Bioresource Technology Reports 21 (2023) 101318

Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports

Life cycle assessment and potential geolocation of a multi-feedstock biorefinery: Integration of the avocado and plantain value chains in rural zones

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ARTICLE INFO

Keywords:
Avocado residues
Facilities location
Geolocation methodology
Multiple raw materials
Plantain residues
Product distribution

ABSTRACT

Logistics has been identified as a hotspot when proposing biorefineries due to transport and environmental issues. This work aims to define the best location for a multi-feedstock biorefinery based on the environmental impact caused by the products transport and commercialization. Avocado and plantain residues were used as feedstocks since large amounts are produced in Colombia. The novelty of this work is addressed to (i) valorize agricultural residues of the avocado and plantain value chains by applying the biorefinery concept and (ii) define the best process location to commercialize value-added products while minimizing CO_2 emissions. Biorefinery product commercialization was identified as the most contributing factor to total CO_2 emissions. The total carbon footprint of the proposed multi-feedstock biorefinery with product commercialization was 2.67 tons CO_2 eq/kg of avocado seed oil. This study elucidates the requirements for complex industrial process locations integrating context aspects and environmental restrictions.

1. Introduction

Biorefineries have been defined as complex systems where biomass is upgraded into a series of value-added products and energy vectors sustainably (Cardona et al., 2018). Biomass has been considered a potential raw material to decrease the use of non-renewable resources and decrease the environmental impact caused by non-controlled exploitation. Agricultural and agro-industrial residues (i.e., second-generation biomass) are interesting for biorefineries since these residues have a low commercial value and low competition as feedstock (Rosales-Calderon and Arantes, 2019). However, issues related to logistics and availability must be overcome before proposing second-generation biomass as a feasible feedstock. Raw materials integration (i.e., multi-feedstock use) has been profiled as an alternative to providing solutions to the scale and availability issues since different literature reports have concluded the need for a high feedstock flow to reach economic feasibility (Zhang et al., 2018; Poveda-Giraldo et al., 2021). There are few reports analyzing the influence of raw materials integration on the technical, economic, environmental, and social aspects of a biorefinery. More studies are needed to increase knowledge about the possibility of mixing different biomass sources in a single process (Shrestha et al., 2022). Multi-feedstock biorefineries consider mixing/integrating two or more biomass sources to obtain a portfolio of value-added products (Acevedo-García et al., 2022). The advantages of a multi-feedstock biorefinery are related to (i) ensuring sufficient total raw material input to reach economic feasibility, (ii) diversifying the products portfolio since more value-added compounds and molecules can be produced, (iii) overcoming availability and seasonality issues, (iv) improve/strength the feedstock characteristics (e.g., carbon-to-nitrogen ratio, volatile matter-to-fixed carbon ratio), and (v) increase yields and productivities. Multi-feedstock biorefineries can be considered the next step towards establishing a bioeconomy since one of the most important limiting factors today is related to feedstock quantity and quality.

Biorefineries can be designed from existing plants (i.e., brownfield process) or as a new project (i.e., greenfield process). However, interest in the location of biorefineries has been growing as a concern that affects all the sustainability dimensions (i.e., economic, environmental, and social) (Pettersson and Harvey, 2013). Therefore, several criteria for

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https://doi.org/10.1016/j.biteb.2022.101318
Received 22 August 2022; Received in revised form 23 December 2022; Accepted 24 December 2022
Available online 30 December 2022

selecting and evaluating different biorefinery locations have been proposed (Sahoo et al., 2016). Moreover, the constraints may increase and influence the definition of the integration objective in the case of integrated biorefineries. An example of such criteria affecting the location of biorefineries is how close these facilities are to the feedstock sources to be used. Especially, when more than one feedstock is involved, logistical and geolocation problems may increase. The market for the products (distribution in strategic areas) is also an important factor in ensuring solid and stable marketing opportunities. Know-how can be an important factor to consider and limit the selection options (Serrano-Hernandez et al., 2017). The location analysis can be defined as finding the best location where the sustainability dimensions are not affected (Sharara et al., 2020). Geolocation studies are based on defining objectives for selecting the best location for processes (Razak et al., 2021). Economic or environmental objectives are the most commonly described in the open literature. These studies have reported results easy to measure and compare with each other. In economic terms, the selected objective may be to find the biorefinery location that generates the lowest logistical costs (i.e., related to transportation, purchase of equipment, employees, etc.). On the other hand, the location problem can be addressed to finding the best location with the lowest carbon footprint or emissions from transport activities (i.e., fuel use, operating cost, water use, and emissions). The location study based on the carbon footprint is an alternative to see the effect of the location on the sustainability of the biorefinery. The raw materials play a crucial role in this decision since this feedstock determines the starting points for raw material procurement. Thus, if different locations are proposed, the carbon footprint will be affected due to the distances and other possible constraints (e.g., fuel consumption caused by land topography) to ensure the processing of both raw materials.

Greenhouse gas (GHG) reduction potential is a clear objective when designing and analyzing biorefineries (Costa et al., 2020). The alternatives to promoting this concept are important and have been scarce. For instance, the implementation of a multi-feedstock biorefinery can help to promote socio-economic growth since these facilities give the opportunity to create new jobs, increase cash flow, and reduce wealth inequality (Burbano-Figueroa, 2019). The *Montes de María*, a region undergoing social and agroeconomic reconstruction, is a clear example of the potential for promoting the bioeconomy (Lissbrant et al., 2018). The availability of crops in the Montes de María region requires the proposal of multiple alternatives to improve the local conditions. The communities have strengthened alliances to attract governmental support and funding. This fact has encouraged boosting different value chains (e.g., avocado, plantain). In this region, several crops are grown. Plantain and avocados stand out as growing crops, and their importance for the sustainability of the community is very high (Arias et al., 2018; Poveda-Giraldo et al., 2021). However, crop residue management is null. Even, fruit losses have been registered since a large amount of agricultural products do not meet the quality requirements for marketing (Solarte-Toro et al., 2022). Therefore, alternatives for recovery will support the communities, the environment, and the consolidation of the peace agreement signed between the Colombian Government and partisans (Guerrilla) (Cardona et al., 2021).

