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STUDY OF AGRICULTURAL BIOMASS WASTE FOR THE INSTALLATION OF A SMALL-SCALE BIOREFINERY

ESTUDIO DE RESIDUOS BIOMÁSICOS AGRÍCOLAS PARA LA INSTALACIÓN DE UNA BIOREFINERÍA DE PEQUEÑA ESCALA

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Abstract

In recent years, lignocellulose residues have been used for producing different bioproducts. Among the countries with this potential is Ecuador, which is characterized by having an agrarian economy, generating waste that constitutes mostly biomass of the lignocellulosic type. The province of Manabí, located on the Ecuadorian coast, is an agricultural area whose residues are usually burned, left in the field or used for animal feed. Based on this premise, a multicriteria analysis was developed through the Analytical Hierarchy Process (AHP), in which 6 agricultural biomasses from the Ecuadorian coast were evaluated: coffee husks, cocoa husks and mucilage, corn cob, banana peels and sugar cane bagasse. They were evaluated by a panel of experts based on their energy potential, biomass composition, yield, processing cost and environmental impact. The composition of the waste (proximal and elemental analysis) was bibliographically consulted, as well as current processing technologies. From the AHP, it was known that the agricultural biomass with the greatest potential to be used in a small-scale biorefinery is sugarcane bagasse (33.20 %), followed by coffee husks (26.10 %), being the recognized sugarcane with the greatest richness in polysaccharides and a promising source for obtaining biofuels and other chemical products. It is expected that the results obtained in this study will be the basis for other research and will be interesting for the bioeconomic development of the country.

Keywords: Biomass, biorefinery, Ecuador, biomass, analytical hierarchy process, agricultural wastes.

Resumen

En los últimos años se ha considerado el uso de residuos lignocelulosos para la producción de distintos bioproductos. Entre los países con este potencial está el Ecuador, el cual tiene una economía agraria, generadora de residuos que constituyen en su mayoría biomasa lignocelulósicas. La provincia de Manabí ubicada en la costa ecuatoriana es una zona agrícola cuyos residuos son por lo general quemados, dejados en el campo o usados para alimentación animal. Atendiendo a esta premisa, se desarrolló un análisis multicriterios a través del proceso de jerarquía analítica (AHP), en el cual se evaluaron 6 biomasas agrícolas: cascarilla de café, cáscara y mucílago de cacao, olote de maíz, cáscara de plátano y bagazo de caña de azúcar. Los mismos fueron ponderados por un panel de expertos en función a su potencial energético, composición, rendimiento de biomasa, costo de procesamiento e impacto ambiental. Para ello se consultó bibliográficamente la composición de los residuos (análisis proximal y elemental), así como las tecnologías actuales de procesamiento. A partir del AHP se conoció que la biomasa agrícola con mayor potencial de ser utilizado en una biorrefinería de pequeña escala es el bagazo de caña de azúcar (33,20 %), seguido de la cascarilla de café (26,10 %), siendo la caña de azúcar reconocida con mayor riqueza en polisacáridos y una fuente prometedora para la obtención de biocombustibles y otros productos químicos. Se espera que los resultados obtenidos sean de fundamento para otras investigaciones y de interés para el desarrollo bioeconómico del país.

Palabras clave: Biomasa, biorefinería, Ecuador, biomasa, proceso de jerarquía analítica, residuos agrarios.

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1 Introduction

The global economy is based on the commercialization of products and the reliance on non-renewable resources such as oil (Navarrete Loza and Saavedra Cuadrado, 2014). Although this has been the predominant business model, many countries are currently striving to transition from a traditional economy to a bioeconomy, in alignment with the goals set by the 2030 Sustainable Development Goals (SDGs).

Bioeconomy is defined as the use of biological resources (biomass), innovative biological processes, and principles to sustainably produce goods and services (Birner, 2018). Biomass is understood as biological-origin material derived from living or once-living organisms, excluding those embedded in geological formations or fossilized (Birner, 2018). Biomass that can potentially be used as feedstock in biorefineries (industrial complexes where biomass is processed) can come from various sources, including agriculture, forestry, domestic organic waste, and microalgae, among others (Hernández Benítez and Céspedes Rangel, 2019).

