



Bioenergy and Biorefinery Potential of Residues: A Representative Case of the Sucre Region in Colombia

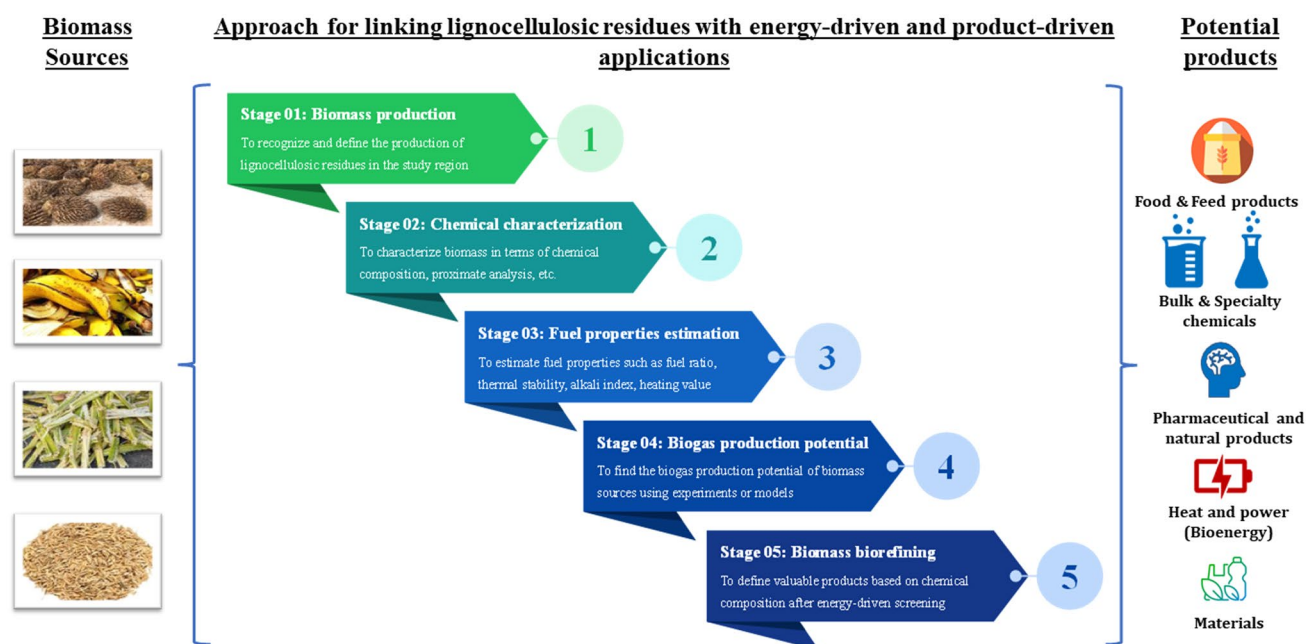
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Abstract

Agricultural and agroindustrial residues are produced worldwide but these residues do not have a specific use. Then, a high potential to produce bioenergy and value-added products has been wasted. Biomass conversion routes should be proposed based on regional needs, making different upgrading processes more reliable and feasible. Thus, bioenergy applications should be analyzed as potential solutions before analyzing prospective products based on the biomass chemical composition. The objective of this research is to provide an approach for defining potential energy-driven applications of lignocellulosic biomass in developing countries with high availability of biomass sources as a result of the agricultural vocation of a region/country. As a case study, this paper shows the Sucre region in Colombia. A methodological approach to define thermochemical, anaerobic digestion, and biorefining upgrading pathways is provided based on chemical characterization, proximate analysis, fuel properties, and biogas production potential. Corn cobs, rice husk, cassava stem, and subverified cassava stem were the most suitable feedstocks for thermochemical upgrading. Avocado seeds, peels, and cassava leaves were selected as the most suitable raw materials for biogas production. Finally, plantain peel, rachis, and organic food waste were selected as potential and prospective raw materials in biorefinery systems to produce high-value-added products.

Graphical Abstract



Extended author information available on the last page of the article

Keywords Anaerobic digestion · Bioenergy · Economic analysis · Environmental assessment · Gasification · Pyrolysis

Statement of Novelty

Lignocellulosic biomass has been profiled as a potential source of value-added products and energy vectors. Nevertheless, several research papers have been published proposing different products without considering regional needs. Most biomass applications have been proposed based on innovative processes, leaving aside applications related to bioenergy production. Few papers have been focused on analyzing the influence of the context on the bioenergy and biorefining potential of lignocellulosic raw materials based on chemical composition and proximate analysis. The statement of the novelty of this research is addressed to propose a systematic approach to define energy-driven and product-driven applications based on the chemical characterization of biomass, proximate analysis, fuel properties, and biogas production potential. This research can serve stakeholders, shareholders, and entrepreneurs to consider a new approach to selecting and implementing more reliable biomass upgrading processes. Moreover, the novelty of this research is related to second-generation biomass (i.e., lignocellulosic biomass) use and management to provide bioenergy solutions and boost rural bioeconomies before proposing complex processes and prospective scenarios. This analysis comprises a methodological approach and a product portfolio to define energy-driven and product-driven biorefineries based on the integral conversion of all biomass fractions.

Introduction

Agroindustrial activities alongside the value chain links allow the transformation of agricultural raw materials into final products. However, waste generation along the links of the value chains is a production inherent factor due to the fast-growing population [1]. Agroindustrial and agricultural waste management, along with the excessive use of fossil fuels in each of these links, represents a critical challenge for environmental sustainability. Furthermore, agricultural and agroindustrial production generates a significant amount of organic and inorganic waste, and the improper management of those wastes represent serious environmental repercussions [2, 3]. Indeed, these wastes can contaminate soil and water, alter local ecosystems, and contribute to the emission of greenhouse gases, such as methane and, NO_x and SO_x compounds [1]. Moreover, the excessive use of fossil fuels in agricultural machinery and the transportation of agricultural products leads to the release of carbon dioxide, a gas

that contributes to climate change. The relationship between these factors is undeniable, since agribusiness and agriculture depend largely on fossil energy to operate and, at the same time, generate waste that will aggravate environmental problems if not properly managed [4]. The lack of efficient waste management systems and the lack of awareness about the importance of proper disposal contribute to waste accumulation and the intensification of environmental impacts [5, 6].