This study aims to analyze the environmental life cycle assessment and potential locations of a multi-feedstock biorefinery in the Colombian context. This analysis was done by proposing a case study the rural zones of the Montes de Maria region in Colombia. Technical and environmental indicators were estimated to elucidate the biorefinery performance. For this, the proposed biorefinery is addressed to upgrade the plantain (*Musa Paradisiaca AAB Simmonds*) and avocado (*Persea Americana var Americana*) produced in the region. The technical performance was done by evaluating a series of mass indicators. The environmental performance was done by implementing the life cycle assessment methodology. An evaluation of logistic environmental impact was conducted considering the feedstock origin, multiple potential biorefinery locations in the study area, and three scenarios based on the product distribution (local, regional, and national). Travel times and distances were calculated through Google Maps Distance Matrix API for the carbon footprint and geographic accessibility measures (Cardona et al., 2021). The criterion for defining the best biorefinery location was based on the lowest carbon footprint and highest raw material accessibility. The document is structured in four sections. Initially, the introduction describes the study scope and establishes the objectives. Subsequently, the methodology includes the description of the study area, the biorefinery design, and the location methodology. Finally, the main results of the work are presented and discussed, as well as some recommendations and conclusions.

2. Methodology

The methodology is divided into four sections (i) avocado and plantain value chains description, (ii) avocado and plantain valorization through the biorefinery concept, (iii) biorefinery geolocation methodology, and (iv) environmental life cycle assessment (LCA). The first section explains the plantain and avocado value chains in the Montes de Maria region. The value chain description was focused on identifying links, actors, and flows. The second section describes the integrated avocado and plantain valorization pathway by applying the biorefinery concept. This valorization was addressed to produce marketable products. The raw materials chemical characterization (i.e., chemical composition, total and volatile solid) considered in this paper is described. The third section describes the geolocation methodology of the biorefinery, considering potential markets. Finally, the fourth section describes the life cycle assessment methodology to define the environmental performance of the proposed biorefinery and the possible potential markets.

2.1. Avocado and plantain value chain

The Montes de Maria region was considered as the study zone. Indeed, the Chalán (9°32′38″N 75°18′45″O) and Ovejas (9°31′33″N 75°13′38″O) municipalities were set as the centroid of the biorefinery project. These cities were fixed as centroid since both cities will provide the required amount of avocado and plantain.

The raw materials considered were plantain (*Musa paradisiaca, var. Dominico Hartón*) and avocado (*Persea Americana, var. Lorena*). Different links are involved in plantain and avocado value chains of the Montes de María. The value chain defined for the region and raw materials is presented in Fig. 1. Both value chains start with the Producers link (mainly small producers). The second link is the Raw materials Marketer, which includes the actors involved in raw materials collection centers. Subsequently, the Transformation link considers the value-added products derived from the plantain and avocado upgrading (i.e., multi-feedstock biorefinery). Finally, the Marketers link considers the distribution of the products. In each scenario, different distribution centres and percentages of products to be distributed are assumed. For scenario 1, 100 % of production is local to Sincelejo. Scenario 2 considers 50 % of production in Sincelejo and 50 % of production in Barranquilla (a port city near to the region). Finally, scenario 3 considers 20 % of product marketing in Sincelejo, 40 % of marketing in Barranquilla, and the remaining 40 % in Medellín (nearby capital city). The scenarios were stablished considering current agricultural commercialization routes. The selected cities are the most important consumers of the agricultural products of the Montes de Maria region (Solarte-Toro et al., 2022).

The processing scale (i.e., feedstock mass flow) of the proposed biorefinery was 133.92 t/month. Feedstock mass input flows were 111.6 tons/month and 23.32 tons/month of plantain and avocado, respectively. This feedstock requirement was supplied by the Montes de Maria region (i.e., Chalan and Ovejas). In this region, avocado and plantain crops are harvested in the same area. The tree distribution is 1111 plantain trees/ha and 180 avocado trees/ha. This crop distribution

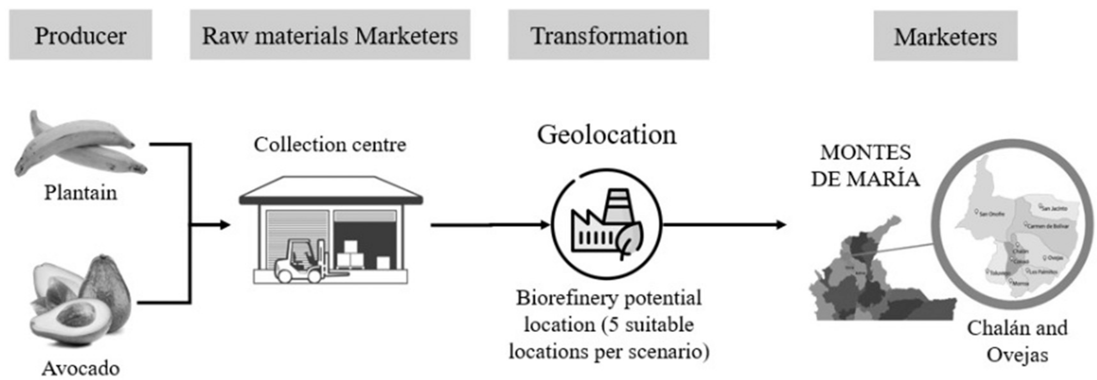

Fig. 1. Value chain of avocado and plantain in Montes de Maria region.

corresponds to 86 % plantain and 14 % avocado. The crop distribution also justifies mixing both agricultural products in the proposed biorefinery. Plantain crop has a productivity of 8.5 t/ha/y. On the other hand, the avocado crop has a productivity of 8 t/ha/y. Both crop productivities were retrieved from farmers interviews. 158 ha of plantain crops are required to satisfy the feedstock demand of the biorefinery. Moreover, 35 ha of the avocado crop is required to generate the established mass flow. The proposed plantain areas required to satisfy the biorefinery feedstock demand agree with the region harvested area in 2020. Indeed, the plantain and avocado crops in Chalán and Ovejas municipalities were 430 ha and 360 ha, respectively. Then, the proposed area can supply the raw materials needs considering the region reality.

2.2. *Multi-feedstock biorefinery based on avocado and plantain*

2.2.1. *Process overview*

The proposed multi-feedstock biorefinery for simultaneous plantain and avocado upgrading corresponds to a complex product-driven biorefinery. The block diagram is presented in Fig. 2. The scheme corresponds to a biorefinery focused on generating bio-based products (i.e., biomaterials, biochemicals, feed, and food). The residues produced after each processing line were used to satisfy a share of the energy demand.

2.2.2. *Raw materials characterization*

The chemical characterization for plantain and avocado were reported by Piedrahita-Rodriguez, (2020). This information was used to define the integration ratio of both raw materials. The integration ratio is the avocado and plantain biomass amount mixed to compose the raw material flow entering the biorefinery. The integration ratio is found after applying the raw materials integration methodology proposed by Piedrahita-Rodriguez, (2020). This methodology considers qualitative aspects of the raw materials based on the context. In this case, the biorefinery was addressed to integrate plantain residues (i.e., peel and pseudostem) and avocado residues (i.e., peel and seed). The selected integration ratio was 1:5 avocado to plantain (15.6 % of plantain peel, 67.7 % of plantain pseudostem, 4.6 % of avocado peel, and 12.1 % of exhausted avocado seed). The selected integration ratio was corroborated with the scale of raw materials available in the region.

