the total avocado cultivated in the region. The activities involved in this link include land preparation, fertilization, and pruning, among others. Producers send the avocados to storage centers, the local market, and processors. The avocados that go to processors represent 49% of production. These avocados are not consumable (rejection avocado) due to attributes associated with visual or organoleptic characteristics. This percentage represents an important bottleneck within the VC. Avocados in good condition are sent to the local market and collection centers. The third link (marketers) involves one actor. The collection centers (CA) are responsible for gathering the production of small producers and marketing them to the local market in urban centers. The CAs receive 45.17% of the avocado production. Seventy percent of the avocados received in the CAs are directed to the local market and the remaining 30% is directed to processing units. Due to the limited information reported in the open literature, the fourth link (processors) was defined generically, without representative actors. These actors are represented by retail processors that direct their products (mainly guacamole) to the local market. On the other hand, to evaluate different transformation routes for avocados and their residues, several scenarios were considered for generating high-value products in this link, which are detailed in other reports. Finally, the fourth link (market) involves two actors. The actors involved are the local market and the national market. The local market receives creole avocados from the collection centers and the products generated from the processors. The national market receives 5.83% of the avocados generated in the processing link. The environmental impacts associated with the market link were not considered for the study (high coverage of routes involved in marketing to the market).

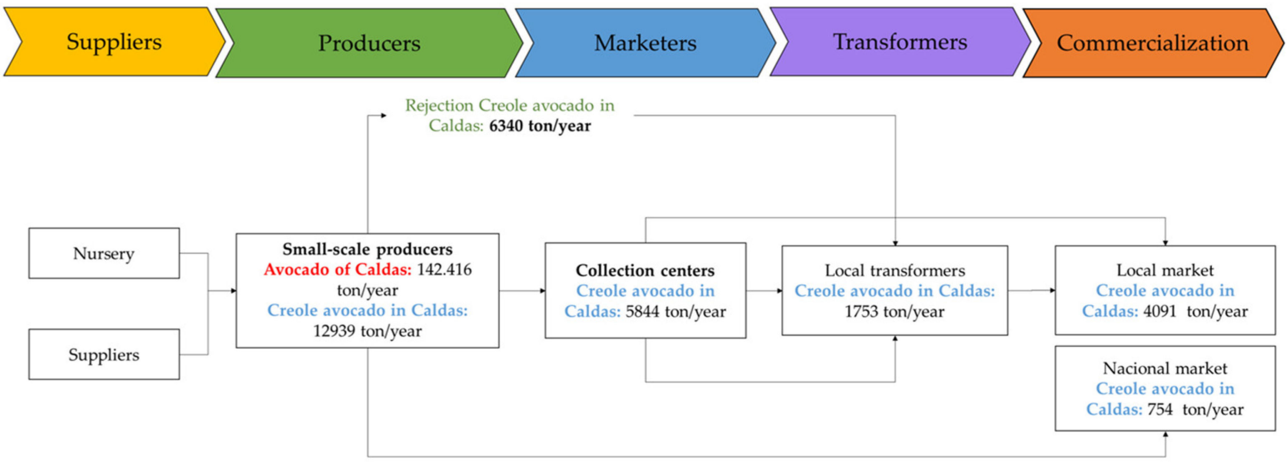

Figure 4. Value chain and production flows of the creole avocado in Caldas, Colombia.

(ii) Environmental impact of the creole avocado VC in the Caldas

The environmental assessment, considering 1 kg of avocado as a functional unit, suggests several dynamics, according to the different links of the VC analyzed. The results presented below are shown by percentage share of the activities carried out per link for different categories of relative impact. The participation of each link in the value chain is also presented for the climate change category. Regarding relative indicators, the results are shown without considering carbon sequestration by the native avocado to determine the potential impacts of the activities for each link. Figure 5 presents the participation in the carbon footprint of each link of the avocado VC in the department of Caldas. Avocado processing and the waste generated in the different links of the chain (see Figure 4) represent nearly 80% of the environmental impact, followed by the producers' link (5%). The marketing link and input suppliers participate similarly. Different studies have shown that using these residues to generate high-value products generates lower environmental impacts than the current disposal of these residues (left in the crop, sent to landfills) [64]. The link to marketers does not represent a significant environmental impact since local distances (not exceeding 50 km) were considered.

