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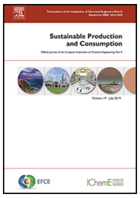

Review article

Prospectives for the development of a circular bioeconomy around the banana value chain

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ABSTRACT

Bananas are one of the most widely consumed crops globally. However, this industry generates a large amount of residual biomass that is currently undervalued. The disposal of banana residues creates an environmental issue. A circular economy is an economic system characterized by minimizing virgin resources extraction and waste disposal to the environment. The bioeconomy is the production of renewable biological resources and the conversion of these resources and waste streams into value-added products. This study has two main aims: (i) to perform a literature review to describe the state-of-the-art regarding the obtention of non-food bioproducts derived from banana residues, and (ii) to propose an envisioned circular bioeconomy around the banana value chain with a focus on closing the loop for material and energy self-sufficiency. This review has made it possible to explore recent advances in the use of residual banana biomass as raw material for obtaining compounds of interest through biologically-based processes and focused on the concept of biorefinery. Likewise, it has been determined that aerobic fermentation is the widely investigated strategy for the production of bioenergy from banana residues, in addition, techno-economic analysis studies indicate that the use of biorefineries are sustainable and economically viable as long as more than one compound of industrial interest is obtained. However, the commitment of stakeholders is crucial to overcome the barriers to a transition from a linear economy to a circular economy. A circular bioeconomy around the banana value chain was depicted, in which the residual banana biomass could cover the energy requirements of primary production at least. Technical feasibility is only one side of the coin; the innovation potential of the system has other barriers associated with economic and cultural issues that must be overcome.

1. Introduction

1.1. The banana value chain, sustainability, and circular economy

Bananas and plantains are among the top ten crops regarding production worldwide (FAO, 2015). In 2018, the world banana production and total planted area were 115,7Mt and 5,7Mha, respectively (FAO, 2019a). World banana production and the harvested area had increased between 2000 and 2017 by 3,2% and 4,6%, respectively (FAO, 2019b). This growth in world production has generated income and employment for millions of households. The main producing countries are India (30,46 Mt), China (11,65 Mt), Indonesia (7,28 Mt), Brazil (6,81 Mt), and Ecuador (6, 58 Mt) (FAOSTAT, 2019). Banana exports contribute to Gross Domestic Product (GDP), as is the case of Ecuador (1,91%) (Corporación Financiera Nacional, 2020), Costa Rica (2%) (CORBANA, 2020), Guatemala (1,05%) (BANGUAT, 2016). However, agricultural production causes negative impacts on soil, air, and water resources (FAO, 2017; Spiertz, 2010). Agriculture is estimated to be responsible for 21% of greenhouse gas (GHG) emissions (FAO, 2015).

Currently, Climate Change is the main threat to sustainability (Brando et al., 2013; Okoko et al., 2017). Climate change is a consequence of the emission of GHG from anthropogenic activities (Clay and Zimmerer, 2020; Solomon et al., 2015; Spiertz, 2010). These emissions are estimated to come mainly from tillage practices, fossil fuel use, fertilizers production, fertilized agricultural

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soils, farm animal manure, and crop residue burning (N. Jain et al., 2014; Kaushal and Prashar, 2020; Praveen and Sharma, 2019). Climate change is likely to affect agriculture negatively by increasing extreme weather events, floods and droughts, modifying production and trade patterns globally (Calzadilla et al., 2013; Manuel et al., 2021; Sultan and Gaetani, 2016; D. Wang et al., 2021). According to Varma & Bebber (2019), Climate change has not affected world banana productivity; however, it could be different in the future, decreasing the production of this food due to extreme changes in the climate. In addition to an increase in the incidence of pest and diseases in the banana crop (Bebber, 2019; Mata et al., 2020). These changes would affect the nutritional diversity, security, and economy of the main producing countries. Furthermore, the supply of bananas to non-producing countries is an essential contributor to dietary diversity that must be ensured.

Governments worldwide have been working on political and economic instruments to address environmental issues (Ahmed and others, 2013; Duque-Acevedo et al., 2020; Egea et al., 2018). Since 1992, based on the Rio Declaration on Environment and Development, models based on sustainable development have been structured, integrating social, economic, and environmental factors. In 2015, the new Agenda for Sustainable Development 2030 was approved, establishing 17 sustainable development goals (SDG) (FAO, 2017b; United Nations, 2015b, 2015a). However, according to the 2019 United Nations report, the measures adopted to date have not made satisfactory progress in achieving these SDGs (United Nations, 2019a, 2019b). The European Union has begun to materialize this challenge through a regulation and management instrument called the Europe 2020 Strategy. The objective is to guarantee smart, sustainable, and inclusive growth for Europe (European Commission, 2014, 2015b). This general framework established the guidelines for elaborating strategies such as the Circular Economy (CE) and the Bioeconomy (European Commission, 2015b). The CE includes all types of processes in which the value of products, materials, and resources is kept in the economy for as long as possible, and the generation of waste is reduced to a minimum (European Commission, 2015). Bioeconomy can be defined as the "production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy"(European Commission, 2012). The "Circular Bioeconomy" is defined as the intersection of these two economic models (Carus and Dammer, 2018).

According to Duque-Acevedo et al. (2020), the CE and the bioeconomy contribute significantly to the achievement of four SDGs. Specifically, SDG 2: "Ending hunger, achieving food security and improving nutrition, and promoting sustainable agriculture"; SDG 11: "Making cities and human settlements inclusive, safe, resilient and sustainable"; SDG 12: "Ensuring sustainable consumption and production patterns," and SDG 13: "Taking urgent action to combat climate change and its impacts."

Sustainable agriculture requires adopting the principles and concepts on which the Circular Economy (European Commission, 2015b) and bioeconomy are based (Ortega-Pacheco et al., 2021; Stegmann et al., 2020). This approach implies using agricultural waste as a raw material for production systems (Wietschel et al., 2019). The underlying idea is to transform an unavoidable by-product of one production system into a resource for a second production system (D'Amato et al., 2017). Using the waste generated from the agricultural sector is an effective way to reduce GHG emissions and improve the performance of agricultural systems (Xian et al., 2020). However, the implementation of a circular model in agriculture is still under development, and at the moment, there are only proposals to achieve the transition from a linear model to a more circular model (Chojnacka et al., 2020; Kapoor et al., 2020; Velasco-Muñoz et al., 2021). In this context, biorefineries are an essential factor in the transition to a circular economy and bioeconomy (Ubando et al., 2020), because they allow the conversion of biomass from one product to multiple products in a similar way as in oil refineries where a single feedstock is used in equipment with high processing capacity to achieve maximum economics of scale (Ball et al., 2018; Wietschel et al., 2019). Biorefineries represent a promising approach as long as they are sustainable, eco-efficient, and competitive (Cristobal-Sarramian and Atzmuller, 2018; Ioannidou et al., 2020). Implementing biorefinery projects requires techno-economic analysis (TEA) to estimate the cost-benefit of producing at different scales, technology, and scenarios (Lauer, 2019). Since sustainability has three dimensions, the environment, society and economic prosperity, it is usual to comprehensively evaluate the use of biorefineries by combining TEA with life cycle assessment (LCA) (Duque et al., 2015; Hill et al., 2006; Hossain et al., 2019; Martínez-Ruano et al., 2018). LCA is a quantitative analysis tool to describe the environmental performance of a product or system standardized by standards ISO 14,040 (ISO, 2006). Furthermore, it is widely accepted by the scientific community because it analyzes the inputs and outputs of a production system, providing an objective basis for comparisons (Fitzgerald et al., 2021; Meier et al., 2015; Vaneeckhaute et al., 2018; Vatsanidou et al., 2020). Therefore, it allows to analyze the environmental performance of bioproducts obtained from agricultural residues (Boschiero et al., 2016; Ginni et al., 2021).