The term biorefinery emerged in the 1990s, based on the concept of Chemurgy, as an attempt to produce a variety of biobased products using agricultural biomass as raw material (Pazmiñon Sánchez et al., 2017). The U.S. National Renewable Energy Laboratory (NREL) highlights that biorefineries are facilities that integrate biomass conversion processes and equipment to produce a wide range of products, including fuels, energy, and chemicals (Redondo-Gómez et al., 2020). These facilities aim to add value to a diverse range of renewable raw materials, including biomass from forestry, aquaculture, and agricultural waste, such as those derived from crop and livestock activities (Katakojwala and Mohan, 2021).

First-generation biorefineries in developed countries such as Belgium, the Netherlands, France, Austria, and Germany report the use of starch or forage from wheat and corn—both human-consumable raw materials—for the commercial production of bioethanol (Gutiérrez Villanueva et al., 2020). Additionally, agricultural residues, such as bagasse, rice straw, and corn stover, are used as raw materials in the pulp and paper industry (Mongkhonsiri et al., 2018). Countries like Brazil employ sugarcane biomass for biofuel production (Pazmiñon Sánchez et al., 2017). At a global scale, studies have reported the use of various agricultural residues, such as rice straw, corn husks and stover, and pineapple waste for bioethanol production (Kumar et al., 2018; Kazemi Shariat Panahi et al., 2020; Chintagunta et al., 2017), as well as orange peels for bioplastics production (Gutiérrez Villanueva et al., 2020).

These agricultural biomasses are classified as lignocellulosic residues, and, in addition to being a renewable substrate in comparison to fossil fuels, they are primarily composed of three constituents: cellulose, hemicellulose, and lignin (Sharma and Saini, 2020). Cellulose is the most abundant organic polymeric material on Earth and is commonly used for cardboard, paper production, and as a precursor for second-generation bioethanol (Yousuf et al., 2020; Korányi et al., 2020). Hemicellulose is an amorphous, branched heteropolysaccharide composed of five- and six-carbon sugars. The presence of reducing sugars in hemicellulose is crucial as a key source for chemical production (Lorenci Woiciechowski et al., 2020; Mankar et al., 2021).

Lignin, another important component of lignocellulosic biomass, is a complex aromatic biopolymer with a high carbon content. Despite being underutilized in biomass processing, lignin holds significant potential as a raw material for the chemical and fuel industries (Mathew et al., 2018; Korányi et al., 2020). Due to their composition, lignocellulosic residues can be used to produce high-value-added bioproducts, such as lactic acid, furfural, and levulinic acid (Espinoza-Vázquez et al., 2020).

The interest in using lignocellulosic residues, especially agricultural ones, lies in their low cost and abundance of compounds suitable for lignocellulosic biorefineries. Studies report that small-scale biorefineries have used agricultural residues for the production of biogas, xylan, glucose, ethanol, and polyhydroxyalkanoates (Parralejo et al., 2019; Dos Santos et al., 2017; Clauser et al., 2018).

In countries such as Ecuador, biomass is abundant due to its megadiverse ecosystem and extensive agricultural activity. In 2020, the country recorded 5.20 million hectares of cultivated land, with sugarcane, bananas, and African palm as the primary crops (INEC, 2020). Manabí is one of Ecuador's provinces with the highest number of agriculture-related economic activities, covering 1.2 million hectares of farmland, which accounts for 15.83 % of the national territory. Additionally, the province hosts small-scale agro-industrial processing centers, including snack producers, banana flour mills, rice and corn processors, and sugarcane and coffee industries, responsible for producing sugarcane, aguardiente, roasted and ground coffee (Manabí Produce, 2021; MANABÍ PRODUCE-EP, 2016).

This agricultural and agro-industrial activity generates residues that are characterized as potentially renewable, sustainable, cost-effective, and economically viable resources for bioenergy production (Gupta and Verma, 2015). Therefore, agricultural, livestock, and urban waste byproducts can be utilized in small-scale biorefineries (Gómez-Soto et al., 2019). Since biorefineries rely on residual biomass, they contribute to reducing energy costs and greenhouse gas emissions, while simultaneously producing energy, materials, and chemicals (Carmona-Cabello et al., 2018).