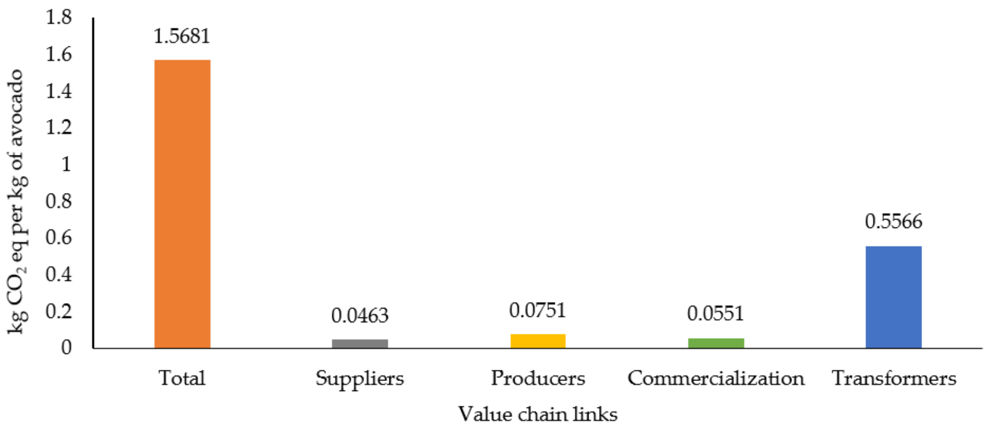

Figure 5. Carbon footprint of the value chain of creole avocado in Caldas for each link.

Table 10 presents the emissions of agrochemicals used in the first two links of the creole avocado VC. The different nitrogen and phosphorus emissions are more representative of the producers' link due to the greater number of fertilizers and agrochemicals used. In addition, CO_2 emissions (31.24 g CO_2/seedling) in the producer's link are generated due to the use of agricultural lime in the soil-conditioning process.

Table 10. Emissions of agrochemicals used in the first two links of the creole avocado VC.

	Nitrogen Emissions		
Input suppliers	Emissions of N_2O—Direct—air	0.23	g N_2O/seedling
	Emissions of N_2O—Indirect—air	0.02	g N_2O/seedling
	Emissions of NH_3—air	0.18	g NH_3/seedling
	Emissions of NO_3^-—water	2.23	g NO_3^-—N/seedling
Producers	Emissions of N_2O—Direct—air	9.64	g N_2O/seedling
	Emissions of N_2O—Indirect—air	1.01	g N_2O/seedling
	Emissions of NH_3—air	7.45	g NH_3/seedling
	Emissions of NO_3^-—water	92.00	g NO_3^-—N/seedling
	Phosphorus Emissions		
Input suppliers	Emissions of PO_4^{3-} water	201.01	g P/ha/a
	Emissions of P soil	0.04	g P/ha
Producers	Emissions of PO_4^{3-} water	246.92	g P/ha/a
	Emissions of P soil	7.26	g P/ha
	CO_2 Emissions		
Producers	Emissions of CO_2—air	31.24	g CO_2/seedling

The categories that had the greatest impact on the input supplier and small producer links were climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), human toxicity (HT), freshwater ecotoxicity (FET), agricultural land occupation (ALO), water depletion (WD), fossil depletion (FD), photochemical oxidant formation (POF), and urban land occupation (ULO). This analysis considered the use of agrochemicals (Vitavax, DAP, 15-30-15, agricultural lime) to disinfect avocado seeds in the nursery; the conditioning of the soil and fertilization of the plants in production are the greatest contributors in the categories evaluated. Figure 6 shows the relative percentage contribution of the different activities carried out by the nursery actor in the input suppliers link and the smallholder actor in the producer link. Agrochemical use represents about 69% of the CC category for nurseries and 92% for small producers. Several authors state a trend of high environmental impact associated with the constant use of agrochemicals and fertilizers [65]. Agrochemicals leach into the surrounding soil and water bodies and enter the chain, leading to bioaccumulation and environmental damage [66]. Organic fertilizers have exhibited a greenhouse gas reduction rate compared to chemical fertilizers. For example, Kitamura R et al. [67] report that a reduction of about 25% is achieved by using manure and slurry as fertilizers. Similar results have been reported elsewhere [68,69].