Agricultural residues can be of two types: (i) lignocellulosic: those whose main components are hemicellulose, cellulose, and lignin such as the wheat straw, the corn fiber, the straw of corn, the artificial grass, the rachis of the banana tree, leaves (Costa et al., 2018b; Gabhane et al., 2014; Luo et al., 2010), and (ii) Non-lignocellulosic or amylaceous material, whose main composition may be starch, pectins such as the fruit of rejection or fruit peel (Anastopoulos et al., 2019; Velásquez-Arredondo et al., 2010; Wadhwa et al., 2015). For agricultural waste to be considered a resource for biorefineries, some factors must be considered, such as bioavailability and biochemical composition (Egea et al., 2018; Kamm and Kamm, 2004).

The United States, India, and China are the countries with the most studies on the use of agricultural residues, mainly from wheat and corn crops, since they are the leading producers (Duque-Acevedo et al., 2020). Recent research on the valorization of agrifood residues includes its use as (i) raw material for the production of value-added food (Eriksson et al., 2021; Gómez-García et al., 2021), or (ii) source of carbon during the fermentation stage in bio-based processes (Bartek et al., 2021; Sanchez et al., 2020), in this sense, agricultural residues and food waste can be bioconverted, through biorefineries, into (i) energy such as bioethanol, biofuel and biogas (Calvin et al., 2021; Mboumboue and Njomo, 2018; Popp et al., 2014; Venkata Mohan et al., 2016) and (ii) compounds of interest as lactic acid, polyhydroxybutyrate (PHB), Bacterial nanocellulose (BNC), biofertilizers, biostimulants and biopolymers (Cristobal-Sarramian and Atzmuller, 2018; Fiallos-Cárdenas et al., 2021; Martínez-Trujillo et al., 2020; Naranjo et al., 2014; Teigiserova et al., 2019; Tsachidou et al., 2021), which allow the reduction or substitution of the use of synthetic compounds in agricultural systems, facilitating the transition towards sustainable circular models (Puglia et al., 2021; Rashid and Shahzad, 2021; Sadhukhan et al., 2020). Likewise, green technologies make it possible to recover value-added molecules from agro-industrial food by-products, allowing their reincorporation into the food supply chain under the concept of circular bioeconomy (Chimphango et al., 2020; Eriksson et al., 2021; Gómez-García et al., 2021). In this context, the importance of LCA and TEA to increase the sustainability of these bioproducts is highlighted (Bartek et al., 2021; Eriksson et al., 2021; Ginni et al., 2021; A. Jain et al., 2022; Rashid and Shahzad, 2021;

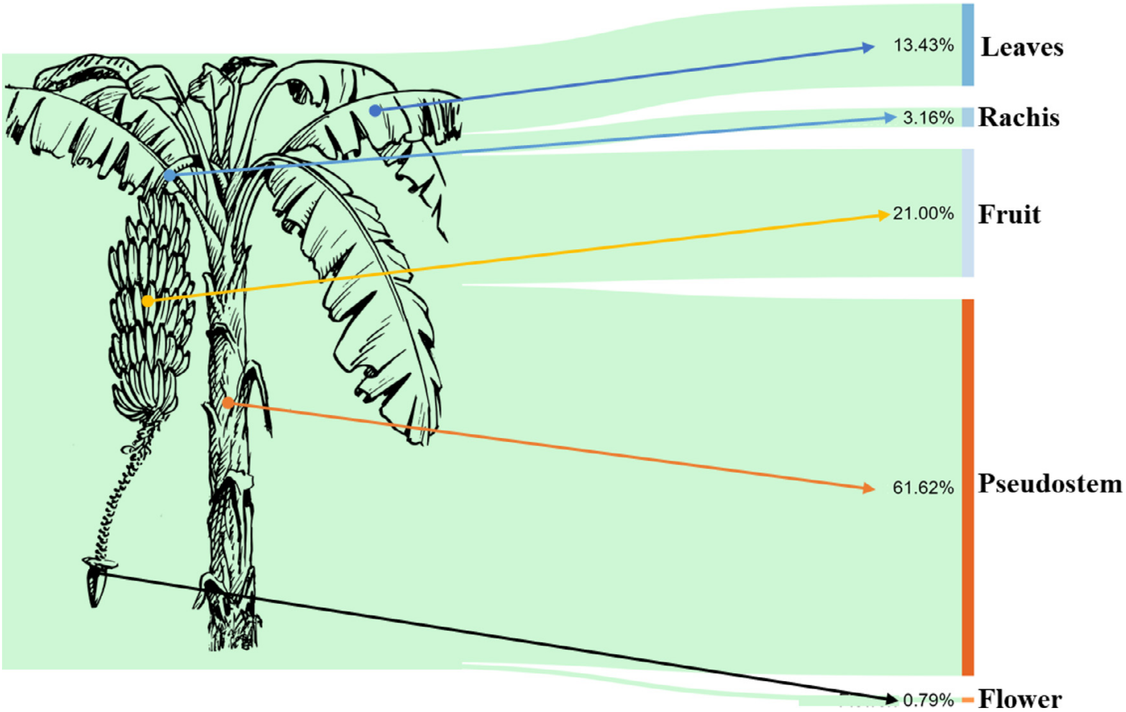

Fig. 1. Average contribution of above ground biomass to the total fresh weight of a banana plant. Adapted from (Ortiz-Ulloa et al., 2020).

Teigiserova et al., 2019). The recovery of agricultural residues and food waste shows promising environmental and economic results (Barros et al., 2020; Eriksson et al., 2021; Ginni et al., 2021; A. Jain et al., 2022; Mishra et al., 2019; Ubando et al., 2020), consistent with some of the SDGs (Barros et al., 2020; Gawel et al., 2019; Sadhukhan et al., 2020; Teigiserova et al., 2019).

1.2. The banana production system and the use of residual biomass

Banana is a plant belonging to the *Musaceae* family considered a perennial crop widely cultivated in tropical and subtropical regions worldwide (Iriarte et al., 2014; Ortiz-Ulloa et al., 2020; Varma and Bebber, 2019). Fig. 1 shows part of the morphology and the average contribution of surface biomass and fruit to the total fresh weight of the banana plant. Regarding the surface biomass of the banana tree, the pseudostem has a greater contribution in terms of total fresh weight. Once the bananas have reached maturity, they are harvested, and the banana leaves and pseudostems are used as raw materials. As a rule, the leaves and pseudotalli are left on the ground for decomposition by fauna and soil microorganisms (Abdullah et al., 2013; Oliveira et al., 2007). This and other practices used in waste management, such as incineration, and landfill disposal are not considered sustainable or environmentally friendly strategies (D'amato et al., 2010; Gómez-García et al., 2021). The harvested bananas are transported to the handling and packaging facilities, usually located on the farm, separated from the rachis, washed, and graded according to their physical and quality characteristics. The sorted fruit is packaged in cardboard boxes and protected with plastic sleeves. The banana rachis is generally discarded, which can have several destinies.

Ecuador is the main exporter of bananas worldwide and it is estimated that the residue / product ratio in banana cultivation is 3.79 and generates approximately 2.65 Mt / year of residues on a dry basis (Ortiz-Ulloa et al., 2020). and 4.92 Mt / year of residues in fresh weight (Correa et al., 2014). It is estimated that banana cultivation in India, the main producer worldwide, generates approximately 220 t/ha of plant waste, mainly lignocellulosic biomass such as pseudostem, leaves, and rachis (Shah et al., 2005). The volume and relatively concentrated location of residual banana biomass generated in producing countries make it a potential source of feedstock for biorefineries.