By the time the research was carried out, besides the sugar mills, there is only one biorefinery in Ecuador, specifically at the Nayón campus of the Pontifical Catholic University of Ecuador. This facility is currently operational, developing products such as ethanol, biogas, biofertilizers, fuel, animal feed, and other high-value chemical compounds (Carvajal, 2013; Cevallos, 2018). However, no industrial complex of this kind has been registered in the province of Manabí, despite the large amount of agricultural waste generated in the region (Sumba et al., 2019). The implementation of a small-scale biorefinery in Manabí would enhance agricultural activities by utilizing waste that currently has a negative environmental impact.

The use of agricultural residues as raw materials presents a promising option to increase economic value while positively impacting the province's economy and the environment. Such a decision requires multicriteria analysis to assess different alternatives and select the optimal one. Various decision-making tools exist, among which stands out the Analytic Hierarchy Process (AHP).

AHP is recognized as a comprehensive evaluation method for renewable energy sources, providing the foundation for proper decision-making by assessing the potential of biomass utilization from a multicriteria perspective (Jiménez Borges et al., 2019). The selection of biomass using AHP has been tested in studies, such as evaluating the sustainability of major biomasses in Cienfuegos, Cuba, where bagasse showed the highest energy contribution (Jiménez Borges et al., 2019). Another application of AHP was in systematically determining the best agricultural residue for polyhydroxyalkanoate production (Requiso et al., 2018).

Within this context, it is innovative to apply the AHP method to evaluate the use of agricultural by-products in a specific area of Ecuador, with the aim of being used as raw material in a small-scale biorefinery.

Thus, this study aims to review agricultural biomass generated in the province of Manabí and apply an Analytic Hierarchy Process to select the most suitable biomass to be used in a small-scale biorefinery. A comprehensive analysis of this process and its results will serve as a framework for bioeconomy development in Ecuador.

2 Materials and Methods

2.1 Multi-criteria analysis method

To select the by-products with the highest importance index, the Analytic Hierarchy Process (AHP) was used. This is a decision analysis method developed by Thomas Saaty in 1980, designed to facilitate decision-making by providing a structured approach for determining the weights and priorities of multiple criteria, standardizing them for comparison (Ramírez et al., 2020). The application of the AHP method follows these steps (Huamaní Huamaní and Eyzaguirre Tejada, 2015):

- Goal Selection: This involves defining the objective to be achieved. It requires access to expert knowledge on the topic to select criteria and propose alternatives.
- Hierarchical Structure: Once the overall goal, criteria, and solution alternatives are defined, a hierarchical model is proposed.

- Matrix Proposal: This step involves making pairwise comparisons using a numerical scale that corresponds to commonly used verbal expressions (Table 1).

The iterative process was repeated for each criterion until the results were obtained and subsequently subjected to a consistency measure. The consistency index, λ_{max}, was determined as a primary eigenvalue based on the eigenvector technique. This was achieved by calculating the multiplication capacity of the matrix of criterion ratings (in the row of the pairwise comparison matrix) and the normalized average of all components (within the column of the normalized matrix), divided by the normalized average of the criterion (Owolabi et al., 2020). Subsequently, the Consistency Index (CI) was calculated (Luna et al., 2019), using Equation 1.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{1}$$

Where n represents the matrix size, and λ_{max} is the maximum eigenvalue. Then, using Equation 2, the Consistency Ratio (CR) is calculated, which compares the Consistency Index (CI) of the matrix derived from the judgments with the Random Consistency Index (RI) of a random matrix (Table 2).

$$RC = \frac{CI}{RI} \tag{2}$$

If the Consistency Ratio (CR) exceeds 0.10, it indicates that the judgments within the matrix are inconsistent and, therefore, unacceptable for decision-making. Conversely, if CR values are equal to or less than 0.10, the consistencies are deemed acceptable, valid, and justified for selecting alternatives.