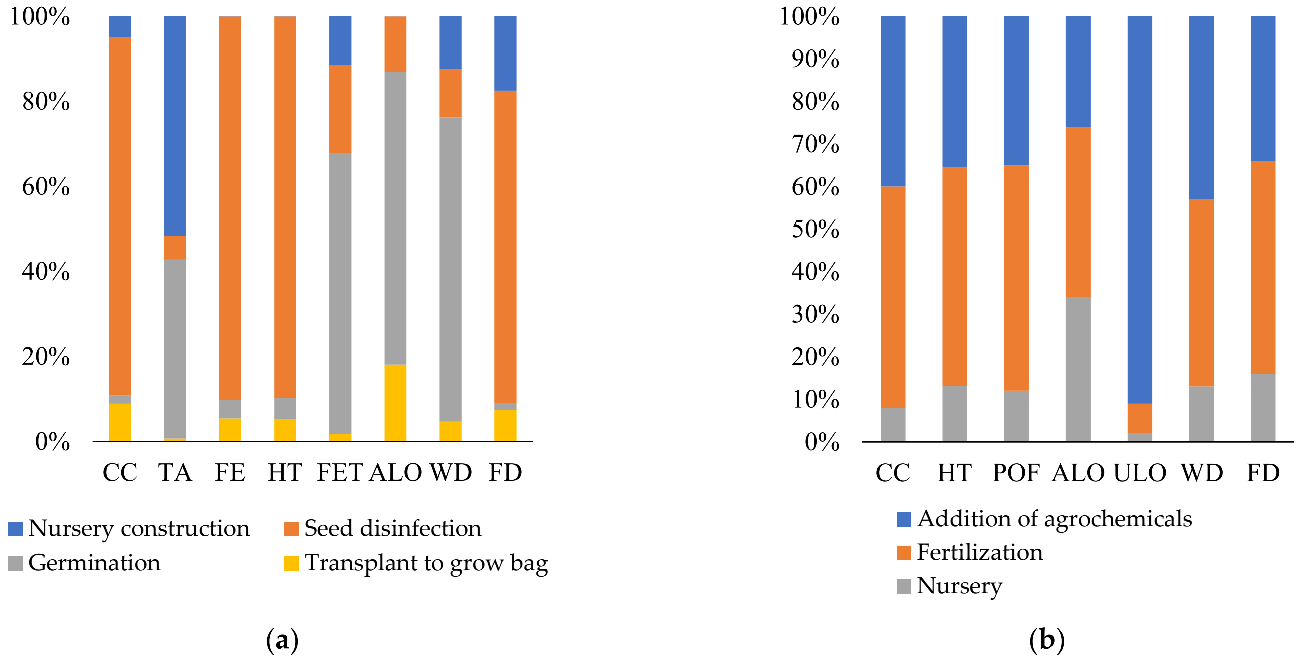

Figure 6. Relative percentage contribution to the environmental impact of different impact categories for (**a**) the actor nursery (first link) (**b**) and the actor small producers (second link). Climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), human toxicity (HT), freshwater ecotoxicity (FET), agricultural land occupation (ALO), water depletion (WD), fossil depletion (FD), photochemical oxidant formation (POF), and urban land occupation (ULO).

The production of 1 kg of creole avocado in the department of Caldas generates 0.09 kg of CO_2 eq in one crop cycle. These results contrast with other avocado crops. For example, Hadjian et al. reported emissions of 1.38 kg CO_2 per kg avocado [70]. d'Abbadie et al. reported emissions of 0.292 kg CO_2 per kg avocado [71]. These results are mainly subject to the type of technology level and productivity of avocado producers. Nevertheless, it is congruent that CO_2 eq emissions from the production of creole avocado in the department of Caldas are lower than other reports since common agricultural practices are managed; in addition, the type of avocado evaluated in this study (creole) is produced in low quantities.