2.3. *Biorefinery geolocation methodology*

The logistic analysis is addressed to find the best multi-feedstock biorefinery location based on the lowest carbon footprint given by raw materials and products transport. The best five suitable locations per scenario were evaluated to determine the best of it. Necessary data (see Fig. 3) to perform the study is related to i) feedstock production in the study zone, ii) Feedstock collection center location (point layer) defined by the authors considering agricultural production in the study zone, iii) urban areas (polygon layer) downloaded from *Marco Geoestadístico Nacional* of *Departamento Administrativo Nacional de Estadística (https://dane.gov.co)*, iv) Natural National Parks (polygon layer) obtained from *Sistema Nacional de Áreas Protegidas de Colombia (https://mapas.parquesnacionales.gov.co)*, v) rivers (line layer) obtained from *Instituto de Hidrología, Meteorología y Estudios Ambientales (https://www.ideam.gov.co)*, vi) road network (line layer) downloaded from Open Street Map (OSM), and vii) product distribution centres (point layer) defined by the authors.

To define the biorefinery potential location, four consecutive stages must be performed. These stages are described below:

a. Biorefinery location limit was defined as 150 km around the centroid of Chalán and Ovejas municipalities (linear radius) to keep the project social and economic benefits in the study zone due to characteristics as region affected by Colombian armed conflict.
b. Potential Biorefinery locations were disposed of through the road network using QGIS 3.16 software (QGIS, 2021). The road network

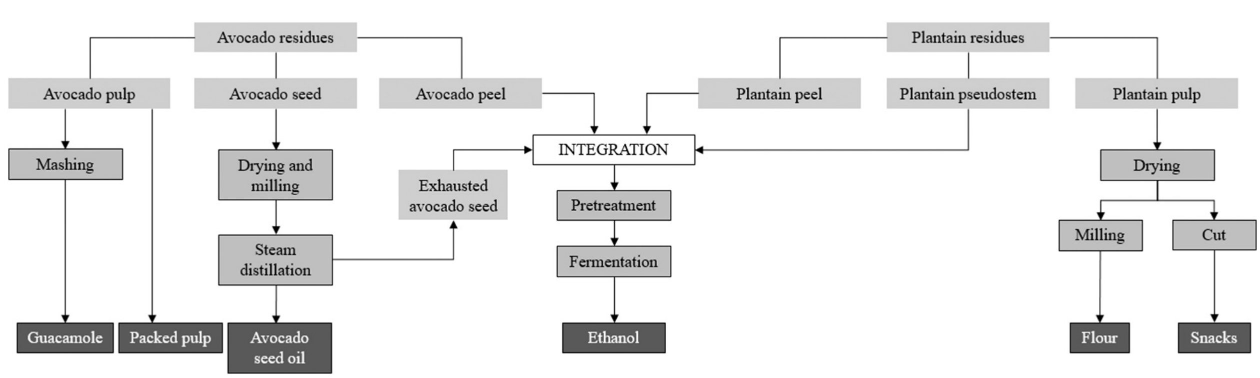

Fig. 2. Block diagram of the biorefinery proposed to improve the avocado and plantain value chain.

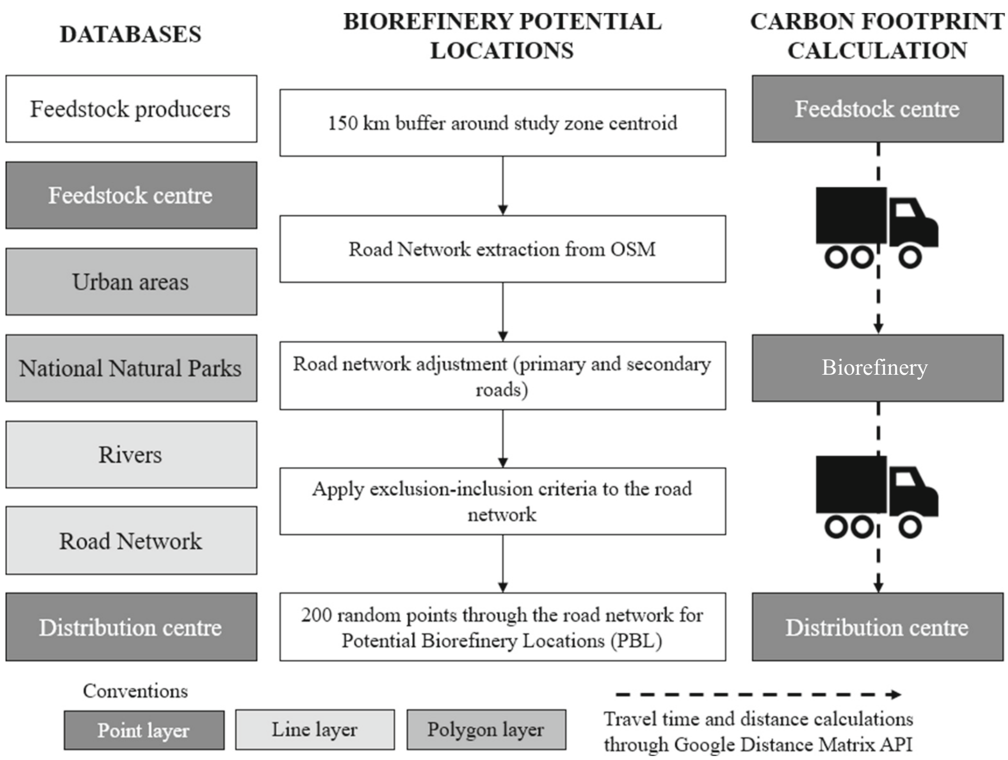

Fig. 3. Methodology applied for geolocation study.

layer was extracted using the 150 km circle buffer and the *QuikOSM* plugin from QGIS. This plugin allows downloading information from OSM, an open-source map service where people contribute to feed and validate the data (Bertolotto et al., 2020). In the last decade, OSM has been validated as a source for transport projects (Graser et al., 2014; Weiss et al., 2018) and planification (Srivastava et al., 2018). Then, the road network layer was processed in QGIS to maintain primary and secondary roads as feasible locations for biorefineries.

c. Exclusion-inclusion criteria were applied to the road network to obtain areas without restrictions to locate the plant (Sahoo et al., 2016; Costa et al., 2020). These criteria could be related to different factors such as environmental, economic, planning, social, among others. In this study, restrictions consider the urban areas (5 km around), hydrology (50 m around rivers), and Natural National Parks (5 km around protected areas) (Sahoo et al., 2016; Costa et al., 2020). Making a spatial intersection within the road network and restriction layers. A final layer was obtained where the potential plant could be located.

d. Finally, 200 random points were situated through the road network to simulate regional plant locations. A spatial separation of 5 km was chosen to limit aggregation around specific zones.