Table 1. Saaty's Scale

Numerical scale	Verbal scale
1	Equally important.
3	The element is moderately more important with respect to the other.
5	The element is strongly more important with respect to the other.
7	The importance of the element is very strong with respect to the other.
9	The importance of the element is extreme with respect to the other.
2, 4, 6, 8	Intermediate values between two adjacent judgments.
Increments 0, 1	Intermediate values between increments (use this scale if you think your assessment needs a high degree of precision).

Source: (Saaty, 2014)

2.2 Selection alternatives

The selection alternatives represented each of the agricultural by-products considered in the study. These were chosen based on data reported by the National Institute of Statistics and Censuses (INEC, 2020), highlighting the top agricultural activities in terms of production in Manabí, Ecuador, in 2020. Consequently, the study focused on waste from coffee (husk), cocoa (shell and mucilage), corn (cob), banana (peel), and sugarcane (bagasse), as their constituents represent a promising source of lignocellulosic material. Additionally, a literature review was conducted to determine the proximate composition (% moisture, volatile solids, ash, and fixed carbon) and elemental composition (carbon, nitrogen, hydrogen, oxygen, and sulfur) of the evaluated residues. Furthermore, the study considered current biomass processing methods as well as the various products that can be derived from them.

Table 2. Consistency index

Matrix size (n)	1	2	3	4	5	6	7	8	9	10
Random Index	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: (Qazi et al., 2018)

2.3 Selection criteria for alternative evaluation

Agricultural residual biomass has the potential to be converted into syngas for energy generation or into a range of basic chemicals derived from compounds such as cellulose, hemicellulose, starch, lignin, lipids, and proteins. The conversion of biomass into chemicals presents diverse opportunities but also poses technological challenges due to its complex structure, which requires pretreatment processes to break down the material into monosaccharides for high-value product generation (Kover et al., 2021). Based on these considerations and previous research on the subject, five selection criteria were established:

- **Energy potential:** Biomass is a renewable energy resource that not only provides clean energy but also ensures long-term energy availability if used sustainably (Morato et al., 2019). This criterion assesses the potential of agricultural residues to be converted into energy.

- **Composition:** The chemical composition of lignocellulosic biomass determines its suitability as a biorefinery feedstock, considering factors such as cellulose, hemicellulose, lignin, and proximate and elemental content (Jaffar et al., 2020).

- **Biomass yield:** Refers to the harvestable quantity of biomass obtained during the production cycle of a given crop (Cobuloglu and Büyüktahtakin, 2015).

- **Processing cost:** Measures the cost of converting biomass into usable products or energy. Biomass can undergo various processing methods depending on the desired end products, utilizing chemical, thermal, thermochemical, and biochemical conversion technologies (Shahbaz et al., 2020).

- **Environmental impact:** Agricultural biomass has been identified as a potential alternative to reduce fossil fuel dependence and mitigate environmental damage (Fantini, 2017). This criterion evaluates the environmental benefits associated with selecting a specific type of residue.

The availability of biomass depends on the production volume and seasonality of each crop. However, these aspects were not included as selection criteria, as the study focused on evaluating the potential of the generated residues to be used in biorefining processes aimed at producing various bioproducts.

2.4 Expert panel

To determine the weight of the selected criteria, expert opinions were sought from a panel of 14 professionals with direct expertise in the subject matter. It is recommended that such panels include 7 to 15 participants to maintain high confidence levels and reliable evaluations (Gómez Montoya et al., 2008). Additionally, a Google Forms questionnaire was structured based on the AHP method, allowing each expert to assess the agricultural by-products according to the established selection criteria to be used as feedstock in a small-scale biorefinery. Once the expert panel evaluated and weighted the selection criteria, a consensus was reached for AHP implementation.

2.5 Software Tools Used

The study employed Super Decisions V3.2, a free educational software developed by Saaty for Analytic Network Processes (ANP) and Analytic Hierarchy Processes (AHP).

3 Results and Discussion

Based on the reviewed literature, the lignocellulosic composition, as well as the proximate and elemental content of the evaluated residues, was determined (Table 3). Depending on their composition, these residues can serve as raw materials for the production of textiles, packaging, steroids, pulp and paper, construction materials, fertilizers, and animal feed. Lignocellulosic materials have applications in both animal and human consumption products. Previous studies have demonstrated their use in the production of alcohol, xylose, xylitol, and xylo-oligosaccharides (Muñoz-Muño et al., 2014).