Figure 7 presents the relative percentage contribution to the environmental impact of different impact categories for the transformer actor in the third link of the creole avocado VC. The most representative categories that had the greatest impact on this link were climate change (CC), human toxicity (HT), freshwater ecotoxicity (FET), agricultural land occupation (ALO), water depletion (WD), and fossil depletion (FD). Figure 7a,b shows similar percentage contributions in the impact categories evaluated. This same trend is evidenced in Figure 7c,d. Biogas production represents about 47% of the CC category of scenario 1, followed by guacamole production (28%). It has been shown that the digestate obtained after the anaerobic digestion process for biogas production can result in atmospheric emission rates; however, these rates are generally lower than untreated biomass [72]. Small-B2 presents a 30% higher carbon footprint than Small-B1, as shown in Table 11, mainly due to the higher energy consumption associated with the animal-feed production process. On the other hand, the production of bioactive compounds using ethanol as a solvent in Small-B3 represents 67% of the percentage contribution in the CC category. It is also the main contributor in the other categories evaluated.

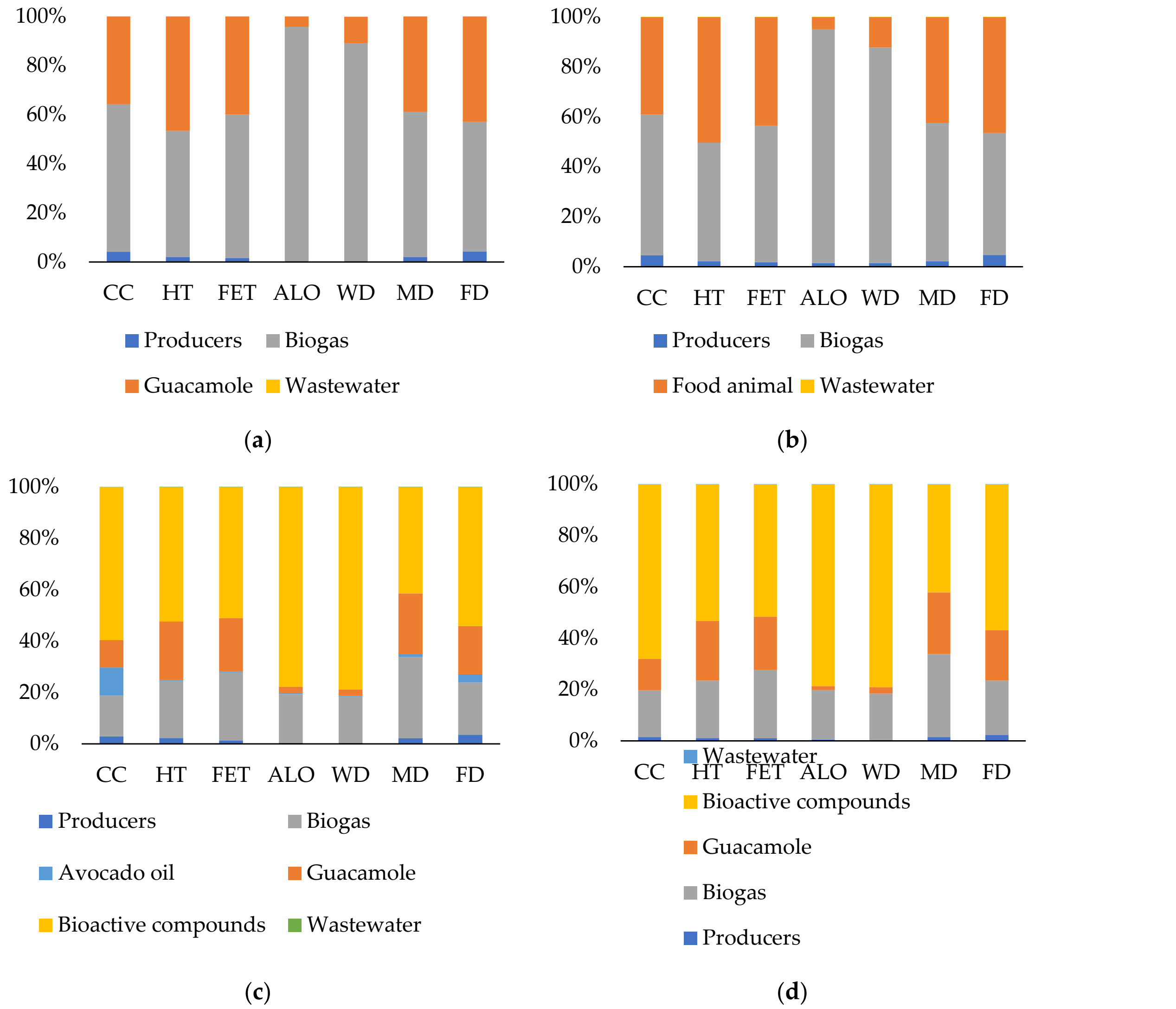

Figure 7. Relative percentage contribution to the environmental impact of different impact categories for the creole avocado processing link. (**a**) Small-B1, (**b**) Small-B2, (**c**) Small-B3, and (**d**) Small- 4. Climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), human toxicity (HT), freshwater ecotoxicity (FET), agricultural land occupation (ALO), water depletion (WD), fossil depletion (FD), photochemical oxidant formation (POF), urban land occupation (ULO), and metal depletion (MD).

Table 11. Carbon footprint of creole avocado processing scenarios.

Category	Small-B1	Small-B2	Small-B3	Small-B4
CC (kg de CO_2 eq per FU)	1.01	1.32	2.41	2.17

For the analysis, the entire processing part is considered until ethanol is obtained, which means that there are direct greenhouse gas (GHG) emissions to the atmosphere due to fermentation and transportation [73]. In addition, large cultivation areas are required, which is reflected in the ALO category (representing 79%). However, avocado-oil production generates a 12% increase in the CC category associated with using solvents such as hexane. In this sense, when considering different routes of transformation and valorization of avocado residues (Small-B3), and comparing it with conventional transformation (guacamole production), it becomes evident that 138% more environmental contribution is generated in the CC category.