Three distribution (local, regional, and national) scenarios were analyzed. The local scenario measured the best biorefinery location when all the production was distributed to Sincelejo, the capital city of Sucre, the department where the feedstock center is located. The regional scenario considered an equal distribution between Sincelejo and Barranquilla, where an important maritime port is located. The national scenario considered Medellín as an extra distribution center (near Montes de María) where 40 % of the production is destinated, Barranquilla receives 40 %, and Sincelejo 20 %.

2.3.1. Best biorefinery location

The best biorefinery location corresponds to the location with the lowest carbon footprint in one year. The best five suitable locations per scenario were evaluated to find the best of it.

2.4. Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) was performed according to ISO 14040 methodology. Four stages were considered in this methodology: Goal and scope, Inventory, Evaluation, and Results interpretation. Each methodological stage considers different aspects and approaches.

The goal of LCA was to evaluate the value chain carbon footprint of a multi-feedstock biorefinery, considering the geolocation problem. Three scenarios were evaluated if the last stage of the plantain and avocado value chain (marketers) targeted local, regional, or national levels. The biorefinery proposed corresponds to a small-scale biorefinery focused on producing value-added products. The cradle-to-gate perspective was performed, applying an attributional analysis (Corona et al., 2018; Rodríguez et al., 2018). Finally, economic allocation was applied in this analysis.

The assessment considered the agronomic aspects of the raw materials (plantain and avocado). Fertilizers and other agrochemicals necessary for both crops were considered as inputs for each raw material crop. For this purpose, secondary data and regional producer interviews were used. The plantain and avocado crops links were defined according to the information provided by the communities in the region. The transformation link was structured through conceptual design, following the conceptual design methodology defined by (Cardona et al., 2016). The processing flow data was taken from the Colombian Ministry of Agriculture (Ministerio de Agricultura y Desarrollo Rural, 2022) and information from producers in Montes de María, specifically in the municipalities of Chalán and Ovejas. Fig. 4 shows the System boundary considered in the study. Each link of the plantain and avocado value chain towards the generation of biorefinery products and their distribution in the three proposed scenarios can be observed.

The functional unit used in the LCA corresponds to 1 kg of avocado seed oil since this product has a higher economic relevance. In the case of the agronomic stages and for inventory considerations for the plantain and avocado value chains, 35 and 158 ha of avocado and plantain were

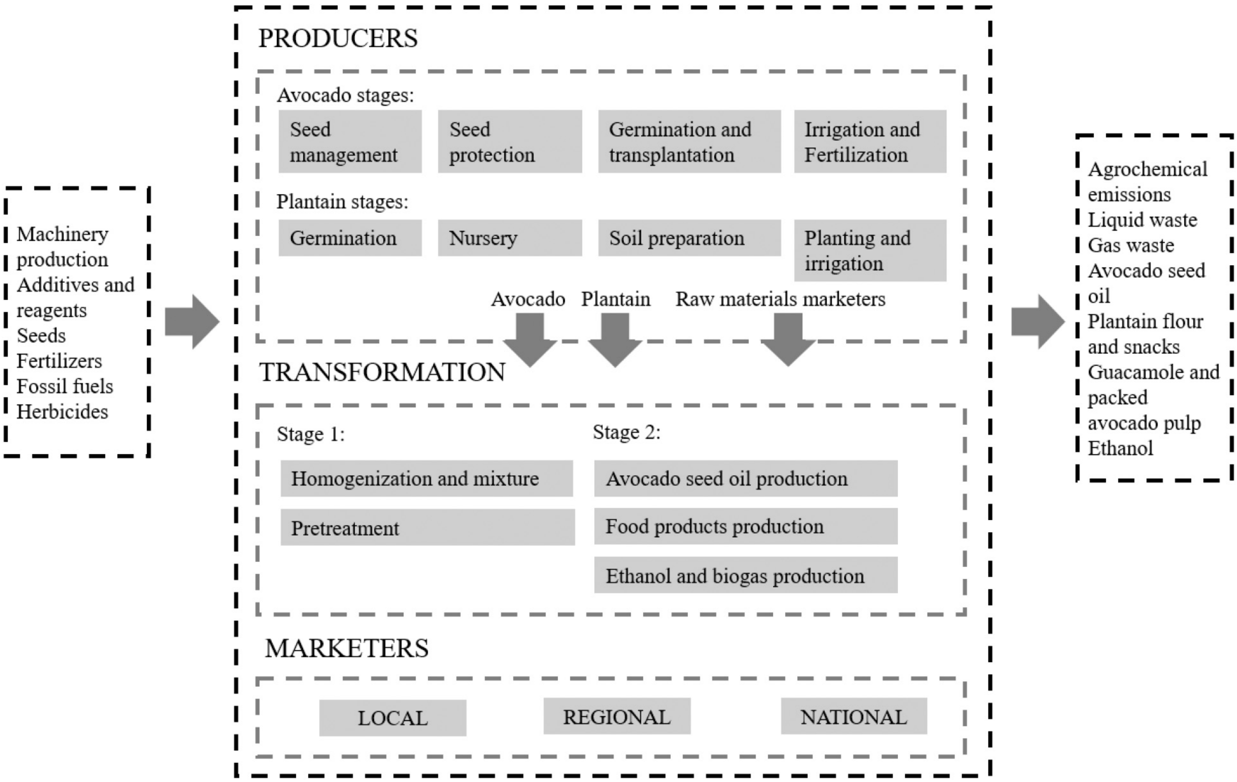

Fig. 4. System boundary for LCA.

assumed as the basis, respectively. Since the integration ratio of plantain and avocado remains constant in each scenario. The quantities of inputs for each agronomic stage of the plantain and avocado value chains are also shown in detail in Table 1:

The mass and energy balances of the avocado and plantain biorefinery were obtained in the simulation process. The Aspen Plus V9.0 commercial software (Aspen Technologies, Inc., EE) was used. Peng-Robinson and Non-Random-Two-Liquid (NRTL) were used as the thermodynamic models. The process begins with valorizing the independent fractions of each raw material.

The biorefinery with multiple raw materials was analyzed considering mass requirements based on simulation results. In this sense, the following mass indicators were calculated. The mass indicators (see Eqs. (1)–(2)) allow evaluation of the transformation potential of raw materials into biorefinery products (Ortiz-Sanchez et al., 2020):

(i) Product yield (Cardona et al., 2018):

$$Y_P = \frac{\dot{m}_{Product,i}}{\dot{m}_{Raw\ material}} \quad (1)$$

where $\dot{m}_{Product,i}$ is the mass flow of product i; and $\dot{m}_{Raw\ material}$ is the mass flow of raw materials.