To address these challenges, promoting sustainable agricultural practices, raising awareness about the importance of responsible management of agricultural and agribusiness waste, and implementing sustainable technologies for using these wastes as biomass, which is valued as raw material, is essential [7]. This last measure helps reduce environmental impact and guarantees long-term economic and social benefits. Consequently, the transformation of biomass is a key strategy to implement a sustainable bioeconomy and move towards a more circular and environmentally friendly economy [8, 9]. The connection between a sustainable transformation of biomass and the bioeconomy is based on the idea of taking advantage of resources from agroindustrial and agricultural practices to produce a wide range of products and energy [10]. In addition, dependence on non-renewable resources is reduced, and the environmental impact is minimized. Different scientific research papers have addressed the transformation of biomass as a strategy to replace non-renewable resources, such as fossil fuels, in producing energy and chemical products. For instance, biomass can be converted into bioplastics, biofuels, and green chemicals, reducing dependence on exhaustible resources and decreasing carbon emissions [1, 11, 12]. Moreover, the concept of bioeconomy promotes the idea of a closed cycle of production and consumption, in which products at the end of the useful life are recycled or converted into new resources [13]. Biomass can play an essential role in this circular economy by being considered a raw material for manufacturing biodegradable and compostable products that minimize waste generation.

Promoting the productive and energy transition through the use of agroindustrial waste as raw material is essential to move towards a more sustainable economy that is less dependent on fossil resources [14]. For this reason, countries with high rates of agricultural and agroindustrial activities are actively working to promote industries to obtain high value-added products and bioenergy from the agricultural waste generated. In open literature, various authors have described different transformation routes of agroindustrial

waste through chemical, catalytic, biological, and thermochemical processes. Biomass comprises different proportions of cellulose, hemicellulose, lignin, fats, proteins, starch, pectin, and extractives. Thus, selecting the best conversion route based on the chemical composition is necessary when defining biomass conversion routes. This issue has been studied and analyzed by Ortiz-Sanchez et al. [15]. These authors proposed a product portfolio and a biorefinery design strategy based on the chemical composition of biomass. The high availability and diversity of lignocellulosic raw materials produced in a region make it difficult to choose the most beneficial biomass valorization process in socio-economic and environmental terms. Indeed, biomass conversion routes should be proposed based on regional needs, making different upgrading processes more reliable and feasible. Accordingly, bioenergy or energy-driven applications should be analyzed as potential solutions before analyzing prospective products based on the chemical composition of biomass.

The objective of this study is to elucidate a methodological approach for defining potential energy-driven and product-driven applications of lignocellulosic biomass in developing countries with high availability of biomass sources as a result of the agricultural vocation of a region/country. The statement of the novelty of this research is addressed to propose a systematic approach to define energy-driven and product-driven applications based on the chemical characterization of biomass, proximate analysis, fuel properties, and biogas production potential. This research can serve stakeholders, shareholders, and entrepreneurs to consider a new approach to selecting and implementing more reliable biomass upgrading processes. Moreover, the novelty of this research is related to second-generation biomass (i.e., Lignocellulosic biomass) use and management to provide bioenergy solutions and boost rural bioeconomies before proposing complex processes and prospective scenarios. As a case study, this paper shows the Sucre region in Colombia since a large amount of lignocellulosic biomass is produced. In addition, a high diversity of residues is available. Indicators to match lignocellulosic residues with suitable valorization pathways are described for this. Finally, process simulation tools and rigorous analysis are done to assess the economic and environmental performance of the proposed upgrading processes.

Methodology

The selection of bioenergy and bioprocessing routes based on chemical characterization seeks to define the most suitable processes to upgrade lignocellulosic biomass. This research proposes to analyze different indicators for screening conversion routes. This screening process is done in

three stages. The first stage concerns recognizing the lignocellulosic residues produced in the study region (i.e., list each residue and identify the total production in a period) and the on-site production characteristics (e.g., moisture content and density). The second stage is related to the samples collection and chemical characterization. The third stage is addressed to estimate the biomass fuel properties. The fourth stage seeks to define the biogas production potential based on the biogas production potential. Finally, the fifth stage is based on the methodology proposed by Ortiz-Sanchez et al. [15] for selecting the most feasible products from a prospective viewpoint. Figure 1 shows the methodological guide for linking lignocellulosic biomass with reliable and feasible applications.

The stages of the proposed approach for screening lignocellulosic biomass conversion routes are applied to the Sucre region in Colombia since many residues are produced without any specific use. Nevertheless, this approach can be applied to any other worldwide region. The stages mentioned above are described below:

First Stage: Recognizing Lignocellulosic Biomass Production and On-Site Characteristics

The lignocellulosic biomass residues produced in the Sucre region were identified based on the most representative crops harvested. Statistical information related to crop harvested area, annual residue production, source, and physical characteristics was retrieved from field visits and Colombian reports [16]. Table 1 shows the crops, harvested area, residues, and annual production of the most representative agricultural products of the Sucre region.

This stage is addressed to identify the lignocellulosic residues with high availability and on-site production characteristics (i.e., centralized production, moisture content, and density). This first stage gives a list of raw materials to be characterized in terms of chemical composition, proximate analysis, and heating value. The residues with high potential to be used in bioenergy production or biorefining are (i) corn cob, (ii) rice husk, (iii) industrial cassava leaf, (iv) lower stem of industrial cassava, (v) upper stem of industrial cassava, (vi) plantain rachis, (vii) plantain pseudostem, and (viii) food residues. This step was the starting point of the experimental, simulation, and techno-economic analysis described in the following stages.