Table 3. Lignocellulosic, proximal and elemental composition of the analyzed wastes

Biomass	Cel (%)	Lig (%)	Hemic (%)	Hum (%)	SV (%)	CF (%)	Cn (%)	C (%)	N (%)	H (%)	O (%)	S (%)	References
Coffee husk	24.50	23.70	29.70	11.30	72.94	7.76	8.00	39.68	3.01	5.41	51.58	0.32	(Murthy and Madhava Naidu, 2012; Zinla et al., 2021)
Cocoa shell	30	35	10	10.91	61.17	19.78	8.14	41.59	1.67	6.18	45.98	0.10	(Martínez-Ángel et al., 2015; Tsai et al., 2020)
Cocoa mucilage	41.68	6.05	21.14	84.71	ND	ND	0.37	66.41	3.44	6.35	18.10	0.05	(Widjaja et al., 2021; Saavedra-Sanabria et al., 2021; González Cabra and Suarez Muñoz, 2018)
Corn cob	50	15.80	33.80	10.20	56.77	41.86	1.37	45.69	5.65	6.18	41.65	0.04	(Montiel and Romero, 2015; Kluska et al., 2020)
Banana peel	13	14	14.80	11.56	88.02	2.70	9.28	35.65	1.94	6.19	45.94	20.75	(Kumar et al., 2016; Kabenge et al., 2018)
Sugarcane bagasse	42.19	21.56	20.60	5.92	81.55	10.91	1.62	45.50	0.80	5.63	48.07	0.21	(Álvarez, 2016; Adeniyi et al., 2019; Zamora Rueda et al., 2015)

Cel: Cellulose, Lig: Lignin, Hemic: Hemicellulose, Hum: Moisture, SV: Volatile solids, CF: Fixed carbon, Cn: Ash, ND: Not determined

The methods of proximal and elemental analysis (Table 3) show potential for reflecting the chemical energy content of biomass, allowing for the evaluation of the sustainability of biorefineries that co-produce bio-oil, biochar, biodiesel, glycerol, and bioelectricity (Aghbashlo et al., 2020). Elemental analysis, or ultimate analysis, estimates the potential emissions of pollutant gases produced during combustion (Rojas et al., 2018). Generally, biomass contains between 70 % and 86 % volatile matter and a low carbon content, making it a highly reactive fuel. Fuels with low volatile solids can result in flameless combustion, whereas a high volatile solids content can ignite easily (Akowuah et al., 2012; Yang et al., 2017). In bio-oil production, a higher volatile matter content implies a greater yield (Cai et al., 2017). Likewise, the higher the fixed carbon content, the higher the temperature during the energy conversion process, as this is the actual fuel present in the biomass (Palacios Vallejos et al., 2020).

Biomass ash can be used as a fertilizer. However, ash elements can also cause problems during combustion. A high ash content reduces process efficiency, which is why biomass with a low ash content is preferred as a fuel source (Yang et al., 2017; Zając et al., 2018). Determining moisture levels is important because high moisture levels can cause boiler issues during combustion processes, while low moisture levels can lead to accelerated combustion (Ku Ahmad et al., 2018).

Another aspect to consider is the processing method used to transform waste. Biomass is a complex raw material, and its conversion into the final product requires processes that can be classified into four main treatments: physical, chemical, physicochemical, and biological to improve the accessibility of its biopolymers in industrial processing (Orejuela-Escobar et al., 2021; Moreno et al., 2019). Mechanical grinding and extrusion are promising physical pretreatment methods for biomass conversion (Moreno et al., 2019). They are responsible for particle size reduction and increase the surface area of lignocellulosic materials (Kumari and Singh, 2018).