(ii) Annual Productivity (Moncada et al., 2013):

$$P_P = \frac{M_p}{M_{Raw\ material} * Wp} \quad (2)$$

where M_p is the total mass flow of products; $M_{Raw\ material}$ is the total mass flow of raw materials; and Wp is the working period during a year.

The Carbon footprint (CF_i) of the products commercialization was calculated for every potential biorefinery location. For this, two stages were considered. The first stage is related to carbon footprint produced to transport the feedstock from the feedstock centre to the potential biorefinery location (CF_{fc-i}) while the second one is related to carbon footprint produced to transport biorefinery products from the location to the distribution centre (CF_{i-dc}).

$$CF_i = CF_{fc-i} + CF_{i-dc} \quad (3)$$

Carbon footprint (CF) (or emission rate in CO_2-eq kg/h or tonnes/year) is calculated following previous studies where fuel emission factors and fuel consumptions from transport logistics were considered (Small and Kazimi, 1995; Craig et al., 2008; Demir et al., 2011; Kurka et al., 2012) and summarized in the Eq. (4).

$$CF = EF^* A^* (1 - ER) \quad (4)$$

The emission factor (*EF*) is the variable for the chemical species emitted per unit process, and it is particular for each fuel type and can vary across countries and regions (Craig et al., 2008). In Colombia calculated and validated *EF* for different fuel types including CO_2, CH_4 and N_2O. On the other hand, the activity factor (*A*) considered transport variables such as fuel consumed, type of vehicle, and kilometres travelled, among others (Craig et al., 2008). To measure *A*, at first a type of vehicle must be chosen to obtain their capacity, fuel types, and fuel consumption. Secondly, the number of vehicles was calculated considering vehicle capacity, feedstock, and production (obtained by simulation procedure). Finally, distance within feedstock centres, potential biorefinery location, and distribution centres was measured using Google Distance Matrix API, which is a web-based trip planner used to estimate the shortest path within points considering different modes of transport and current or historical traffic data (Cardona et al., 2020; Lahoorpoor, 2020; Cardona et al., 2021; Hossain and Cooper, 2021). In this study, a standard type of vehicle was chosen considering their capacity (5 t), fuel type (Diesel with an EF of 10.15 $kgCO_2$ per gallon), and fuel consumed (24 km per gallon). The carbon footprints calculation was performed in Python 3.7. Consequently, information on the type of vehicle could be adapted by considering capacity, fuel type, and consumption. The carbon footprint of the process was estimated based on the energy consumption and the possible carbon dioxide emissions after

Table 1
Life cycle inventory of avocado and plantain crops considering the required crop hectares to supply the raw material requirements.

Stage	Compounds	Amount	Unit
Avocado crop (35 ha)			
Seed management	Seeds	525	–
	Water	140	L
Seed protection with fungicide	Seeds	35	kg
	Vitavax	350	g
	Water	35	L
	Benomyl	1750	g
	Water	35	L
	Captan	12,250	g
Sowing in the germinator	Base volume	35	m^3
	Base sand bulk	875	bulk
	Sowing volume required	11.69	m^3
	Sand bulk required	280	bulk
	Sand bulk weight	1400	kg
	Sand bulk weight required	11,690	kg
	Chicken manure	3507	kg
Transplant to bags	Bag	1277.9	g
Substrate for bags	Sand	364	kg
	Rice husk	364	kg
	Soil	477.75	kg
	Compost	259.35	kg
	Manure	182	kg
Substrate disinfection	Area	836.5	m^2
	Metansodium	385	g
	Water	5600	L
	Base area	350	m^2
	Basamid	15.75	kg
Irrigation	Time in bags	175	months
	Irrigation time	105	Every 3 days
	Amount of irrigations	1750	–
	Water per bag	35	L
Fertilization	Fertilization time	1050	Every 30 days
	Amount of fertilizations	175	–
	Water per application	3500	L
	Bayfolan by application	10.5	L
Plantain crop (158 ha)			
Germination	Wood	205,4	kg
	Camera (rice husk)	158	kg
	Plastic (high density)	7,9	kg
Nursery	Sodium hypochlorite	2844	kg
	Tiabendazol	6,32	kg
	Rise husk - bags	31,6	kg
	Poultry manure	118,5	kg
	Water	110,6	L
	Soil	0,316	kg
Soil preparation	Disc harrow	379,2	–
	Construction of drains (machinery)	0,158	–
	Fertilizer	0,158	kg
Planting and irrigation	Bags	101,12	kg
	String	63,2	kg
	Bamboo	3476	kg
	Karmex	0,948	g
	Benomyl	1896	g
	Citroline	15,8	kg
	Glyphosate	15,8	L
	Mancozeb	568,8	kg
	Phosphonitrate	101,12	kg
	Potassium sulfate	63,2	kg
	Compost + humus	3476	kg

the combustion process. The carbon footprint analysis of the biorefinery was done using the SimaPro software since this package can estimate the gasses emissions to air based on the type of fossil fuel and generation system.

LCA was analyzed using the SimaPro V. 8.3.0.0 software (Pre-Sustainability, Netherlands). The database used was EcoInvent V3.3. The ReCiPe Midpoint 1 (H-Hierarchism) method was applied. The mass and energy balances served as input data for this analysis, as well as the results from the geolocation study. This result corresponds to the stages of collection and distribution of raw materials as well as the distribution of products. The other stages are similar in each proposed scenario (crop and biorefinery). Finally, the results of this analysis will allow understanding that the integration of geolocation issue in LCA affects all the stages in the value chain of an integrated process.

The LCA results were analyzed for the three product distribution scenarios. Eight impact categories were evaluated for each scenario. Therefore, the analysis allows identifying the most relevant categories according to the proposed value chain scheme. The results were analyzed and compared with the carbon footprint calculation results, performed for the location study.

3. Results and discussions

3.1. Biorefinery simulation

The biorefinery with multiple raw materials, based on plantain and avocado residues for Montes de María, was designed to obtain guacamole, packed pulp, avocado seed oil, snacks, plantain flour, and ethanol. Table 2 shows the material and energy balances of each biorefinery processing unit. The processing units addressed to produce food (guacamole, packed pulp, snacks, and plantain flour) do not have steam and cooling water requirements. The absence of these utilities can be explained based on the type of process. Indeed, the generation of these food products is based on physical transformation processes of the raw material (grinding and cutting, frying), requiring only electricity.

The technical analysis determined indicators such as yield and productivity for each product. This information allows making comparisons with other results reported in the literature. The mass indicators were calculated using the material balances obtained in the process simulation. The product yield indicator highlights the amount of each product obtained in the biorefinery per kg of raw materials processed. Since this biorefinery integrates multiple feedstocks, this indicator can be expressed based on the mass sum of the processed feedstocks, assuming the concept of "global feedstock" (Piedrahita-Rodriguez, 2020).