Second Stage: Samples Collecting and Chemical Characterization

The second stage is addressed to collect the raw materials identified in the previous stage. The chemical

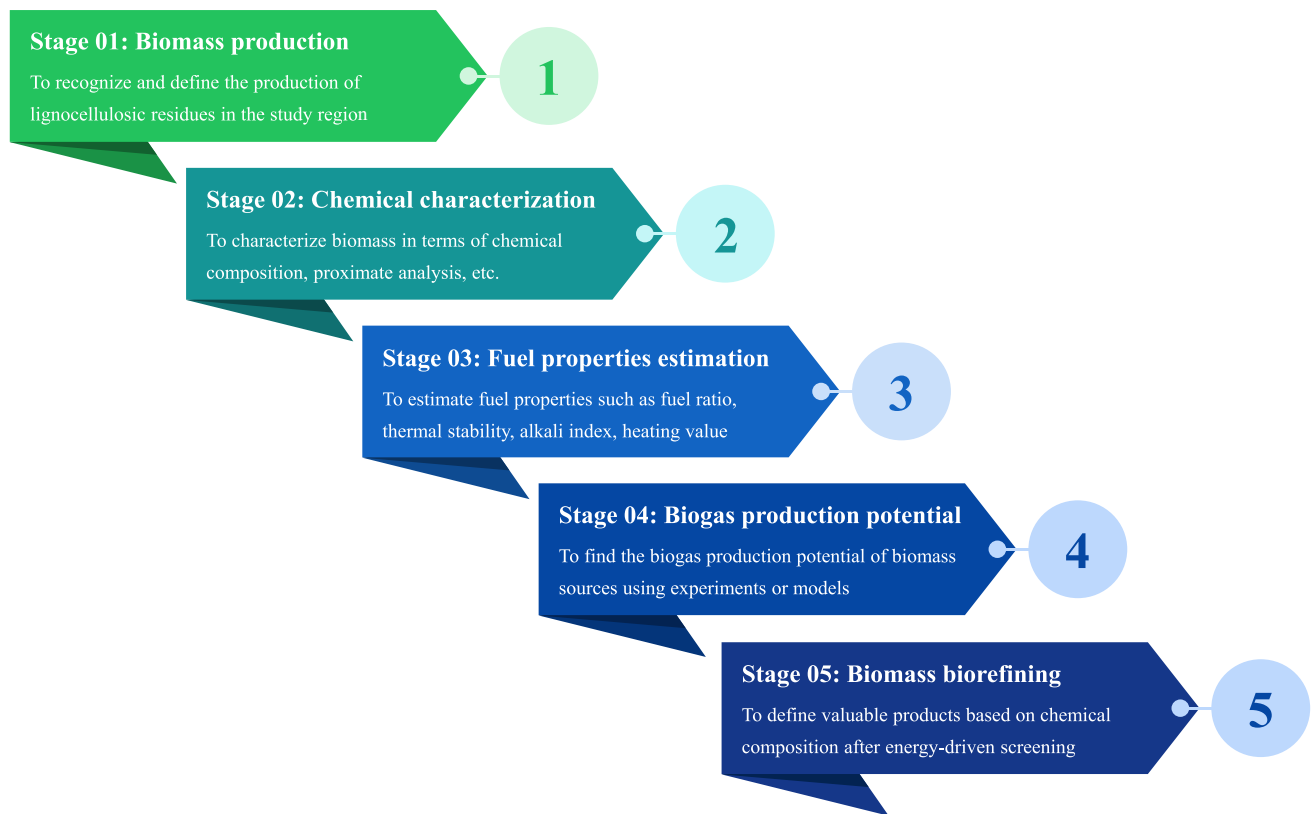


Fig. 1 Methodological approach for linking lignocellulosic residues with energy-driven and product-driven applications

Table 1 Lignocellulosic biomass produced in Sucre, Colombia: land occupation, production, source, and physical characteristics [16]

Crop	Land occupation (%) ^a	Residues	Production (tonnes/year)	Source	Physical characteristics	
					Moisture (%)	Bulk density (kg/m ³)
Rice	41.30	Rice husk	27,843	Agroindustry	6	120
		Rice straw	146,178	Agriculture	9	450
Corn	18.30	Stover	57,392	Agroindustry	N.R	60
		Cob	55,642	Agroindustry	7	190
		Leaves	92,501	Agriculture	8	82
		Stalks	157,672	Agriculture	7	127
		Leaves	6922	Agriculture	72	70
Cassava	22.04	Stem	15,653	Agriculture	59	160
		Subverfied stem	6467	Agriculture	52	220
		Rachis	312	Agriculture	71	N.R
Plantain	1.69	Pseudostem	7085	Agriculture	87	97
		Peel	416	Market-consumption	76	N.R
		Leaves	1041	Agriculture	69	75
Avocado	0.54	Peel	372	Market-consumption	67	N.R
		Seed	294	Market-consumption	64	N.R
ORFW	N.A	ORFW	5198	Market-consumption	82	N.R

^aLand occupation is defined as the ratio between the crop harvested area and the total area destined to agriculture

ORFW organic retail food waste, N.A not apply, N.R not reproted

characterization of these raw materials must be done to elucidate upgrading possibilities.

Raw Material Origin and Reagents

The samples of the above-mentioned raw materials were provided as agroindustrial value chain residues from the Department of Sucre (10°08'03" and 08°16'46" N and 74°32'35" and 75°42'25" W) in Colombia. For the chemical characterization procedures, the following chemical compounds were used: 99.8% ethanol (Mallinckrodt), 96% acetic acid (Chemi), sodium chlorite industrial grade (JT-Baker), sodium hydroxide (Merck), and sulfuric acid 98% (Chemi).

Chemical Characterization

The samples were subjected to a forced-air convection drying oven at 40 °C until constant weight. To analyze the moisture, extractives, lignin, cellulose, hemicellulose, overall solids, volatile solids, and ash content in the raw material, a knife mill (Gyratory mill SR200 Gusseisen from Redsch GmbH, Germany) was used to grind the samples into a powder with a particle size of 0.425 mm (40 Mesh ASTM). The raw materials were stored at room temperature until use. The chemical composition analysis was done to determine the water and ethanol soluble extracts, fiber (i.e., cellulose, hemicellulose, and lignin), and ash contents. International standard methods were followed. All the experimental procedures were done in triplicate.