Pathak et al. (2016), studied the feasibility of using banana peel as a raw material for the synthesis of nanomaterials. Also, as a substrate in the production of biofertilizers, bioenergy, industrial enzymes, animal feed, and dietary fibres. In addition, they proposed a biorefinery scheme based on this residue alone. The researchers determined that the availability of banana peel and the selective separation of the compounds of interest are the main problem. Redondo-Gómez et al. (2020), reviewed the possibility of generating biopolymers, energy and products for water treatment, from the residual banana biomass through the use of biorefineries. Kraithong & Issara (2021), analyzed the biological potential of banana peel and flowers for the development of new food products. Acevedo et al. (2021), examined the potential of obtaining different compounds of interest, such as biofuel, biopolymers, fertilizers, cellulose, silver nanoparticles, nanofertilizers and nanocellulose, from banana residues such as leaf, pseudostems, rachis, and peel. They indicated that the valorization of residual biomass can contribute to the circular economy growth in Latin America and countries with emerging economies. El Barnossi et al. (2021), discussed the use of banana, tangerin, and pomegranate peels to produce fertilizers, animal feed, compost and bioadsorbents. They also analyzed the valorization of these wastes to obtain value-added products with potential use in the food, medical and cosmetic industries. In addition, they examined the use of these shells for bioenergy production. They also discussed the valorization of microorganisms isolated from these wastes and which are of medical, agronomic, and industrial interest. In conclusion, it was determined that the valorization of these husks in different fields of application requires further studies to achieve more efficient and truly sustainable processes. Uchôa et al. (2021) evaluated the production of ethanol from banana pulp, peel, and pseudostem, simultaneously. In addition, they conducted an economic analysis for scaling up a future biorefinery plant in a Brazilian municipality, de-

Table 1

Inclusion and exclusion criteria for literature selection from 2013 to 2021 on Scopus search engine.

Thema	Objective of review	Inclusion Criteria	N° selected documents [c]
Valorization of the residual banana biomass	To identify and describe different operation bioprocesses and their alternatives to valorize the residual lignocellulosic biomass to obtain different bioproducts and bioenergy will be described	banana peel/ banana rachis/ banana leaf/ banana pseudostem/ bioproducts/ ethanol/ biofuels/ organic acids [a] Those considered unrelated to this research or not indicating the yield of the process were discarded.	65 / 52 / 13
Techno-economic analysis of banana	To identify techno-economic benefits of bioproducts obtained from the residual lignocellulosic biomass	techno-economic/ banana / analysis [a]	3 / 3 / 3
Environmental impact of the banana value chain	To describe the environmental impact generated in the banana value chain.	banana sustainability assessment/ banana carbon footprint/ banana life cycle analysis [b] Only those analyzing the environmental impact on banana crops or the valorization of residual banana biomass were left.	55 / 39 / 15
Barriers fot the transition to a circular bioeconomy	Analyze the barriers to transition to a circular economy model.	"Circular bioeconomy"/ Circular-bioeconomy transitions/ Circular-bioeconomy barrier/ Circular-bioeconomy agriculture/ Development bioeconomy / agriculture waste[b].	43 / 20 / 10

[a] These phrases were applied with the "AND" operator.

[b] These phrases were applied with the "OR" operator.

[c] N° encountered documents/ N° selected scientific articles/ N° relevant to theme scientific articles.

termining that cogeneration of energy is necessary for the project to be viable. These studies demonstrated the feasibility of valuing the residual biomass generated in the banana production system. However, a "closing the loop" strategy in the banana production system has not been studied, which is a crucial circular strategy (Hobson, 2016; Tomić and Schneider, 2018; Zabaniotou et al., 2015). Circularity in biosystems usually involves the valorization of one system's by-product to be used in other systems (Tomić and Schneider, 2018)

"Closing the loop" is a circular approach in which materials, components and products of a system are recovered for reuse, recycling or reclamation (Bourguignon, 2016; Giampietro, 2019; Tomić and Schneider, 2018). However, this approach has often been studied for systems based on technical materials systems (Bourguignon, 2016; Hahladakis and Iacovidou, 2018; Morseletto, 2020), but not for biosystems. This approach could allow the integral management of lignocellulosic residues generated in the banana production system, for its subsequent recovery and reincorporation into the production system, replacing or reducing the use of chemical synthesis inputs.

This study has two main aims: to describe the state-of-the-art regarding the obtention of non-food bioproducts derived from banana residues and to propose an envisioned circular bioeconomy around the banana value chain using a "closing the loop" strategy. The former is accomplished by performing a literature review (i) to analyze information on the stages, operations, and yields of the different bio-based bioproducts obtained from the valorization of banana residues, (ii) to examine cases of techno-economic analysis of bio-based processes for banana residues, (iii) to understand the environmental impact generated by the banana value chain, and (iv) to identify barriers to the adoption of practices that favor a circular economy. The latter aim is accomplished by (i) schematizing a system based on the circular bioeconomy that could be developed around the banana value chain, and (ii) analyzing the potential of using residual banana biomass as feedstock for the material and energy requirements in the banana system.

2. Methods

The methods section has two subsections corresponding to the aims of this study.

2.1. Non-food bioproducts derived from residues from the banana agricultural system

A literature review was conducted on quantitative studies focused on the use of banana lignocellulosic residues. The review included the stages of the recovery process of the lignocellulosic residual biomass of bananas through biological-based processes. The information on the techno-economic analysis of biorefineries based on banana residues as raw material, LCA of banana production, and barriers for a circular economy are also reviewed. Literature published in English was considered, excluding articles referring to health, nutrition, and food, and book chapters, reviews, and conference proceedings. The abstract and methodology of each study were reviewed to verify the exclusion criteria and the topic's relevance. The review criteria and the number of publications sorted by thema are presented in Table 1.

2.2. Prospective for a circular bioeconomy based on the residual biomass of bananas

A system for the valorization of residual banana biomass, using these residues as raw material to obtain bioproducts and bioenergy, is envisioned. A closing the loop strategy will developed aiming at using the produced bioproducts and bioenergy as inputs in the banana value chain.

The methodology includes the analysis of the possibility of energy and material self-sufficiency in the banana value chain. Material and energy requirements for banana system production and packaging will be quantified at a generic level taking into account publicly available, peer-reviewed banana LCA publications. Packaging materials and electricity, and fuels are considered in the analysis.

The capacity of the banana system to supply material and energy was analyzed based on the calculation of 1 ton of export bananas and taking into account the information on yields and energy requirements in the bioprocessing systems for banana residues available in the literature reviewed by pairs. The glossary of terms of the equations can be found in the Supplementary Material. Eq. (1) is used to estimate the amount of glucose syrup obtained from banana pseudostem, leaf, and rachis residues. The mass of glucose will serve as a carbon source for the production of biofuel and bioproducts.

$$m_{glucose}[kg] : (m_P C_P + m_L C_L + m_R C_R) \cdot \eta_{A.T} \cdot \eta_{H.T} \tag{1}$$

The pathway for fuel supply is the production of ethanol from banana residues by fermentation and distillation. Equation 2 was used to estimate ethanol production. The fuel is assumed to be 100% ethanol, i.e., it will not be mixed with other fuels.

$${}_{ethanol}[l] : \frac{m_{glu\cos e} \cdot RT_{ethanol} \cdot \eta_{m.o} \cdot \eta_{Distillation}}{\rho_{ethanol}} \tag{2}$$

The expected route for electricity supply is the use of ethanol in internal combustion engines to generate energy. Eq. (3) allows estimating the amount of energy generated from ethanol.

$$E = V_{Ethanol} \cdot NEV \cdot \eta_e \tag{3}$$

3. Results and discussion

3.1. Non-food bioproducts derived from residues from the banana agricultural system

3.1.1. Valorization of the residual banana biomass

The valorization of agricultural and agro-industrial residues is considered an essential strategy for environmentally friendly production (Freitas et al., 2021). These residues can be used as feedstock in bio-based productive sectors and bioenergy (Duque-Acevedo et al., 2020). In this section, the chemical composition of residual banana biomass and the treatments carried out in different studies were reviewed to obtain bioproducts or increase glucose yield. In addition, the yields of fermentation processes for obtaining bioproducts were reviewed. Finally, techno-economic studies based on the utilization of residual banana biomass are analyzed.