The productivity indicator determines the possible amount of product to obtain for a given time with the conditions defined for the biorefinery. For this work, the results of this value are expressed per month.

In the case of avocado seed oil, a yield of 0.01 kg/kg of raw materials was achieved, and a productivity of 1.18 tons/month. As this product is obtained exclusively from avocado seed (i.e., there is no integration with other raw materials), this yield can be expressed per kg of avocado processed. Thus, the yield of avocado seed oil obtained is 0.05 kg/kg avocado. The steam distillation technique for avocado seed oil extraction has been little studied. (Shiferaw, 2019) reported that Hass avocado seed oil extraction yield by steam distillation is 0.07 kg/kg. Comparing other methods, such as solvent extraction, the yield obtained in the biorefinery is higher than that reported by Dagde (2019), obtaining a yield of 0.03 and 0.04 kg/kg avocado, respectively, using Soxhlet extraction with hexane. Since the processes are purely mechanical, the yield of food products does not vary considerably. The productivity obtained was 8.27 tons/month for products obtained from avocado pulp and 8.30 tons/month for products obtained from plantain pulp. These values correspond to the distribution of pulp present in both raw materials. About 74 % of all avocado corresponds to the pulp that is converted into products (García-Vargas et al., 2020). Besides, plantain pulp corresponds to 65 % of the fruit converted into products (this value depends directly on the ripening stage of the plantain) (Adi et al., 2019). Finally, in terms of ethanol produced in the biorefinery, a yield of 0.02 kg/kg raw materials was achieved, and a productivity of 2.20 tons/month. In this case, as the product is obtained from integrating raw materials, it is worth comparing with processes for obtaining ethanol from independent raw materials. It is done to establish whether the integration ratio proposed for the process benefits and increases

Table 2
Mass and energy balance of the multi-feedstock biorefinery.

Subsystem	Process	Input		Output		Electricity required	Steam required	Cooling water	Products	
		Material	kg/h	Material	kg/h	MJ/h	Flux (kg/h)	Flux (kg/h)	Material	Flux (kg/h)
Avocado seed oil	Steam distillation	Avocado seed	3.81	Waste water	6.53	67.41	451.53	336.34	Avocado seed oil	1.64
		Water	61.1	Steam	106.16					
Plantain flour	Milling and sieving	Plantain pulp	41.73	No waste		27	0	0	Plantain pulp flour	11.53
Guacamole	Pulp blend	Avocado pulp	11.14	Waste water	13.54	21.65	0	0	Guacamole	11.49
		Water	13.54	Ripened pulp	0.56					
		Additives	1.29							
Plantain snacks	Frying	Plantain pulp	41.73	Used palm oil	38.73	32.82	0	0	Plantain pulp snack	11.53
		Palm oil	387.25							
		Additives	0.27							
Avocado packed pulp	Cutting and slicing	Avocado pulp	11.14	Waste water	13.54	21.65	0	0	Avocado packed pulp	11.49
		Water	13.54	Ripened pulp	0.56					
		Additives	1.29							
Ethanol	Fermentation and distillation	Avocado peel	4.84	Calcium sulfate	3.48	105.69	746.92	652.74	Ethanol	3.05
		Plantain peel	44.94	Stillage	59.64					
		Plantain pseudostem	128.37	Carbon dioxide	5.87					
		Water	49.27	Solids	49.88					
		Enzyme	5.65							
		Sulfuric acid	28.49							

bioethanol yield. Sudhagar et al. (2018) reported bioethanol production from the plantain peel, achieving an overall yield of 0.01 kg/kg plantain peel. On the other hand, Woldu and Tsigie (2015) reported a yield of 0.03 kg/kg of avocado seed. Considering these results, the proposed biorefinery integrating plantain and avocado waste in the small-scale context proves to have better yields than processing only plantain. However, it is lower in terms of avocado seed processing. Nevertheless, in the proposed biorefinery, the avocado seed has already transformed to generate value-added products, such as avocado seed oil. This processing could cause the final composition of the seed to be reduced in available carbohydrates, as they could be solubilized in the steam distillation system, affecting the overall composition available for the fermentation stage. Additionally, the avocado variety used in the work of Woldu and Tsigie (2015) is different from that of the study region, so the initial raw material composition cannot be compared. These results confirm the importance of defining the objectives of feedstock integration in biorefinery design. These objectives can be purely technical in guaranteeing the integration of an overall feedstock composition that achieves higher yields than possible if each feedstock is processed independently. The productivity values obtained for the proposed biorefinery were used in the geolocation study to determine the type of vehicles needed (i.e., liquid or solid transportation), and the capacity.

3.2. Biorefinery location study

Fig. 4.A presents the road network under the 150 km buffer around Chalan and Ovejas centroid. The road network reaches a total length of 3530 km. Besides, restrictions layers are present. Firstly, the study zone covers 89 urban areas of 7 departments (Antioquia, Atlántico, Bolívar, Cesar, Córdoba, Magdalena, and Sucre) with an area of 55,600 ha. Secondly, Colombia has 59 Natural National Parks that preserve more than 17 million hectares. *Los Colorados* Natural National Park is in the study zone and covers 1000 ha. Thirdly, five rivers produced restrictions in the study zone, including the largest in the country river Magdalena, and Cauca. After applying the restrictions to the road network, 2152 km remain available to dispose the 200 random points of potential biorefinery location. Fig. 4.B shows distribution of travel times and distance between feedstock centre and potential biorefinery locations extracted from Google Distance Matrix API using their advanced services that consider congestion in real time. The average travel time and distance are 184 min and 153 km while the maximum are 373 min and 306 km. Both distributions have similar behavior and present an average speed of 48 km per hour.

Fig. 5 presents the average travel time and distance of the shortest path measured between the potential biorefinery locations and the three distribution centres (Sincelejo, Barranquilla, and Medellín). The average travel times vary from 286 to 484 min. The lowest average travel times are located at the west and south zone of the feedstock centre, while the locations with the highest average travel times are in the north part of the Antioquia department and the east part of the study zone. On the other hand, the average distance results are from 244 to 404 km while the location with the best access is around the feedstock centre while the highest ones are in the east part of the study region. This analysis shows a slight difference between travel time and distance because the Google Maps Distance Matrix API updated their conditions through road user data, consequently it could capture operation conditions in real-time.