The NREL/TP-510-42619 procedure was applied to evaluate the amount of extractives present [17]. The cellulose and hemicellulose fractions were quantified using the sodium chlorite method [18]. First, holocellulose was extracted from the raw material by reacting with sodium chlorite. Holocellulose represents the sum of the cellulose and hemicellulose fractions. The solid resulting from this extraction was subjected to reactions with sodium hydroxide solutions, followed by washing with distilled water and acetic acid. The hemicellulose content was determined by calculating the difference in weights. To determine the content of insoluble acid lignin, the method specified in the TAPPI T222 standard was applied [19]. Finally, the ash content was quantified using the method described in the NREL/TP-510-42622 standard [20].

Proximate Analysis

Volatile matter (VM), ash, fixed carbon (FC), and moisture are the main elements to estimate in a proximate analysis. The ash content was estimated by applying the NREL/TP-510–42622 standard. The VM content was quantified as the difference between the amount of the initial sample and the sample after being burned in a platinum crucible inside

an oven at 950 °C for 7 min according to ASTM E872-82 standard method [21]. FC was estimated as the difference in mass necessary to complete 100% between ash and volatile matter (on a dry basis) [22]. The higher heating value of the lignocellulosic residues (HHV) was calculated using the correlation reported by Nhuchhen et al. [23].

$$\begin{aligned} \text{HHV} = & 20.7999 - 0.3214\left(\frac{\text{VM}}{\text{FC}}\right) + 0.0051\left(\frac{\text{VM}}{\text{FC}}\right)^2 \\ & - 11.2277\left(\frac{\text{ASH}}{\text{VM}}\right) + 4.4953\left(\frac{\text{ASH}}{\text{VM}}\right)^2 \\ & - 0.7223\left(\frac{\text{ASH}}{\text{VM}}\right)^3 + 0.0383\left(\frac{\text{ASH}}{\text{VM}}\right)^4 \\ & + 0.0076\left(\frac{\text{FC}}{\text{ASH}}\right) \end{aligned} \quad (1)$$

where: (VM) is the volatile matter content, (FC) corresponds to the fixed carbon content, and (ASH) is the ash content of raw material.

Solids Analysis

Total solids (TS) and volatile solids (VS) contents were quantified according to the standard method ASTM E1756-08 [24]. In brief, TS were estimated at 105 °C until constant weight. VS were estimated at 550 °C using the dried raw materials. The samples (1 g) were ignited for 60 min. TS and VS were measured before the anaerobic digestion processes. TS and VS were estimated as potential indicators of the residues' biodegradability. Higher values of the VS/TS ratio higher biogas production potential [25].

Third Stage: Fuel Properties Estimation Based on Chemical Characterization

The Sucre region has different issues related to the energy supply in different rural zones. The same issue can be identified in other rural worldwide regions. Even if no energy supply issues are detected, bioenergy transition has been established to reduce environmental impact and fossil fuel dependence. Efforts to use biomass as an energy source must be made. Nevertheless, not all biomass sources are suitable for producing bioenergy and/or energy vectors applying thermochemical routes (e.g., gasification, pyrolysis, and combustion). This stage seeks to elucidate the bioenergy production potential of different biomass sources and identify the most suitable technology for thermochemical upgrading. For this, the fuel ratio, thermal stability, heating value, ash content, and alkali index are analyzed [26, 27]. The equations of the fuel ratio and thermal stability are presented below:

$$\text{Fuel ratio} = \frac{\text{FC}}{\text{VM}} \quad (2)$$

$$\text{Thermal stability} = \frac{\text{FC}}{\text{FC} + \text{VM}} \quad (3)$$

$$\begin{aligned} \text{Alkali index (kg/MJ)} = & \frac{1000}{(\text{HHV})} \times \frac{\text{Ash}(\%, \text{db})}{(100)} \\ & \times \frac{\text{K}_2\text{O}(\%, \text{ash}) + \text{Na}_2\text{O}(\%, \text{ash})}{(100)} \end{aligned} \quad (4)$$

The biomass fuel properties can help to elucidate the best thermochemical conversion route of lignocellulosic material. Table 2 briefly describes the fuel properties and some guidelines for defining biomass processing alternatives.

Fourth Stage: Biogas Production Potential

Thermochemical processing of biomass cannot be applied to all lignocellulosic materials according to the fuel properties elucidated in the third stage. Nevertheless, bioenergy solutions can be derived from biotechnological conversion based on anaerobic digestion. This stage looks to define the biogas production potential of different residues using experimental or model-based approaches [25]. Experimental setups have been reported in the open literature to find the biogas production potential of biomass [31–33]. Moreover, model-based approaches using stoichiometric factors and kinetics have been reported [34, 35]. This stage is addressed to screen those raw materials with high biogas production potentials for producing bioenergy in decentralized systems. The previous stages ensure the use of biomass as an energy source through technologies with a high technological readiness level—TRL (i.e., energy-driven applications can be easier to implement than a complex conversion process for value-added product obtaining). Biomass-to-bioenergy screening

boosts energy transition and increases energy security (especially in rural regions in developing countries).

Fifth Stage: Biomass Biorefining Based on Products Portfolio

The selection of different value-added products based on chemical characterization must be made after biomass screening for energy-driven applications. The products portfolio proposed by Ortiz-Sanchez et al. [15] is used in the final stage since these authors proposed a systematic approach for defining the most suitable products based on the chemical composition of biomass. In brief, this methodology for selecting feasible bioproducts from biomass comprises five steps (i) Defining the sustainability objective, (ii) Selecting bioprocesses based on the TRL, (iii) Bioprocesses screening based on context, objective, and preliminary techno-economic and environmental metrics, (iv) Formulating scenarios or superstructure, and (v) Assessing selected bioprocesses using simulation tools and techno-economic, environmental, and social indicators (i.e., rigorous analysis).