3.1.1.1. Chemical characterization of the residual banana biomass. It is essential to characterize the feedstock before its chemical processing (Batista Meneses et al., 2020; de Souza et al., 2017; Guerrero et al., 2018). This information definines the operations necessary to transform the residual lignocellulosic biomass into a carbon source for different microorganisms (Palacios et al., 2017; Sarkar et al., 2019). Table 2 shows the chemical composition of residual lignocellulosic biomass of banana in dry weight percentage, determined in different studies. The chemical components mainly analyzed are cellulose, hemicellulose, and lignin. It is observed that the pseudostem has a higher concentration of cellulose (38.2%) compared to the rachis (32.1%), banana leaf (28.2%), and peel (23.4%). Somerville et al. (2010) estimate the cellulose content to be 38–50% by weight of the lignocellulosic biomass. However, Watkins et al. (2015) indicate it to be 10–25%. In Guerrero et al. (2018), the cellulose content in the pseudostem (20.1%) is lower than the values found by other authors. The cellulose content in banana leaves (21–33%) and rachis (26–36%) varies considerably. The content of lignin, hemicellulose, and extracts in the pseudostem varies among the different studies. The banana leaf has high hemicellulose and lignin content compared to the rest of the residual banana biomass. Banana rachis has a higher ash content, probably due to the presence of minerals (Gabhane et al., 2014). Shimizu et al. (2018) claim that the lignocellulosic nature of residual banana biomass hinders the enzymatic digestion of cellulose. Regarding the mineral composition in the banana peel, the values are quite different, this may be due to the variety of the species and the management of the crop.

The difference in the values of the chemical composition of the residual biomass of bananas may be due to different factors such as crop variety, type of farm management (conventional or organic), and method of analysis. It has been determined that during the harvest stage, banana plants are not homogeneous in size and weight; these variations may be associated with the geographical characteristics of the crop (Ortiz-Ulloa et al., 2020). On the other hand, Gabhane et al. (2014) consider that these variations may be due to the different environmental conditions where the plant develops or to the banana species.

3.1.1.2. Pre-treatment and enzymatic hydrolysis of residual banana biomass. The residual lignocellulosic biomass of the banana is fibrous, and chemically it is mainly composed of cellulose and hemicellulose; however, these polysaccharides are closely associated with lignin which prevents access to these fermentable sugars. Therefore, a delignification process is required to break the stiffness of the fiber and make the polysaccharides available for later stages (Chittibabu et al., 2014; Costa et al., 2018a; Haldar and Purkait, 2021; Singh et al., 2014). Biorefineries that use lignocellulosic residual biomass generally consist of the following stages: (i) Pretreatment, the lignocellulosic structure is modified or eliminated; (ii) Enzymatic hydrolysis of cellulose, enzymes hydrolyze complex sugars to fermentable sugars (for example, glucose and xylose); (iii) Fermentation, fermentable or simple sugars are used as a carbon source by a microorganism to obtain a compound of interest (for example, ethanol, lactic acid, nanocellulose, biogas), fermentation can be aerobic or anaerobic (Garcia et al., 2012; Sarkar et al., 2019; Suhag et al., 2020). Of these stages, pretreatment is considered to greatly impact the later stages of biobased processes (Duque et al., 2015; Haldar and Purkait, 2021; Meramo-Hurtado et al., 2020). In this sense, different types of pretreatment methods have been studied, which can be classified into (i) physical: mechanical and non-mechanical; (ii) chemical: hydrolysis by oxidizing agents such as acids, bases or peroxides; (iii) biological: uses bacteria, 24fungi and enzymes (Baruah et al., 2018; Damayanti et al., 2021; Romero Bonilla et al., 2015; Świątek et al., 2020). Even combinations of these treatments are often used (Eliana et al., 2014; Govumoni et al., 2013). Pretreatment is considered the most expensive stage in biobased processes (Luo et al., 2010; Singh et al., 2014).

Table 3 shows the different pretreatment methods used for residual banana biomass. Pretreatment with saturated steam (160 - 240 °C) can modify lignin, hydrolyze hemicelluloses, decrease the degree of polymerization and cellulose crystallinity, and increase the contact surface (Auxenfans et al., 2017; Hendriks and Zeeman, 2009; Kumar and Sharma, 2017; Paul Langan et al., 2013). The pseudostem, rachis, and banana peel, when subjected to steam, provides high yields in bioethanol production compared to chemical pretreatments; this could be because, during acid hydrolysis, fermentation inhibitor compounds are generated (Kumar and Sharma, 2017), and the use of chemical agents generate wastewater that must be treated (Yang and Wyman, 2008). On the other hand, milling before chemical treatment can increase the yield for obtaining bioproducts (Delgenes et al., 2003; Lin et al., 2010), but it has a high energy cost on an industrial scale (Hendriks and Zeeman, 2009). However, grinding after chemical treatment has some benefits, such as (i) it reduces energy consumption; (ii) it reduces the cost of separation between solids and liquids; (iii) it does not lead to the production of fermentation inhibiting compounds (Licari et al., 2016; Zhu et al., 2010). The type of mill should be considered to increase yields (Lin et al., 2010; Zakaria et al., 2015).

Biological pretreatment does not generate any inhibitors that could affect fermentation (Baruah et al., 2018). The parameters that affect this pretreatment include the type of biomass, pH, type of microorganism, moisture content, amount of oxygen, temperature, and incubation time (Sindhu et al., 2016). On the other hand, pretreatment is more effective compared to an individual physical, chemical, or biological pretreatment (Kumar and Sharma, 2017; Sindhu et al., 2016). However, the banana leaf rib contains a juice

Table 2
Average chemical composition of above-ground parts expressed as mean - range in% dry weight.

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Extractives (%)	Total (%)	Banana species	Reference
Pseudostem							
44,32	22,0	9,66	14,0	–	89,9	*Musa*	(Gabhane et al., 2014)
38,00	8,70	8,90	17,60	24,10	96,00	*AAA subgroup Cavendish.*	(Guerrero et al., 2016)
44,00	17,50	37,30	11,00	9,70	119,50	*Musa* spp.	(Abdullah et al., 2013)
20,10	9,60	10,10	18,50	14,70	–	*Musa Acuminata Colla (AAA) “Dwarf Cavendish”*	(Guerrero et al., 2018)
44,60	36,00	19,40	–	–	–	*Musa* spp.	(Hossain et al., 2019)
Leaves							
32,56	12,00	21,80	19,40	–	85,80	*Musa*	(Gabhane et al., 2014)
21,90	12,80	21,50	15,70	18,00	88,60	*Musa* spp.	(Guerrero et al., 2016)
26,70	25,80	17,00	8,70	–	78,20		(Fernandes et al., 2013)
31,70	17,80	39,10	–	15,50	–	*Musa* spp.	(Abdullah et al., 2013)
Rachis							
36,14	7,00	16,43	26,80	–	86,40	*Musa*	(Gabhane et al., 2014)
26,40	10,20	9,40	26,60	19,90	91,00	*Musa* spp.	(Guerrero et al., 2016)
36,50	22,30	26,50	15,20	–	–	-	(Costa et al., 2018b)
26,10	11,20	10,80	29,90	18,20	–	*Dwarf Cavendish*	(Guerrero et al., 2018)
35,30	17,90	6,00	28,50	9,70	–	Grande naine (*Musa* spp.)	(Tiappi Deumaga et al., 2020)
Banana peel							
23,37	12,33	12,33	12,75	–	–	*Tabasco* variety	(Palacios et al., 2017)
14,80	13,40	18,80	1,10	–	–	*Musa cavendishii*	(Martínez-Trujillo et al., 2020)

rich in simple sugars, which can be obtained only by grinding, being a cost-effective and sustainable process (Tan et al., 2019).