Table 3 shows the carbon footprint calculation per scenario. The local scenario results in CO_2 emissions between 2.83 and 52.03 t per year while the regional scenario in CO_2 emission shows results between 5.97 and 57.61 t per year, and the national scenario in CO_2 emissions within 12.32 and 58.51 t per year. The analysis shows an increased behavior because of higher distances between the potential biorefinery locations to the distribution centres in Barranquilla and Medellin. Furthermore, locations with the lowest CO_2 emissions are near the feedstock centre because near to 70 % of the carbon footprint is produced during the transport from the feedstock centre to the potential biorefinery locations. The bottom part of Fig. 6 presents the best five potential locations per scenario. Locations are identical in the regional and national scenario while three of those points are equal in the local scenario. The best location is 7.5 km at the north of Chalán municipality. It is the nearest point to the feedstock centre. This point is the best option in all the scenarios studied.

3.3. Environmental analysis

In terms of Carbon footprint, Table 3 shows the equivalent CO_2

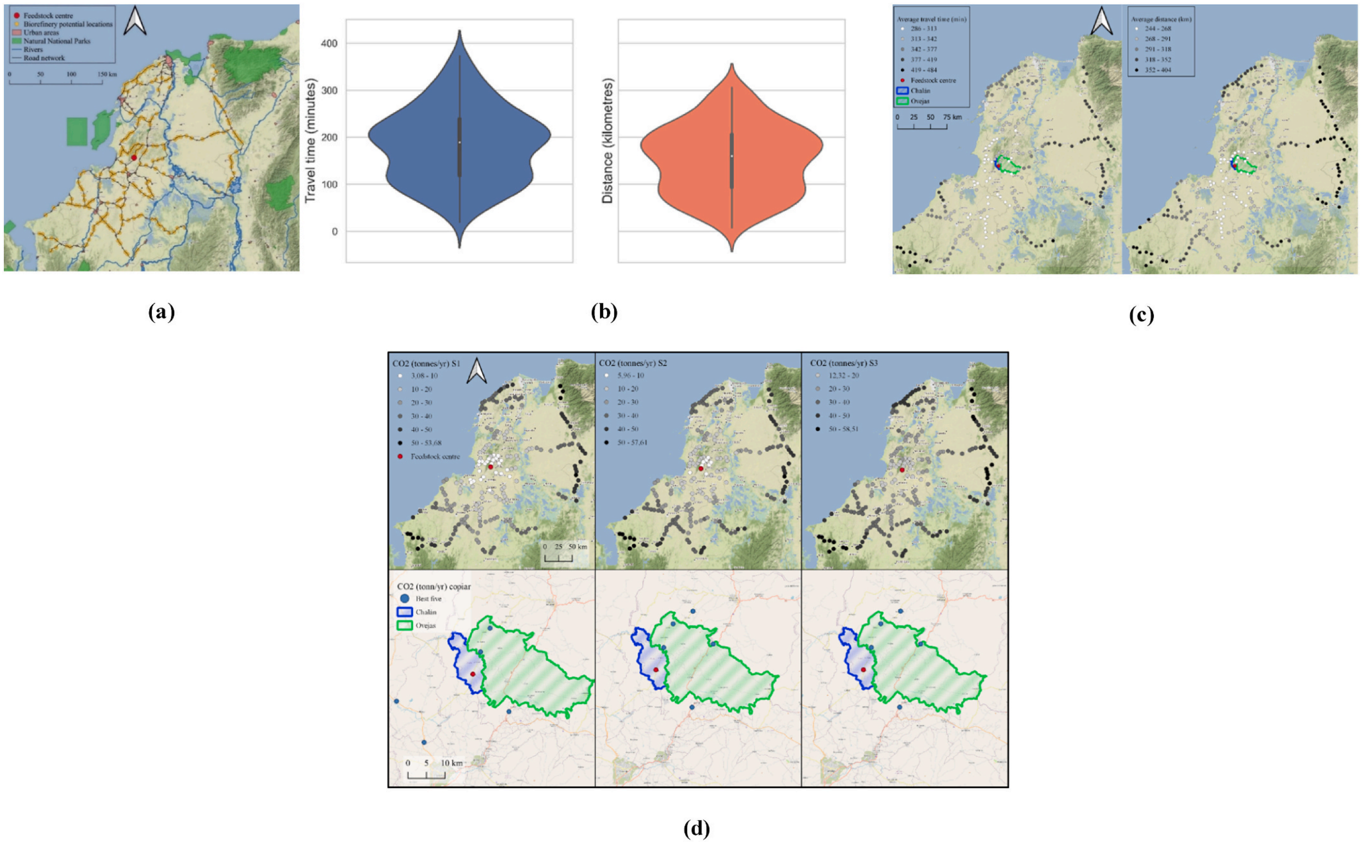

Fig. 5. (a) Geographical data; (b) Travel time and distance distribution between feedstocks centre and potential biorefinery locations; (c) On top carbon footprint; (d) Below the best five potential biorefinery locations. Analysis per scenario: local (left), regional (centre), and national (right).

Table 3
Environmental results for cradle-to-gate scheme for each scenario.

Impact category	Units	Scenario 1 (local)	Scenario 2 (regional)	Scenario 3 (national)
Global warming	kg CO_2-eq	2.67	5.11	10.49
Terrestrial acidification	kg SO_2-eq	0.42×10^{-3}	0.43×10^{-3}	0.45×10^{-3}
Human toxicity	kg 1.4-dB-eq	0.022	0.022	0.023
Photochemical oxidant formation	kg NMVOC	0.33×10^{-3}	0.33×10^{-3}	0.34×10^{-3}
Particulate matter formation	kg PM10-eq	0.15×10^{-3}	0.18×10^{-3}	0.21×10^{-3}
Freshwater ecotoxicity	kg 1.4-dB-eq	0.43×10^{-3}	0.51×10^{-3}	0.63×10^{-3}
Agricultural land occupation	m^2a	68.10	79.15	94.52
Water depletion	m^3	4.98	6.79	10.01
Fossil depletion	kg oil-eq	25.13	34.59	48.02

Scenario	Carbon footprint	Carbon emissions per functional unit of LCA
1. Local distribution	3.08 t CO_2-eq/year	0.11 kg CO_2-eq/Avocado seed oil
2. Regional distribution	5.97 t CO_2-eq/year	0.20 kg CO_2-eq/Avocado seed oil
3. National distribution	12.32 t CO_2-eq/year	0.42 kg CO_2-eq/Avocado seed oil

emissions (tonnes/yr) for the best potential biorefinery location considering transportation. The national distribution scenario registers the highest emissions rate because distances are larger than scenarios 1 and 2. On the other hand, the best location is the same for all the scenarios analyzed consequently, the biorefinery could implement a logistic program for distribution in several municipalities keeping their transport carbon footprint to a minimum.