The product portfolio proposed by Ortiz-Sanchez et al. [15] comprises several processes to upgrade all biomass components. The products portfolio describes the whole conversion of biomass through pyrolysis, gasification, combustion, and anaerobic digestion. At the same time, other processes, such as fermentation, catalytic upgrading, and extraction are defined based on the relative amount of cellulose, hemicellulose, lignin, pectin, fats, and starch. This paper emphasizes those routes addressed to produce bioenergy and/or energy vectors (i.e., thermochemical conversion routes and anaerobic digestion). The product portfolio methodology is applied to those residues without energy-driven applications. This methodology is applied as explained by Ortiz-Sanchez et al. [15]. Nevertheless, this research paper makes more emphasis on the last step since the rigorous

Table 2 Biomass fuel properties and description

Indicators	Description	Reference value	References
Fuel ratio	High fuel ratios are related to difficult fuel ignition, causing more unburnt carbon	Fuel ratios lower than 0.25 are useful for fast pyrolysis. Values between 0.25 and 0.33 are useful for gasification, and values higher than 0.33 are useful for slow pyrolysis	[26, 27]
Thermal stability	Thermal stability indicates more recalcitrance and resistance to thermal degradation. This indicator has been widely applied in biochar characterization	Thermal stability values closer to 1 have high resistance to thermal degradation	[28]
Heating value	The heating value determines the heat released by combustion per unit mass of biomass. High values are desired for combustion processes	Biomass sources with heating values lower than 17 MJ/kg are not suitable for thermochemical processing in the present form	[29, 30]
Alkali index	The Alkali index determines the likelihood of slagging and clinker formation. High values are not desired	Alkali indices higher than 0.17 kg/GJ promote clinker and ash fouling. Values higher than 0.34 kg/GJ ensure fouling	[26]

analysis of energy-driven or product-driven routes must be specified.

The lignocellulosic biomass elucidated for thermochemical conversion, anaerobic digestion, and biorefining were used as input data to simulate energy-driven and product-driven applications. The conceptual design of the gasification, pyrolysis, and anaerobic digestion processes is described in detail. The simulation procedure applied to find the mass and energy balances of the lignocellulosic residues is given. Finally, the methodology to perform the techno-economic and environmental assessment of all the energy-driven and product-driven biomass conversion processes is described.

Gasification and Fast Pyrolysis

Thermochemical conversion of biomass to bioenergy and energy vectors comprises three stages: (i) biomass conditioning, (ii) conversion, and (iii) product purification. Biomass conditioning is addressed to reduce the moisture content and particle size of the raw material. Biomass drying is performed using a continuous rotary drum dryer. This process reduces the moisture content by up to 15% (or less). Industrial equipment operates at 270 °C using natural gas as a heat source. Biomass is milled until 2 cm particles using primary and secondary crushers. The biomass feeding conditions for the gasification and pyrolysis processes are 15% moisture content and a particle size of 2 cm. The conversion stage is done in a fluidized bed gasifier and pyrolyzer. The temperature of the gasification and pyrolysis processes were 800 °C and 500 °C, respectively. The equivalence ratio in the gasification process was set at 0.25, as reported by Abdul Azees et al. [36]. The pyrolysis process is done without air supply [37]. Finally, the product purification stage consists of ash removal, gas cleaning, and bio-oil separation. These processes have been proposed since the TRL of gasification and pyrolysis is high (i.e., TRL 9). These processes are suitable to be implemented in any region. Another advantage related to these processes is related to the modular technologies developed to provide decentralized energy.

Anaerobic Digestion Process

The anaerobic digestion process was performed in a continuously agitated tank due to the large volume of residues to be treated (i.e., 1 ton/h). The agitated tank was selected based on the existing biogas facilities in Europe. The anaerobic digestion process occurs at 35 °C (i.e., mesophilic conditions). The hydraulic retention time (HRT) was set to 25 days. The organic dry matter (ODM) load per m³ of the reactor was fixed at 5 kg/day. The total solids inside the reactor were 3% based on industrial models reported implemented in EU countries [25]. An inoculum was used to start

the anaerobic digestion process. Sludge recycling was done to maintain a stable biogas production. Hydrogen sulfide (H₂S) was removed from biogas using a biological filter. Moisture was removed in a heater [38]. Biogas was subjected to a generation plant for electricity production. The anaerobic digestion process was described based on a high technological development since tanks and other equipment are required. Even so, the anaerobic digestion process can be implemented in rural regions to generate decentralized energy using simpler technologies (i.e., polyethylene bags) [25, 39]. This process has a high TRL (i.e., 9) since several developed and developing countries have implemented anaerobic digestion to upgrade crop residues and livestock waste [40].

Simulation Procedure

An initial processing scale of 1 ton/hour (dry basis) was set for the lignocellulosic biomass conversion routes. The processing scale was set based on the high amount of agricultural and agroindustrial residues produced in Sucre, Colombia. The mass and energy balances of the conversion routes were obtained using the software Aspen Plus v9.0 (Aspen Technology Inc. USA). The simulation process used the Peng-Robinson Equation of State (PR EoS) and the Non-Random Two Liquids (NRTL) activity model. The thermodynamic properties reported by the National Research Energy Laboratory (NREL) were used to introduce components such as cellulose, hemicellulose, and lignin unavailable in the software database [41]. Indeed, temperature-dependent thermodynamic properties such as vapor pressure, ideal gas heat capacity, the heat of vaporization, solid molar volume, solid heat capacity, and liquid heat capacity were added. Scalar properties such as liquid molar volume, critical temperature, critical pressure, molecular weight, acentric factor, ideal gas heat of formation (DHFORM), ideal gas Gibbs free energy of formation (DGFORM), solid standard enthalpy of formation (DHSFRM), solid standard Gibbs free energy of formation (DGSFRM), and standard enthalpy of combustion (HCOM) were introduced to the software [41]. Specifically, the DHSFRM, DGSFRM, and HCOM properties were estimated based on the methodology reported by Peduzzi et al. [42]. Further information related to the simulation of the proposed processes (i.e., Aspen models, specifications, operating conditions) has been reported in the open literature elsewhere. The fast pyrolysis process was simulated based on the kinetic model described by Humbird et al. [43]. This model was used since describes accurately the bio-oil, biochar, and NCG yields of different lignocellulosic materials [44]. The biomass gasification process was simulated by applying an equilibrium-based approach [36]. The anaerobic digestion process was simulated using the model proposed by Rajendran et al. [35]. Finally, the simulation process of

the other processes reported in the products portfolio proposed by Ortiz-Sanchez et al. [15] have been simulated based on previous studies reported elsewhere.