The enzymatic hydrolysis stage is influenced by enzyme efficiency, structural and morphological characteristics of the lignocellulosic material (Ferreira da Silva et al., 2020). The concentration of hemicellulose and lignin in the residual banana biomass prevents enzymes from contacting the cellulose, which generates a very low rate of enzymatic hydrolysis (Watkins et al., 2015). Therefore, prior removal of lignin and hemicellulose by pretreatment is necessary (Sun et al., 2016).

3.1.1.3. Bioproducts and bioenergy derived from the banana residues. After pretreatment, different configurations can be used to obtain bioenergy through bio-based processes, such as (i) separate hydrolysis and fermentation (SHF); (ii) simultaneous saccharification and fermentation (SSF); (iii) semi-simultaneous saccharification and fermentation (SSSF) (Cotana et al., 2015), and (iv) saccharification and fermentation (Costa et al., 2018b). Residual lignocellulosic biomass from bananas has been used to produce bioenergy and other molecules of industrial interest. Table 3 shows the methodology used, the type of microorganism used, and the product yield. Most of these studies focus on the production of ethanol-2 G. It is observed that the highest yield for bioethanol production is obtained from banana rachis and pseudostems; however, this requires acid and enzymatic hydrolysis, increasing production costs. In general, it is observed that yields depend on process conditions, microorganisms, and substrate characteristics (Cotana et al., 2015; Nguyen et al., 2017).

Another way to valorize banana waste biomass is through anaerobic digestion (AD), a biological process in which the organic substrate is decomposed by different microorganisms without the presence of oxygen, resulting in methane (50–75%) and carbon dioxide (25–50%) (Frigon and Guiot, 2010). It is considered a cost-effective technology for producing electricity, heat, and methane gas (Zheng et al., 2014). On the other hand, the banana peel shows lower yields for obtaining bioethanol. Other bioproducts and molecules of interest have also been obtained from the peel (Dorantes-Landa et al., 2020; Pure and Pure, 2016; Romero Bonilla et al., 2015).

3.1.2. Techno-economic analysis of bioproducts derived from banana residues

Three published studies on TEA of bioproducts and bioenergy obtained from residual banana biomass were identified (Table 4). These studies performed simulations based on literature or experimental data and applied different production models and processing scales.

Based on the studies in Table 4, it is observed that the studies are not comparable as the methodology for the TEA varies among them. However, the studies carried out by Martínez-Ruano et al. (2018) and Hossain et al. (2019) conclude that banana pseudostem could be used as a feedstock with the potential for economically viable bioenergy production. Biorefineries are an alternative for producing bioenergy and different bioproducts of interest; however, it is still an emerging sector. Therefore, more advanced biorefineries models that allow integrated conversion pro-

Table 3
Bibliographic review of different methodologies applied for the pre-treatment of residual lignocellulosic biomass of banana.

Pre-treatment	Enzymatic Hydrolysis cellulose	Fermentation	Results	Reference
Pseudostem				
Steam explosion 177 °C, 5 min; 2,2% H_2SO_4 (v/v).	15,1% of solid loading and 14,9 filter paper unit (FPU) per gram of glucan of enzyme dosage.	Simultaneous Saccharification and Fermentation	Glucose: 38,9 ± 1,1 $g.L^{-1}$ Bioethanol: 112 $L.t^{-1}$	(Guerrero et al., 2018)
Liquid hot water 210 °C a 40 min.	The enzyme used was Cellulase Cellic C Tec 2 at an activity of 50 FPU. g^{-1} dry matter	Simultaneous saccharification and fermentation (SSF) at 25 °C for 120 h. *Saccharomyces cerevisiae* NCYC 2826	Glucose: 74 wt.% Bioethanol: 0,167 wt.% - 95 wt.%.	(Ferreira da Silva et al., 2020)
H_2SO_4, 0,5 M heat to 90 min at 90 °C. After, neutralize the media with 1 M of sodium hydroxide, pH 4,0–6,0.	5 g cellulose enzyme. Incubator shaker at 37 °C, 150 rpm for 72 h.	*S. cerevisiae* Fermentation time: 7 h.	Glucose: 5614 $g.L^{-1}$ (yield during acid hydrolysis). Glucose: 40,61 $g.L^{-1}$. (Yield during enzymatic hydrolysis).	(Hossain et al., 2019)
The sample was reduced in size by physical methods. Then, it was subjected to different chemical treatments (NaOH, H_2SO_4 and Peroxide) and finally to enzymatic hydrolysis.	The following enzymes were used in this stage: 15 FPU/g total cellulase and 15 U/g of β-glucosidase.	This operation was not applied.	Glucose: 80 wt.%.	(Shimizu et al., 2018)
Size reduction H_2SO_4 2%, 120 °C, 15 min; and NaOH 3%, 120 °C, 15 min	Enzymes: Cellic CTec2 y HTec2	Temperature: 30 °C; pH: 5 and 120 rpm	Bioethano: 41 wt%	(de Souza et al., 2017)
Leaves				
Sample of semi-dried leaves, 500 ml of sludge solution and 2% urea was added to the solution.	This operation was not applied.	Anaerobic digestion	Methane: 65,28 wt%	(Jena et al., 2017)
Particle size reduction, Different pretreatments: H_2SO_4 5% (v/v), NaOH 1% (p/v), microwaves 180 °C, 700 W, ultrasonication 25 kHz, 150W	50 FPU/g cellulase enzyme Incubator 50 °C for 48 h	This operation was not applied.	Reducing sugars: 47,33 wt%	(Gabhane et al., 2014)
Banana fronds need only a milling process for the extraction of sugars to fermentation medium	This operation was not applied. After the pre-treatment, it is directly transferred to the fermentation stage.	The Banana Frond Juice (BFJ) at 80% (v/v) supplemented with yeast extract at 15 g/L with optimum pH at 6.8. *Saccharomyces cerevisiae*	Glucose. 18,90 $g.L^{-1}$ Bioethanol: 42,47 $g.L^{-1}$	(Tan et al., 2019)
Rachis				
Acid-catlyzed with 1,5% H_2SO_4 (v/v); steam explosion 198 °C, 5 min.	17,6% of solid loading and 16.0 $FPU.g^{-1}$ glucan of enzyme dosage.	8 h prehydrolysis followed by a Simultaneous Saccharification and Fermentation. *Saccharomyces cerevisiae* Ethanol Red	Glucose: 3,4 $g.L^{-1}$. Bioethanol: 103 $L.t^{-1}$	(Guerrero et al., 2018)
1. Glacial acetic acid: acetone: water (10:50:40) 2. 96% Ethanol 3. NaClO 5% 4. $HClO/ClO^-$ 5. H_2O_2 2% 6 H_2O_2 2% + NaOH 5% 7 Treat. #4 + Treat. #1 8 Treat. #4 + Treat. #2	Enzymatic hydrolysis 50 μL of cellulose from *Trichoderma reesei* with 50 μL de beta-glucosidase from *Aspergillus niger*	This operation was not applied.	Glucose: 51,4 wt%	(Costa et al., 2018b)
Banana peel				
Different concentrations of sulfuric acid (0, 0.5, and 1% v/v) and temperatures (28 and 121 °C at 103 kPa in an autoclave)	48 h at 50 °C, 150 rpm. 15 FPU/g cellulase.	20% (w/w) banana peel, 24 h of fermentation. *Kluyveromyces marxianus*	Bioethanol: 21 gl^{-1}	(Palacios et al., 2017)
Particle size reduction Steam heating and filtration	No use	5% (p/v) sucrose 0,5 urea (w/v) Acetic acid 10% (v/v) *Gluconacetobacter xylinum*	0.50 cm thickness of bacterial nanocellulose	(Sijabat et al., 2019)
Drying and milling *A. Niger* (2,3 ± 0,16 g/L), and *A.flavipes* (4,99±0,16 g/L), 12 h of treatment.	Enzimatic crude extract (oxidases/pectinases/ hemicellulases/cellulases). Saccharification yield 83%.	*Lactobacillus delbrueckii*	28 g/l of Lactic acid	(Martínez-Trujillo et al., 2020)