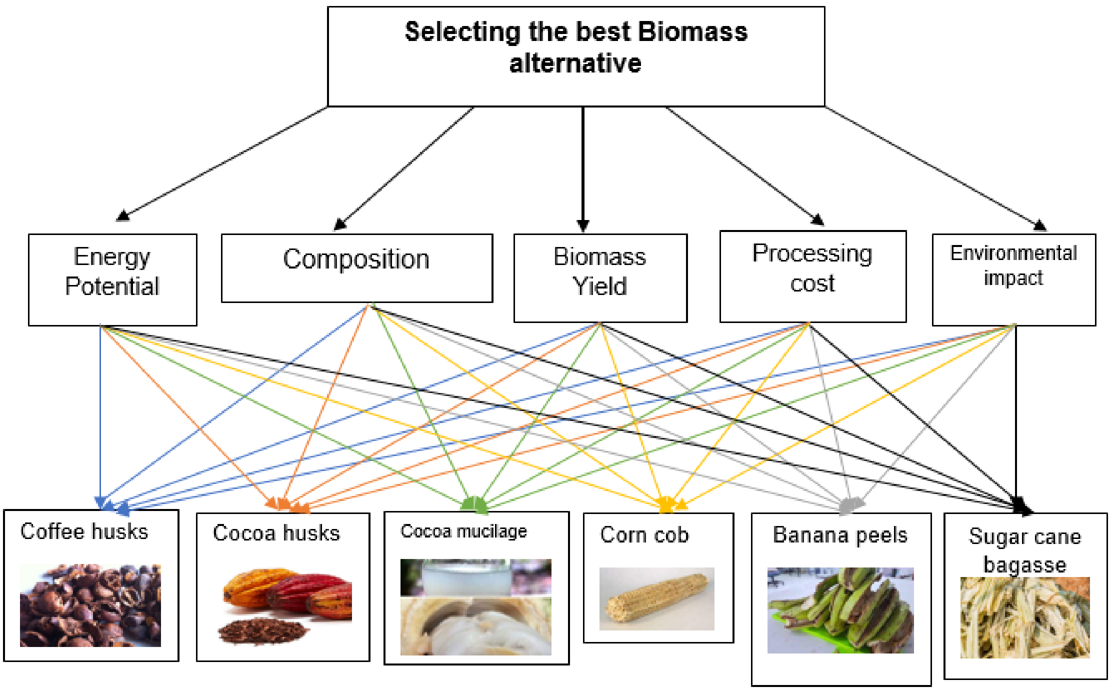

Figure 1. Hierarchical structure of the selection of agricultural by-products in the province of Manabí.

Chemical treatment is one of the most promising methods for improving cellulose biodegradability by removing lignin and hemicelluloses (Behera et al., 2014). This treatment can be further classified into alkaline, acidic, sulfite, organosolv, and ionic methods (Oh et al., 2015). In the paper industry, these chemical methods have been used for delignification, which aims to remove non-cellulosic fractions through alkaline treatment (Michelin et al., 2020). Physicochemical conversion includes methods that combine physical changes and chemical reactions during processing, with steam explosion being one of the most widely used physicochemical biomass pretreatments. This type of conversion process leads to the production of high-density biofuels (Jędrzejczyk et al., 2019).

Biological treatments use enzymes or organisms to hydrolyze cellulose and hemicellulose and ferment sugar molecules (Kumari and Singh, 2018). The goal is to produce biofuels, as well as various types of chemicals such as biogas, hydrogen, ethanol, butanol, acetone, etc. Biomass with a high percentage of biodegradable organic matter and high moisture content is generally preferred. The most commonly used processes of this type are anaerobic digestion and fermentation (Zinla et al., 2021; Garba, 2020).

The industrial-scale processing of biomass involves a combination of the described processes, depending on the production system design and the expected products. Considering the above and to select the most important agricultural byproduct for its utilization in a biorefinery facility, the analytical hierarchy process was applied. To achieve this, a multilevel hierarchical structure was developed, linking selection criteria and alternatives (Figure 1). The normalized matrices for each selection criterion were obtained based on the weighting provided by the expert panel (see Annexes). Subsequently, the normalized matrix of the selected criteria (Table 4), the priority of the alternatives (Table 5) and the consistency ratio of each criterion (Table 6) were obtained.