Economic Analysis

The economic analysis was based on the estimation of comparative metrics such as the Net Present Value (NPV), the Payback Period (PBP), the Turnover Ratio (TR), Earnings Before Interest and Taxes (EBIT), and Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA). EBIT and EBITDA were calculated to specify the operating profitability of the second generation valorization routes without considering financing costs. All economic metrics were calculated in US dollars (USD) considering an exchange rate of 1 USD=4191.28 COP (June 30, 2023). The economic analysis was addressed to estimate the discounted cash flow of the waste valorization routes. This estimation considered aspects such as gross profit, depreciation, amortization, Operating Expenditures (OpEx), Capital Expenditures (CapEx), and taxes (e.g., tax rate and interest rate). The income tax and the Weighted Average Cost of Capital (WACC) used were 33% and 10%, respectively, considering the Colombian context. The working hours were 8400 in a year (i.e., continuous process facility with three 8-h shifts). The project lifetime was set at 20 years.

The OpEx was calculated considering the material and energy balances after rigorous simulation. The mass balances were used to estimate the expenses based on the needs of raw materials, chemical reagents, and utility (i.e., energy, steam, cooling water). The labor cost was determined considering the number of employees required, working time, and wage in Colombia. The operators' number of the lignocellulosic processing plants was calculated considering the total working hours of a Colombian employee (47 h per week according to the 2021 labor law) and the total operating time of the processes. Supervisors were defined based on processing areas (one processing area requires three supervisors). The operator and supervisor wages were 1.16 USD/h and 2.32 USD/h. Other OpEx aspects, such as the general and administration costs, laboratory charges, general plant expenses, insurance and taxes, capital depreciation, and maintenance, were considered following the methodology reported by Towler and Sinnott [45].

CapEx was estimated using the methodology reported by Rueda-Duran et al., [46]. The equipment cost of the thermochemical pathways (e.g., gasification and pyrolysis) was retrieved from the open literature and quotations. For instance, the gasification plant cost was 1006 USD/kW installed [47]. The pyrolysis plant cost was 125,000 USD with a processing scale of 1 ton/h [48]. In general, the feeding conditions for the thermochemical routes were 2 cm and 15% of particle size and moisture content. Auxiliary

equipment such as dryers, crushers, and conveyors were considered. The equipment cost of the other second generation conversion routes was calculated using the Aspen Process Economic Analyzer v.9.0 software. The equipment cost estimated by Aspen Plus v9.0 is based on purchasing prices in 2015. The equipment costs were updated to 2023 using the Chemical Engineering Plant Cost Index (CEPCI). The Value Added Tax (VAT) of 19% was considered for all equipment and plants evaluated according to the Colombian context. The costs of equipment installation, instrumentation and control, electrical, civil, and service installation, legal expenses, contingencies, and engineering and supervision were considered following the Towler and Sinnott shares for the Inside Battery Limit (ISBL) and Outside Battery Limit costs (OSBL) [45]. Finally, a sensitivity analysis was carried out based on the sales price of the products and the processing scale of the raw materials to determine the equilibrium point (i.e., profits are equal to costs) and the Minimum Processing Scale for Economic Viability (MPSEF). The costs and sales prices used in the economic analysis are presented in Table 3.

Life Cycle Assessment

Life cycle analysis (LCA) uses the four steps defined in the ISO 14040 and 14044 standards [53]. The first step is to define the objective and scope of the analysis, where the type of LCA, system limits, and functional unit are specified. The second step is to perform the life cycle inventory (ILCA). Finally, the third and fourth steps are related to the assessment and interpretation of the results. In this sense, the objective of the LCA was to compare the environmental impact of the potential bioenergy production using different

Table 3 The costs and prices of raw materials, chemical reagents, utilities and products

Item	Cost	Unit	References
Feedstock			
Raw material	0.05	USD/tonne/km	This work
Food waste	35.81	USD/tonne	
Utilities			
Natural gas	0.49	USD/m ³	This work
Electricity	0.15	USD/kWh	
Cooling water	0.04	USD/m ³	
Operators	1.47	USD/hour	
Products			
Bio-oil	0.23	USD/kg	[49]
Biochar	2.48	USD/kg	[50]
Biogas	0.79	USD/m ³	[51]
Solid digestate	7.36	USD/tonne	[52]
Liquid digestate	4.16	USD/tonne	[52]

raw materials in Sucre, Colombia. An attributional type LCA and a gate-to-gate approach were considered where only the biomass conversion stage was evaluated. The functional unit selected was the 1 MJ of bioenergy produced (or potential bioenergy). The inputs and outputs of the scenarios (ILCA) were obtained from the process simulation. The LCA was carried out using SimaPro v8.3 software. The method used was Greenhouse Gas Protocol v.1.02. Other impact assessment methodologies can be used instead of the proposed method in this research paper. The objective of the environmental assessment is addressed to elucidate the best alternative for upgrading biomass in a series of energy-driven or product-driven biorefineries. An advantage of the proposed methodology is related to providing a guideline for selecting the best upgrading alternative based on technical, economic, and environmental criteria. Thus, the most important idea is not generating a strict dependence of software tools to make any decision.

Results and Discussion

The screening of energy-driven applications of lignocellulosic biomass was done by applying the above-mentioned methodological approach. The results are described considering stages 2 to 5. Stage 1 was described in Sect. 2.1. The raw materials subjected to chemical characterization were: (i) corn cob, (ii) rice husk, (iii) industrial cassava leaf, (iv) lower stem of industrial cassava, (v) upper stem of industrial cassava, (vi) plantain rachis, (vii) plantain pseudostem, and (viii) food residues.

Second Stage: Samples Collecting and Chemical Characterization

The chemical characterization of all samples is presented in Table 4. Residual lignocellulosic samples are polymeric materials of great industrial interest since these are considered renewable and biodegradable products. The chemical composition of agroindustrial residues depends on the type and origin, as well as the environmental and cultivation conditions of the land where they are grown [54]. These characteristics directly affect the contents of cellulose, hemicellulose, and lignin.