Keeping the scale fixed, the distribution in terms of maximum radius increases from local to national. Although the distribution increases the impact of carbon footprint, all these values should be considered with caution. They are only valid to decide if the market that is handled locally is sufficient to supply the production scale. Otherwise, these results would be useless because they only focus on the environmental part, forgetting the economic dimension.

Given the above, what is important in these results is the possibility of considering how the growth of the distribution of the products of a biorefinery based on raw materials of rural origin impacts the environmental component. It is vital to understand how biorefineries, in a general concept of the value chain, can be designed with great efficiency and reduce the Carbon footprint. However, factors outside the biorefinery design can decompensate (up to 4 times more) the low impacts achieved by a good design.

The inclusion of constraints and limitations zones are an intrinsic step in spatial analysis for location problems (Sahoo et al., 2016). Constraints related to water bodies, National Natural Parks, and urban zones were included considering the available data meanwhile, the buffer around the study area were defined regarding the economics and social benefits that will bring the biorefinery construction to the study zone, a highly impacted area by Colombian armed conflict. It is important to invest in those municipalities to strengthen the peace (Cardona et al., 2021). The number of potential biorefinery locations evaluated were defined contemplating access constraints to free services Google Maps Distance Matrix Api (Cardona et al., 2021). The best biorefinery potential locations were optimized considering the lowest carbon footprint emissions. Besides, the calculations considering travel time and distance in the distinct stages consequently a geographic accessibility evaluation was conducted showing a relationship between the lowest carbon footprint and the highest accessibility conditions (Cardona et al., 2021).

Regarding the LCA results, the values of the environmental impact categories for the biorefinery scenarios are shown in Table 3. For scenario 2 and 3, a high value of CO_{2}_eq can be observed, which could be responsible for the warming and acidification of the ocean (Connell et al., 2013). This behavior also increases the amount of H^+, contributing to reducing pH in the water source. Biotechnological processes are characterized by extensive water use for their different process stages. Besides, the agronomic stage also impacts in this category. The national distribution scenario registers the highest emissions rate because distances are larger than scenarios 1 and 2. On the other hand, the best location is the same for all the scenarios analyzed consequently, the biorefinery could implement a logistic program for distribution in several municipalities keeping their transport carbon footprint to a minimum.

Comparing both analyses, it is possible to show that the tendency to define the scenario with the most negative impact in terms of carbon footprint is maintained. However, considering all the links in the value chains as a whole, it is possible to understand how each link contributes environmentally. In all cases, the Transformers and Marketers links are the most relevant in the results of emissions to air, soil, and water. It is important to emphasize that the location analysis should be permanently linked to the LCA analysis to integrate all the links in the value chains and consider their impacts.

4. Recommendations

The potential location is a constant question in terms of bioprocess design. This issue is approached from different aspects (technical, logistical, environmental, economic, among others). Some limitations of the study are related to the available data, especially to define exclusion zones. Besides, the access to Google Maps Distance Matrix Api is limited for analyzing the combination of feedstocks centres, potential biorefinery locations, and distribution centres. Nevertheless, this work had some assumptions that are worth mentioning. Initially, this conceptual analysis elucidates the basic considerations to the evaluation of the location of a biorefinery. Besides, it allowed finding the relationship of these considerations with environmental factors such as the carbon footprint. However, for the analysis to be much deeper and closer, the infrastructure restrictions of the area in question must be considered. Post-conflict zones are limited regions in several aspects related to access and interconnection. It is important to continue making progress in this area and to include more precise variables to strengthen the location analysis. At the same time, this type of studies could demonstrate the required potential to attract the government and private sector for invert more in the infrastructure of these regions.

5. Limitations and future scope

The study limitations of the proposed multi-feedstock biorefinery can be divided into two key aspects (i) environmental assessment and (ii) greenfield process for upgrading agricultural residues. The methodology for estimating the carbon dioxide emission in the transport process can be improved since specific variables such as the engine type, vehicle type, and fuel demand in a hill are not considered. Indeed, these variables can help to make a more accurate estimation of greenhouse gas emissions than those estimated by the emissions factor method. Regarding the greenfield multi-feedstock biorefinery, a product screening should be done to contextualize those with high potential to improve the region's socio-economic development. Then, market analysis should be involved to have a better understanding of the region. The future scope of the study should be addressed to involve economic and social aspects. Indeed, an integral assessment of the sustainability of the proposed biorefinery should be done to find the best location. However, it is expected that any new products configurations should affect the environmental assessment, based not only on processing emissions but also on the distribution and marketing requirement.

6. Conclusions

In this work, the technical and environmental evaluation of a multi-feedstock biorefinery in rural areas in Colombia was made. Moreover, an analysis of the best location of the biorefinery was assessed to ensure a good economic performance. The proposed multi-feedstock biorefinery presented a good technical performance since most of the avocado and plantain residues were upgraded into a series of value-added products with commercial value. The environmental performance of the process is better when proposing near feedstock collection and product distribution points to the biorefinery. Indeed, the best location of the multi-feedstock biorefinery is near to the avocado and plantain residues production and marketable products commercialization. The commercialization stage was identified as the most contributing factor for the CO_2 generation in the proposed value chain with a 60 %-72 % of the total CO_2 emissions. This study allows understanding the minimum requirements for defining industrial process locations integrating context aspects. At the same time, in rural zones, where the transformation infrastructure is very limited, it is expected a big influence of this factor on the fuel costs and environmental performance of the proposed biorefinery. Then, this type of analysis could be a key factor to ensure a successful project to be implemented in these zones, where different feedstocks are required and the raw material location can be different.

CRediT authorship contribution statement

Sara Piedrahita Rodríguez, Santiago Cardona Urrea: Conceptualization, calculations, modeling, writing and revising-.

Diego Alexander Escobar García, Carlos Ariel Cardona: Revising.

Mariana Ortiz-Sánchez, Juan Camilo Solarte-Toro: Modeling and English revising.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Carlos Ariel Cardona Alzate reports financial support was provided by Colombia Ministry of Science Technology and Innovation.

Data availability

Data will be made available on request.

Acknowledgements

The authors express their gratitude for the financial support given by the program: PROGRAMA DE INVESTIGACIÓN RECONSTRUCCIÓN DEL TEJIDO SOCIAL EN ZONAS DE POS-CONFLICTO EN COLOMBIA SIGP Code: 57579 within the research project "COMPETENCIAS EMPRESARIALES Y DE INNOVACIÓN PARA EL DESARROLLO ECONÓMICO Y LA INCLUSIÓN PRODUCTIVA DE LAS REGIONES AFECTADAS POR EL CONFLICTO COLOMBIANO" SIGP Code: 58907. Funded within the framework of Colombia Científica, Contract No FP44842-213-2018. Besides, to the Research group Movilidad Sostenible (GIMS) of the Universidad Nacional de Colombia – Manizales.

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