The results obtained indicate that among the evaluated byproducts, the best one for the intended purpose was sugarcane bagasse, with a priority vector of 33.20 %, followed by coffee husk at 26.10 %. These two biomasses would perform best as raw materials in a small-scale biorefinery within the analyzed context. Regarding the evaluated criteria, composition and environmental impact prevail over the rest, suggesting the possibility of using lignocellulosic residues such as sugarcane.

Table 4. Standardized matrix of selected Criteria

Criterion	PE	C	RB	CP	IA	Normal	Ideal
PE	1	0.33	0.2	1	0.33	0.074	0.221
C	3	1	3	5	1	0.334	1
RB	5	0.33	1	5	0.33	0.202	0.606
CP	1	0.2	0.2	1	0.2	0.057	0.171
IA	3	1	3	5	1	0.334	1

PE: Energy potential, C: Composition, RB: Biomass yield, CP: Cost of processing, IA: Environmental impact

Table 5. Priority of alternatives

Graphic	Alternatives	Total	Normal	Ideal	Classification
	1 Coffee husk	0.131	0.261	0.787	2
	2 Cacao shell	0.103	0.205	0.618	3
	3 Cocoa mucilage	0.021	0.042	0.125	5
	4 Corn cob	0.021	0.041	0.125	6
	5 Plantain peel	0.059	0.118	0.355	4
	6 Sugarcane bagasse	0.166	0.332	1	1

In a similar study, the sustainability of different biomasses (agricultural and forestry residues) was evaluated using ecological economics tools, including AHP. The results from the multicriteria analysis showed that sugarcane bagasse (Jiménez et al., 2020), with a priority vector of 0.57, had the highest energy contribution. In terms of energy, sugarcane bagasse represents one of the largest sources of bioenergy (Amezcua-Allieri et al., 2019). The results obtained have a consistency index equal to or lower than 0.10, meaning that the consistencies were acceptable and valid for decision-making.

The main reasons for the relatively higher preference for sugarcane bagasse are its richness in polysaccharides, making it a promising raw material for biofuel production and other chemicals under a biorefinery concept. Proper management of this waste resource creates an opportunity to generate additional income (Konde et al., 2021; Restrepo-Serna et al., 2018).

In biotechnological processes, sugarcane bagasse can be used as a carbon source to produce second-generation ethanol, xylitol, biogas, and platform products such as glucose and xylose, from which other high-value compounds can be derived (Antunes et al., 2021; Nosratpour et al., 2018). In recent years, succinic acid, a value-added chemical, has been derived from sugarcane bagasse and investigated as a biorefinery co-product (Nieder-Heitmann et al., 2019). Additionally, this residual biomass can be used in fermentation processes to obtain compounds such as butanol, lactic acid, and poly-3-hydroxybutyrate (PHB), which have been identified for its inclusion in the range of multiproduct biorefineries (Restrepo-Serna et al., 2018).

Second in priority is coffee husk, whose interest arises due to its high potential value. Given its composition rich in polysaccharides, along with a significant number of other active biomolecules, it is possible to obtain value-added products from this biomass (Oliveira et al., 2021; Mora-Villalobos et al., 2021).

Table 6. Consistency ratio obtained in the criteria.

Matrix	RC
Energy Potential	0.103
Composition	0.096
Biomass Yield	0.099
Processing Cost	0.088
Environmental Impact	0.093

Coffee husk can yield bioproducts such as citric acid, lactic acid, polyhydroxyalkanoates, biofuels, cosmetics, and others (Aristizábal-Marulanda et al., 2017; Iriondo-DeHond et al., 2020). Additionally, coffee husk has been proposed as a filler in polymeric matrices as a low-cost alternative. Moreover, due to its high cellulose and hemicellulose content, along with its high calorific value, it is a promising raw material for bioenergy production (Rambo et al., 2015; Sisti et al., 2021).

4 Conclusions

The application of an analytical hierarchy process allowed for the identification of the best biomass option to be used as a raw material in a small-scale biorefinery in the province of Manabí. The most important evaluation criteria were raw material composition and environmental impact, both of which received equal global weight among all those assessed. Through multicriteria analysis, it was determined that sugarcane bagasse is the most promising alternative compared to the other studied biomasses.