The ash content might vary from 1.75%w/w (dry basis) to 21.14%w/w for corn cob and plantain rachis, respectively (see Table 4). According to open literature, ash content in rice husks tends to be the highest when referring to agroindustrial residues. Moayed et al. [55] suggest that this material might be used in the cement and concrete industry, waste management and could be destined for biochar, catalyst, and fertilizer production due to the high ash content. Nevertheless, the experimental results demonstrate that the growing

Table 4 Chemical characterization and proximate analysis of the selected raw materials in Sucre

Crop	Sample	Water extractives	Ethanol extractives	Cellulose	Hemicellulose	Lignin	Ash	VM	FC	HHV
Corn	Cobs	11.08 ± 1.02	7.29 ± 5.62	48.94 ± 1.82	17.89 ± 1.57	13.54 ± 0.58	1.75 ± 0.01	86.76 ± 1.07	11.25 ± 1.07	18.41
Rice	Husk	9.05 ± 0.12	5.49 ± 1.94	37.48 ± 1.51	11.53 ± 1.62	22.39 ± 1.51	14.06 ± 0.09	70.30 ± 0.46	12.16 ± 0.37	16.58
Cassava	Leaves	10.13 ± 0.02	4.92 ± 0.12	46.49 ± 3.83	18.82 ± 1.21	11.26 ± 0.46	8.38 ± 0.17	78.00 ± 0.42	11.85 ± 0.59	17.53
	Stem	14.17 ± 0.58	9.91 ± 0.34	40.03 ± 2.92	11.78 ± 2.83	9.10 ± 0.06	15.01 ± 0.02	77.11 ± 0.07	8.09 ± 0.05	16.21
	Subverified stem	10.82 ± 0.18	7.51 ± 7.21	38.87 ± 2.15	6.81 ± 0.81	23.76 ± 0.15	12.22 ± 0.03	75.45 ± 0.47	12.83 ± 0.50	17.46
Plantain	Rachis	21.40 ± 0.05	7.66 ± 6.55	31.48 ± 1.11	11.20 ± 0.52	7.13 ± 0.44	21.14 ± 0.32	70.28 ± 0.62	11.65 ± 0.30	16.45
	Pseudostem	20.25 ± 1.72	10.27 ± 0.48	45.45 ± 2.03	3.15 ± 1.18	7.54 ± 0.22	13.34 ± 0.45	75.63 ± 0.33	11.21 ± 0.11	17.05
Avocado	Peel	16.30 ± 1.35	14.49 ± 0.98	21.64 ± 1.26	15.04 ± 0.06	9.95 ± 1.08	3.27 ± 0.11	80.26 ± 1.26	16.47 ± 0.68	18.05
	Seed ^a	6.54 ± 0.09	19.92 ± 3.95	37.96 ± 0.45	9.30 ± 0.21	7.78 ± 0.98	2.86 ± 0.10	79.91 ± 0.92	17.23 ± 0.51	18.37
ORFW	ORFW	15.75 ± 1.68	6.64 ± 0.81	50.97 ± 0.68	13.07 ± 1.71	9.20 ± 0.96	4.36 ± 0.35	81.03 ± 0.31	13.04 ± 0.04	18.22

^aSeed cellulose content refers to cellulose and starch content

ORFW organic retail food waste

conditions and the sample-collecting procedures might affect the chemical composition [56]. According to Gottipati et al. [57], in thermochemical applications of biomass, specifically pyrolysis, an increase in lignin content decreases the overall reaction rate but controls the reaction rate in combustion processes. Pasangulapati et al. [58] studied different biomasses for thermochemical upgrading pathways and established that those with elevated lignin content are responsible for greater methane emissions, while CO₂ and CO emissions are increased when using cellulose-rich biomasses. The upper stem of industrial cassava and rice husk are the most feasible raw materials for combustion processes but high CH₄ emissions will be ensured. Finally, raw materials with low lignin and high cellulose content, contribute to incomplete combustion and charring due to the degradation of the cellulose fraction. The heat evolved from burning is limited [59].

Proximate analysis is useful to identify potential thermochemical applications and find the maximum carbon conversion efficiencies achieved in any conversion process [60]. The upcoming analysis helps to elucidate the application of the raw material in combustion, pyrolysis, and gasification processes, at least from a conceptual perspective. Table 2 presents the results of the proximate analysis of agro-industrial waste, as well as the value corresponding to the HHV calculated from Eqs. 1 and 2, along with the average value.

Depending on the type of thermochemical process expected to be carried out with each raw material, the conditions in terms of volatile material and fixed carbon must meet certain specifications. A widely used indicator is the volatile matter/fixed carbon (VM/FC) ratio [61]. With this indicator, the possible behavior of the raw material when subjected to high temperatures can be demonstrated. The VM/FC ratio for these residues covered a range of 6.03 to 9.53 for the plantain rachis and lower stem of industrial cassava respectively. For pyrolysis processes, high contents of volatile matter guarantee greater production of bio-oil. Furthermore, high contents of volatile matter lead to shorter degradation times for combustion processes [27]. Nevertheless, when the process is lead for biochar obtaining from slow pyrolysis, a low fixed carbon content means lower yields, so a lower VM/FC ratio would be expected.

Saffe et al. [62] indicated that biomass with low ash content contributes to greater HHV values, which is proved with the corn cob, upper stem of industrial cassava, and fruit residue samples. Further upgrading processes of these biomasses for biofuel obtaining, must consider that high contents of ash and impurities lead to lower initial degradation temperatures [62]. Finally, Dorez et al. [59] studied the influences of fiber content on pyrolysis and combustion and concluded that lignin-rich raw materials exhibit high effective heat of combustion and high char yield.