4. Conclusions

The environmental and social analysis of the different scenarios of small-scale biorefineries exposes the different environmental impact categories and the most relevant social indicators for their application in the Caldas region. The LCA methodology allows for identifying the links with the highest environmental impact and which products represent the largest carbon footprint. Likewise, the social impact methodology shows that all of the scenarios benefit the social context. However, the economic evaluation expressed in terms of CapEx and OpEx, in addition to the economic retribution expressed through NPV, payback period, and MPSEF shows that although Small-B1 presents the lowest costs, it also presents the lowest performance indexes. Therefore, it was proposed that the biorefinery of animal feed, bioactive compounds, biogas, and fertilizer was the best option to be implemented. In conclusion, the process has a good economic return, a moderate environmental impact, and a positive social influence. However, it is important to look for alternatives to reduce the water footprint of this crop, as well as to look for options to delay the ripening time of the creole avocado, which is between 4–6 days, which puts at risk the guarantee of its applicability before becoming a deteriorated raw material. Nevertheless, this low-complexity biotechnological process can be developed with funding from the national government and the financing of projects that seek the technification of crops and industrial development in rural areas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13092229/s1, Figure S1: General scheme of guacamole, fertilizer, and biogas production (Small-B1); Figure S2: General scheme of animal feed, fertilizer, and biogas production (Small-B2); Figure S3: General scheme of guacamole, oil, bioactive compounds, fertilizer, and biogas production (Small-B3); Figure S4: General scheme of guacamole, animal feed, bioactive compounds, fertilizer, and biogas production (Small-B4); Table S1: Raw materials, utilities, and parameter economics; Table S2: Inventory of the creole avocado VC in the department of Caldas for the first three links; Table S3: Composition of agrochemicals used in the first two links of the creole avocado VC. References [42–45,74–78].

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