Table 4
Characteristics of studies on techno-economic analysis (TEA) in the valorization of residual biomass from the banana value chain.

Objectives	Methodology	Main findings	Reference
To evaluate the environmental and techno-economic impact of biogas generation from banana peel (*M. paradisiaca*), considering different processing scales.	The TEA was evaluated in terms of net present value (NPV) using the Aspen Process Economic Analyzer software. The environmental analysis was performed based on the overall process balance and net energy consumption.	The production of biogas from banana peel is a viable alternative through the biorefinery model and its profitability will depend on the production capacity.	(Martínez-Ruano et al., 2018)
Techno-economic and environmental analysis for the production of electricity from bioethanol obtained from banana stems.	TEA and environmental analysis were performed with HOMER software (The Micropower Optimization Model, Homer Energy for LLC). The data were obtained through experimental research.	Bioethanol from banana stalk generates lower CO_2 and SO_2 emissions than diesel. Likewise, the TEA shows that it is more profitable to produce electricity from bioethanol compared to diesel.	(Hossain et al., 2019)
A techno-economic and environmental analysis of industrial ethanol production from 10 agricultural residues, including pseudostems and banana peel, is carried out.	The techno-economic analysis was performed with the Aspen Process Economic Analyzer software. The environmental analysis was performed based on the overall process balance and net energy consumption; WAR software was used	The banana pseudostem is the highest yield (0,259 kg of ethanol/kg of raw material) among the residues analyzed. This yield could be due to its low moisture content, high cellulose and hemicellulose content.	(Duque et al., 2015)
Techno-economic and environmental analysis for the production of Polyhydroxybutyrate (PHB) from rejecting banana and banana peel.	The TEA was performed in Aspen Economic Analyzer software and the environmental impact was determined in WAR-GUI software.	PHB production under the biorefinery concept could decrease production costs and have negative environmental impacts.	(Naranjo et al., 2014)

Table 5
Carbon footprint results of banana in the literature.

Functional unit(FU)	Simplified system boundaries	Carbon Footprint(kg CO2e/FU)	Reference
1 Kg banana *Cavendish*, sold to a customer in Norway	Agriculture, packaging, overseas transport, transport to wholesale, retail.	1,37	(Svanes and Aronsson, 2013)
1 Kg banana *Cavendish*, consumed in Norway	Agriculture, packaging, overseas transport, transport to wholesale, retail, consumption, waste management.	1,77	
1 Kg of bananas *Prata*, available at retail in the domestic market	Agriculture, packaging, retail.	0,209	(Coltro and Karaski, 2019)
1 Kg of bananas *Cavendish*, available at retail in the domestic market	Agriculture, packaging, retail.	0,226	
1 kg of fruit *Cavendish* reaching the consumption stage has been chosen, taken into account product losses along the value chain	Agriculture, packaging, overseas transport, European transport, retail, consumption.	1,28	(Roibás et al., 2015)
	Conventional Agriculture, packaging.	0,302	
	Organic agriculture, packaging.	0,249	
1 Kg of *Cavendish* Ecuadorian premium quality banana delivered to a European port	Agriculture, packaging, overseas transport.	0,45	(Iriarte et al., 2014)

cesses and produce a greater variety of products of industrial interest should be further developed (Hassan et al., 2019).

3.1.3. Environmental life cycle assessment of banana agricultural systems

Despite the importance of bananas for its economic development (FAO, 2004), there are few LCAs of this product(Coltro and Karaski, 2019; FAO, 2017; Iriarte et al., 2014; Roibás et al., 2015, 2016; Svanes and Aronsson, 2013). Most of the studies have included at least the results of the Global Warming Potential impact category indicator, usually called carbon footprint (CF), ranging from 0.22 to 1,37 kg CO_2-eq kg^{-1} bananas (Table 5). Life cycle Water Footprint results range from 313 to 330 l kg^{-1} banana (Coltro and Karaski, 2019; Roibás et al., 2015). When included, overseas refrigerated transport is the highest contributor to the CF (Iriarte et al., 2014; Svanes and Aronsson, 2013), when not, primary production is the highest contribution (Iriarte et al., 2014; Roibás et al., 2015). When transport is not included, the contribution of packaging is between 7 and 13% (Coltro and Karaski, 2019; Roibás et al., 2016). It should be noticed that besides system boundaries, some other issues may turn LCA results not comparable such as methodological choices, modeling assumptions, cutoff criteria, characterization models, the technology and practices themselves, among others.

Usually, LCA studies dealing with circular economy regarding agricultural residues have an output-based approach. The biobased products or bioenergy derived from residues is the main product of the system. System boundaries may include agricultural production (Boschiero et al., 2016; Quispe et al., 2019; Z. Wang et al., 2019). Another used approach is the input-based LCA as in waste management systems (Vaneeckhaute et al., 2018). In any of the approaches, information should be provided regarding the amount of residues from each part of the life cycle chain taken into account in the inventory.

LCA has been prompted as the main tool to assess the sustainability of circular economy (Peña et al., 2021) and circular bioeconomy systems (Sevigné-Itoiz et al., 2021). A valuable approach would be to focus on the main agricultural product (the banana product) and expand the system to include all the effects associated with its residues-derived products in the same system and other value chains. However, this would result in a highly resource-demanding LCA.

3.1.4. Barriers to transitioning to a more circular bioeconomy around the banana value chain

It is essential to identify the actors/ stakeholders to transition from a linear economy to a more circular bioeconomy and the bar-

Table 6
Stakeholders and barriers to a transition to a circular bioeconomy.

Stakeholders	Barrier	Reference
The government	Lack of policy instruments to foster technological development and drive demand. Also, lack of long-term vision and consensus on the direction of change.	(Gottinger et al., 2020)
	Implement differentiated policy instruments to address system weaknesses, such as market formation, the main bottleneck of innovation systems.	(Wydra, 2019)
	Bureaucracy in development processes and political stability	(Angouria-Tsorochidou et al., 2021)
Private sector	Bio-based companies are niche markets and therefore require little residual biomass as raw material, and the processes for obtaining bioproducts require personnel with skills and education in different areas of knowledge such as engineering, biotechnology, mathematics, and statistics. This context makes it challenging to hire adequate personnel.	(Philp, 2018)
	The private sector must face challenges such as the costs of technology, infrastructure, skills, and enabling regulatory requirements. Besides, poor collaboration and partnership between the public and private sector hinder technology transfer.	(Lokko et al., 2018)
Civil society	Several factors may influence farmers' decisions on the management of agricultural residues and their use as raw material in circular models, including lack of access to credit or government subsidies for the purchase of equipment or infrastructure, low market demand, low or variable sales prices, as well as beliefs or assumptions about the benefits to the soil of residues during their decomposition.	(Härri et al., 2020)
	Older farmers are resistant to change due to a lack of knowledge about the market structure. They are unwilling to change their traditional farming practices. Farmers with higher levels of education are more likely to be part of the circular market.	(Ymeri et al., 2020)
Academia – research ($I + D + i$)	There is no bio-based approach in current technologies. Technologies with the potential to valorize biomass are niche innovations and require political support.	(Laibach et al., 2019; Salas et al., 2021)
	Efficient management system for the collection of residual biomass or proximity to processing plant facilities. Coexistence between agricultural farms and bioprocessing plants.	(Kircher, 2014)

riers that must be overcome. Table 6 lists some barriers to the transition to a circular economic model found in the literature.