Thus, this agricultural residue represents an interesting alternative for the country's bioeconomic progress, as it creates opportunities for the development of new products and participation in the global market. Lignocellulosic residues are renewable sources, and their composition and structural properties have significant effects on their conversion within a biorefinery processing perspective. Understanding the composition of these residues makes it possible to predict the type of treatment required to obtain a wide range of bioproducts.

Authors' contribution

J.M.S.B.: Research, methodology, writing- original draft, visualization. G.A.Z.V.: Research, methodology, writing- original draft, visualization. R.E.C.C.:

Validation. M.A.R.: Conceptualization, supervision, validation, writing- review and editing.

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Appendix

Table A 1. Normalized energy potential criteria matrix.

	Coffee husk	Cocoa shell	Cocoa mucilage	Corn cob	Banana peel	Sugarcane bagasse	Normal	Ideal
Coffee husk	1	5	5	5	5	0.2	0.246	0.495
Cocoa shell	0.2	1	1	0.333	0.2	0.143	0.036	0.073
Cocoa mucilage	0.2	1	1	0.333	0.333	0.143	0.039	0.078
Corn cob	0.2	3	3	1	0.333	0.143	0.068	0.137
Banana peel	0.2	5	3	3	1	0.2	0.115	0.231
Sugarcane bagasse	5	7	7	7	5	1	0.497	1

Table A 2. Normalized composition criteria matrix

	Coffee husk	Cocoa shell	Cocoa mucilage	Corn cob	Banana peel	Sugarcane bagasse	Normal	Ideal
Coffee husk	1	0.333	7	7	5	1	0.231	0.530
Cocoa shell	3	1	7	5	5	5	0.435	1
Cocoa mucilage	0.143	0.143	1	1	0.333	0.143	0.035	0.079
Corn cob	0.143	0.2	1	1	1	0.143	0.046	0.107
Banana peel	0.2	0.2	3	1	1	1	0.081	0.187
Sugarcane bagasse	1	0.2	7	7	1	1	0.172	0.397

Table A 3. Normalized biomass yield criteria matrix

	Coffee husk	**Cocoa shell**	**Cocoa mucilage**	**Corn cob**	**Banana peel**	**Sugarcane bagasse**	**Normal**	**Ideal**
Coffee husk	1	5	7	7	3	0.2	0.234	0.471
Cocoa shell	0.2	1	3	5	0.333	0.143	0.075	0.150
Cocoa mucilage	0.143	0.333	1	1	0.2	0.143	0.033	0.067
Corn cob	0.143	0.2	1	1	0.2	0.143	0.032	0.064
Banana peel	0.333	3	5	5	1	0.2	0.129	0.260
Sugarcane bagasse	5	7	7	7	5	1	0.497	1

Table A 4. Normalized processing cost criteria matrix

	Coffee husk	**Cocoa shell**	**Cocoa mucilage**	**Corn cob**	**Banana peel**	**Sugarcane bagasse**	**Normal**	**Ideal**
Coffee husk	1	1	1	5	1	0.333	0.148	0.401
Cocoa shell	1	1	3	9	7	3	0.370	1
Cocoa mucilage	1	0.333	1	3	3	0.333	0.117	0.317
Corn cob	0.2	0.111	0.333	1	1	0.143	0.037	0.101
Banana peel	1	0.143	0.333	1	1	0.2	0.060	0.161
Sugarcane bagasse	3	0.333	3	7	5	1	0.267	0.721

Table A 5. Normalized environmental impact criteria matrix

	Coffee husk	**Cocoa shell**	**Cocoa mucilage**	**Corn cob**	**Banana peel**	**Sugarcane bagasse**	**Normal**	**Ideal**
Coffee husk	1	7	9	5	3	1	0.328	0.875
Cocoa shell	0.143	1	1	5	0.2	0.143	0.063	0.169
Cocoa mucilage	0.111	1	1	1	0.2	0.143	0.040	0.106
Corn cob	0.2	0.2	1	1	0.2	0.143	0.036	0.097
Banana peel	0.333	5	5	5	1	0.2	0.158	0.421
Sugarcane bagasse	1	7	7	7	5	1	0.375	1