These barriers could be overcome through coherent and strategic policy approaches. In addition, the government should develop better incentive mechanisms for the agricultural and private sectors (Ali et al., 2021; Xia and Ruan, 2020) and strategies for promoting and discussing the potential risks and benefits of biotechnology for society (Jun and Xiang, 2011; Teigiserova et al., 2019). Each country must create the appropriate conditions for technology transfer through collaboration and partnership among the private, academic, and governmental sectors. However, it should be taken into account that each country is at a different stage of technological development and, therefore, faces its challenges and priorities (Lokko et al., 2018). A bioindustrial development aware of adapting policies and models is critical for tropical countries (Ortega-Pacheco et al., 2018).

Furthermore, Lescot (2012) pointed out that access to primary and disaggregated data is complicated. Some banana operators did not wish to publish the primary data but only aggregated results. Moreover, the methodology should be an issue since the scope of the studies may be different, some data are collected directly from the field, and some are derived from expert opinion.

3.2. Prospectives for a circular bioeconomy based on the residual banana biomass

This section proposes a system for the valorization of residual banana biomass, using these residues as raw material to obtain bioproducts and bioenergy (Fig. 2). The proposal is based on a conventional monoculture banana production system (Pérez Neira, 2016). The system brings together the following stages (1) the current banana value chain, (2) bio-based processing, (3) bio-based final products.

The first stage requires specific inputs such as fertilizers, pesticides, crop protection material, electricity, and fuel. The residual biomass of bananas generated during the cultivation, packaging, processing, and consumption of banana fruit can be used to produce bioenergy and biocomposites of interest through the integral management of these residues. The residual biomass must first go through a pretreatment based on a physical-mechanical method to take advantage of the energy produced by the biobased process. Then the pretreated biomass goes through an enzymatic cellulosic hydrolysis process, transforming complex sugars into simple fermentable sugars. These sugars will serve as a carbon source for the metabolic processes of microorganisms. Depending on the characteristics of the microorganism, the conditions for the fermentation stage are established. As a product of this stage, compounds such as ethanol, PHB, lactic acid, methane, bacterial nanocellulose, among others, can be obtained. These bioproducts must be purified by physical or chemical methods before being used as raw material to produce bio-based products. For example, 100% ethanol could be used as an input in electricity generating equipment and a fuel for the transportation sector. Biopolymers could also be used to produce protective materials or packaging used in the banana value chain or other production systems. In this way, the consumption of petroleum-based chemical synthesis compounds would be reduced, reducing the generation of GHGs from the banana production system.

This proposed new banana value chain considers several conceptual aspects of the bioeconomy, such as (i) waste management (Lokko et al., 2018), (ii) fossil decarbonization (Atinkut et al., 2020; van Zyl et al., 2011), (iii) creation of new sectors and chains (Stegmann et al., 2020), (iv) new bioproducts, and (v) use of waste biomass (Muscio and Sisto, 2020). This scheme is based on bio-based processes with a biorefinery approach. Allowing the production of bioproducts such as bioenergy and bioplastics, which can be used as inputs in the banana value chain or other productive sectors contributing to the achievement of SDG 2, sustainable food production, SDG 7 affordable energy for all, and SDG 8, new sources of decent work and sustainable economic development. In addition, the biorefinery concept is associated with the possibility of closing production cycles through the valorization of residual banana biomass and innovative processes, contributing to SDG 9, industry and innovation, and SDG 12, responsible production and consumption.

On the other hand, it has been said that sometimes circular approaches do not consider the thermodynamic limits of the system and, therefore, are unrealistic (Cullen, 2017; Geissdoerfer et al., 2017; Giampietro, 2019; Kirchherr et al., 2017). However, it is recognized that it is necessary to use external inputs in each process,

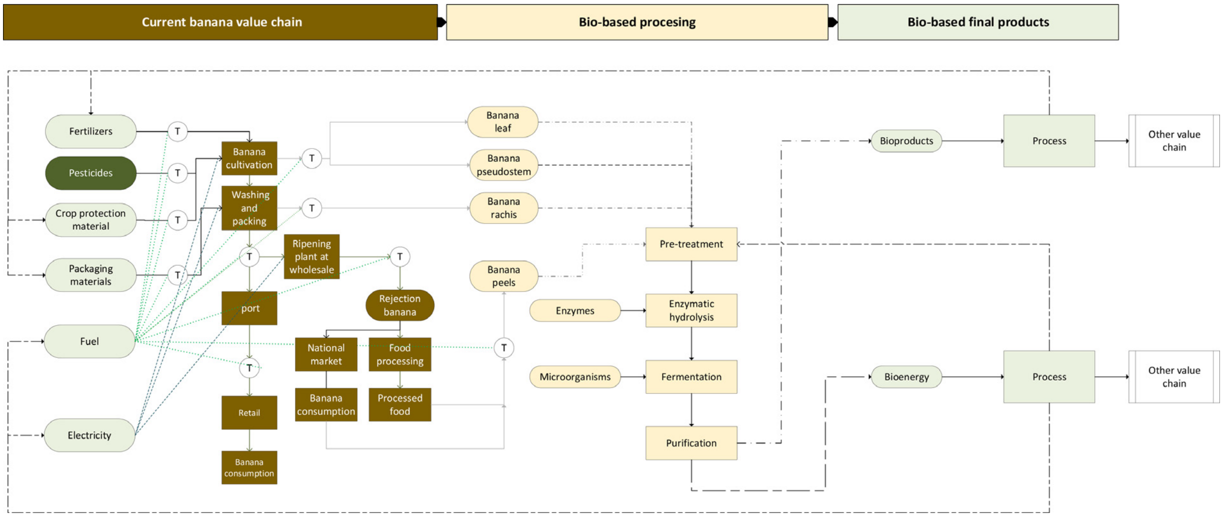

Fig. 2. Flowchart for an envisioned circular bioeconomy based on the banana value chain. The diagram describes a possible scenario where the residual lignocellulosic biomass is used as a carbon source in a bio-based process, generating products depending on the fermentation conditions and microorganisms. In general, Bioproducts or bioenergy could be obtained, which must go through a bio-based process, partially or substituting the production of inputs necessary for the banana value chain or other value chains. (T: transport). The continuous lines show the input and output flows of the different production stages. Dashed lines indicate the input and output flow of biomass and bioproducts in the processes.

Table 7
Plastic, cardboard, and energy inputs used during the banana cultivation and packaging processes.

Item	Units	Farm type[a]		Material[b]	Weight(g)[c]
		Organic	Conventional		
Cover	u/t	58,74	50,58	HDPE/LDPE	25,00
Bow tie	u/t	0,00	93,35	LDPE	2,28
Banana hand cover	u/t	32,19	6,88	LDPE	8,68
Tape	u/t	37,98	19,08	PP	9,07
Nunś neck	u/t	67,99	135,93	LDPE	18,14
Cardboard box	u/t	55,13	55,13	Cellulose	1.324,49
Plastic bag	u/t	49,00	55,13	LDPE	28,9
Rubber	u/t	49,00	55,13	LDPE	9,07
Label	u/t	1.800,81	1626,24	PP	5,44
Fuel	(l/t) / (MJ/t)	2,49/ 81,42	2.79/91,23	Petrol	N/A
Fuel	(l/t) / (MJ/t)	23,14/ 831,65	14,85/533,71	Diesel	N/A
Electricity	(kWh/t)/(MJ/t)	1,82/ 6,55	4,53/16,31	Energy	N/A

[a] Clasification and data according to Roibas et al. (2015).
[b] HDPE & LDPE hight- and low-density polyethylene, PP: Polypropylene.
[c] Information obtained from a production site for this study; N/A: Not applicable.

such as fertilizers. Furthermore, solar energy and carbon dioxide are external inputs for photosynthesis during primary production.

3.2.1. Potential material and energy self-sufficiency

The banana value chain requires various inputs such as packaging materials based on cardboard and synthetic polymers. It is estimated that 70,9 kg of cardboard and 1,4 kg of low-density polyethylene (LDPE) are required per ton of bananas (Svanes and Aronsson, 2013). Energy consumption is also considered to be another essential input. Table 7 shows the different inputs based on cardboard or synthetic plastic and energy consumption in the banana value chain.

Fig. 3. Energy and material self-sufficiency process diagram for a conventional banana value chain. The solar energy required for primary production is not included in the calculations. The solid black line signifies the flow of inputs and outputs in the different stages of the banana value chain, the dashed black line delimits the banana production system, the solid green line indicates the input and output flows in the banana residual biomass valorization process, the dashed green line shows the flow of bioproducts entering the banana value chain. P.E. means production efficiency and m.o., microorganism.

For this purpose, a production of 1 ton of bananas for export was taken as a basis for calculation, according to Iriarte et al. (2014) approximately 6% of the bananas harvested are rejected. This data allowed calculating the amount of banana harvested and thus estimating the amount of residual lignocellulosic biomass that would be generated during primary production. The generation of banana pseudostem, rachis, and leaf was calculated using the ratio product / residual biomass (Ortiz-Ulloa et al., 2020). The mean value of the cellulose percentages is shown in Table 2, and the production yields (PY) for the pretreatment of the residual biomass is sulfuric acid (90%), because it is generally considered the best option for biomass with high lignin content together with enzymatic hydrolysis (55%) (Velásquez-Arredondo et al., 2010). The process was designed for ethanol production because this compound can be used as an input for electricity generation and as a fuel. The theoretical stoichiometric yield for ethanol production from glucose is 0,511, the ethanol production yield of *Saccharomyces cerevisiae* is 35% (Gonçalves Filho et al., 2013), and the yield of the distillation tower is 80% (Duque et al., 2015). It is assumed that the ethanol produced will be used for electricity generation and biofuel without blending with fuel obtained from petroleum synthesis. The net energy value (NEV) for ethanol is es-

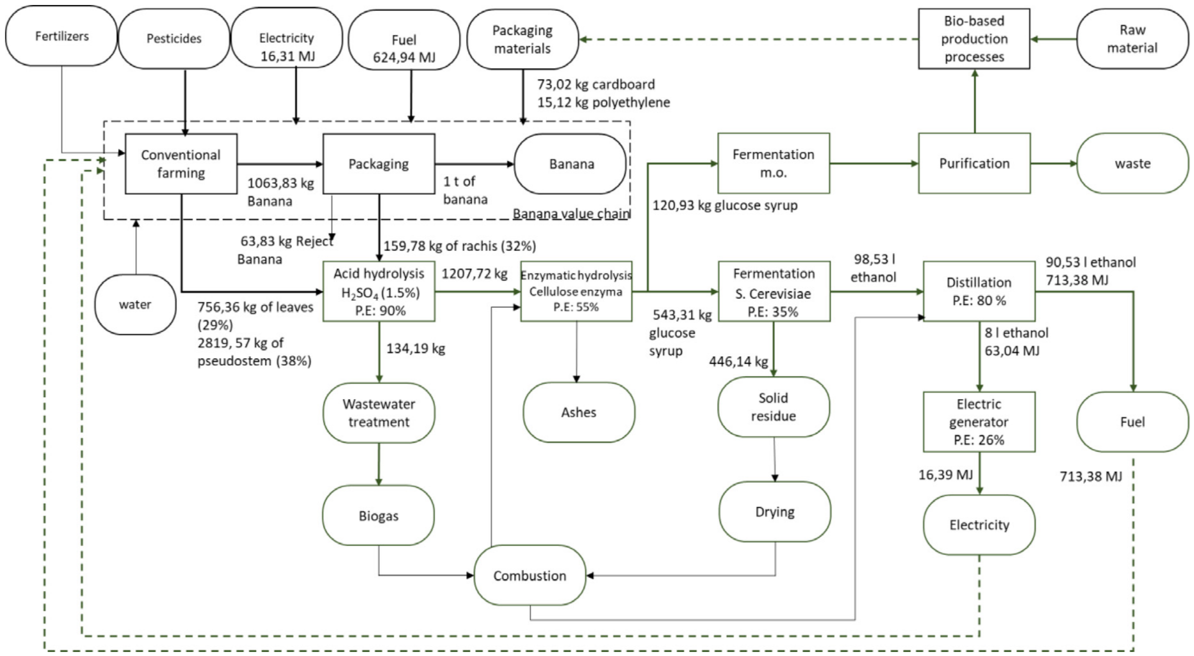

Fig. 3. presets the analysis of the potential energy self-sufficiency of the banana value chain from the residual lignocellulosic biomass (pseudostem, rachis and leaf).

timated to be 7,88 MJ/l (Guerrero and Muñoz, 2018), the electricity conversion efficiency is 26% (Ridwan et al., 2020).

Although it is feasible to obtain bio-based biopolymers, such as BNC and PHB, from banana waste (Naranjo et al., 2014; Redondo-Gómez et al., 2020). The literature reviewed does not include information on the yields of biopolymers obtained for packaging production. This is a research gap identified during this study.

4. Conclusions

Current management practices for waste generated in the banana production system, such as incineration and landfill are not considered environmentally friendly strategies. The valorization of this residual biomass and its reinsertion into the production system with a "closing the loop" approach is a strategy that could reduce waste generation and GHG emissions in banana cultivation, in addition to promoting the development of the bioeconomy and the fulfillment of SDGs 2, 7, 8, 9, and 12. The amount of residual biomass generated by banana cultivation and its chemical composition in terms of cellulose, hemicellulose, and lignin content make it an attractive raw material for bioenergy and bioproducts. The valorization process of these residues usually consists of the following stages: pretreatment, chemical hydrolysis, enzymatic hydrolysis, fermentation, and purification. However, using the juice extracted from banana biomass as a carbon source is a simpler, more economical, and sustainable process.

This work proposes a new banana value chain based on the conceptual frameworks of Circular Economy and Bioeconomy. It is estimated that it is possible to "close the loop" in the banana value chain in terms of energy. Reviews of techno-economic analyses show the potential of residual banana biomass for bioenergy production. However, the production of biopackaging through bio-based processes needs further research. The proposed scheme must have a biorefinery approach to be economically viable.

Technical feasibility is only one side of the coin; the innovation potential of the system has other barriers associated with economic and cultural issues that must be overcome. In addition, more studies are needed to evaluate the potential of banana residues as a raw material to produce different bioproducts that can substitute or reduce the use of petroleum synthesis-based products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Manuel Fiallos-Cárdenas: Conceptualization, Investigation, Methodology, Writing – original draft, Visualization, Funding acquisition. **Simón Pérez-Martínez:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Angel D. Ramirez:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

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