Table 5 Fuel properties of different lignocellulosic feedstocks produced in Sucre, Colombia

Crop	Sample	Fuel ratio	Thermal stability	HHV (MJ/kg)	Alkali index ^a (%)
Corn	Cobs	0.13	0.11	18.41	N.R
Rice	Husk	0.17	0.15	17.08	0.50
Cassava	Leaves	0.15	0.13	17.53	0.60
	Stem	0.10	0.09	16.55	0.48
	Subverified stem	0.17	0.15	17.46	0.56
Plantain	Rachis	0.17	0.14	16.45	N.R
	Pseudostem	0.15	0.13	17.05	N.R
Avocado	Peel	0.20	0.17	18.05	N.R
	Seed ^a	0.21	0.18	18.37	N.R
ORFW	ORFW	0.16	0.14	18.22	N.R

^aValues reported in the open literature. Rice husk and cassava leaves [26] and cassava stems [63]

ORFW organic retail food waste

Third Stage: Fuel Properties Estimation Based on Chemical Characterization

The chemical composition and proximate analysis presented in Table 4 allow for estimating the fuel properties described in Sect. 2.3. Nevertheless, alkali index was not estimated since chemical composition of biomass ashes are not reported. Values given in the literature are used in this case. The fuel properties of the agricultural residues are presented in Table 5.

Table 5 presents the fuel properties of different agricultural and agroindustrial waste produced in Sucre, Colombia. Corn cobs, avocado residues, and ORFW are the residues with the highest heating value. Nevertheless, avocado residues and ORFW have a high raw moisture content (see Table 1). These residues are not suitable for thermochemical conversion since a large amount of energy is required to dry the raw materials, affecting the overall energy balance. Avocado residues and ORFW have a high starch content. In this sense, raw materials with high calorific value, lower fuel ratios, and low thermal stability are desired. Rice husk, cassava stem, and cassava subverified stem are the residues with the lowest moisture content. These raw materials are suitable for thermochemical upgrading. The fuel ratios reported in Table 5 (and the proximate analysis in Table 4) allow elucidating the fast pyrolysis process as the best thermochemical application for these raw materials since a high volatile matter content is present. Indeed, these fuel ratio values are in agreement with the range reported in Table 3. The fuel properties reported in Table 5 can change for the same raw material since crop conditions, agrochemicals, and soil properties can change the physiochemical characteristics

of the raw materials. However, the approach can be applied similarly to elucidate the potential bioenergy applications of biomass feedstocks. This statement can be evidenced in different reports done in the open literature related to corn cobs and rice husks. Indeed, corn cobs can have a fuel ratio of 0.23, 0.21, and 0.18 as reported by different authors [64–66]. In the same way, cassava stems and other agricultural waste fuels ration can change depending on the region [23, 29].

Raw materials are prone to volatilize at lower temperatures since all biomass residues decompose at temperatures higher than 200 °C. This thermal decomposition is attributed to cellulose and hemicellulose devolatilization [67]. Raw materials with a high lignin and ash content have higher thermal stability values (i.e., rice husk and cassava subverified stem) [27]. All raw materials fuel ratios are lower than other values reported in the open literature. For instance, cedar wood and pine sawdust have a fuel ratio of 0.25, according to the reported data by Alauddin et al. [64]. These raw materials are suitable for the gasification process. A fast pyrolysis process is proposed for upgrading rice husks, corn cobs, and cassava stems since fuel ratios are lower than 0.25. Biomass gasification is not suitable since all biomass residues in Table 5 do not have not sufficient fixed carbon to produce biochar and promote gasification reactions (e.g., Boudouard reaction) [68]. The alkali index of rice husk and cassava stems is too high for this application since fouling and slagging can occur. Indeed, these raw materials are not recommended to be used in a downdraft gasification equipment [26]. The statement is applied to justify the no selection of the slow pyrolysis process as a thermochemical upgrading alternative. Combustion is always an alternative present in thermochemical processing since directly usable energy in the form of heat and electricity can be produced. Nevertheless, no value-added products are obtained. The combustion process must be carried out as an alternative to reduce biomass disposal issues of different agroindustries. Indeed, Ortiz et al. [69] reported the use of orange peel waste as an energy source for heating a small industry

in Colombia. The same concept can be applied in the rice husk agroindustry.

Fourth Stage: Biogas Production Potential

Raw materials must be selected based on the biogas production potential for biogas production. Table 6 presents the biogas production potential of those residues unsuitable for thermochemical upgrading.

The raw materials with the higher biogas production are cassava leaves, avocado seeds, and avocado peels. These raw materials are proposed as a source of biogas (and electricity) instead of value-added products based on the energy supply issues in Sucre. These raw materials are selected since lower amounts are required to produce 1 MW of energy with an internal combustion engine. 1 MW was selected as a base case since the Colombian government gives financial support to those projects addressed to have more than 1 MW installed. Indeed, the user who produces electrical energy to meet their needs without using distribution and/or transmission components are defined as Small-Scale Self Generators (SSSG). SSSG are classified considering the installed self-generation capacity. SSSG are those users with the potential to produce less than 1 MW according to Resolution 281 of 2015 given by the UPME. Typical SSSG users are rural populations in non-interconnected zones (NIZ) or those companies with an installed electricity capacity lower than 1 MW.

Fifth Stage: Biomass Biorefining based on Products Portfolio

The other raw materials, such as plantain rachis, plantain pseudostem, and ORFW, are more suitable to propose a series of value-added products based on the products portfolio proposed by Ortiz-Sanchez et al. [15]. For instance, ORFW has been evaluated to produce polylactic acid with good techno-economic and environmental performance [70]. The implementation of each one of the steps described by these authors was not described. Nevertheless, the rigorous analysis of the fast pyrolysis and anaerobic digestion processes proposed as an energy-driven application to upgrade agricultural and agroindustrial residues is discussed based on economic and environmental information and methodologies described in Sect. 2.5.4 and Sect. 2.5.3. The following subsections describe the main results of the rigorous analysis:

Economic Analysis: Fast Pyrolysis and Anaerobic Digestion of Agricultural Reisdues

The economic metrics calculated for the pyrolysis route are presented in Table 7. The CapEx for the pyrolysis plant was 604,440 USD, where equipment, direct (e.g., equipment

Table 6 Biogas potential of different lignocellulosic feedstocks produced in Sucre, Colombia

Sample	Biogas potential [m ³ /kg RM*]	Raw material required to produce 1 MW (kg/h)
Cassava leaves	1.01	518.81
Plantain rachis	0.32	1637.51
Plantain Pseudostem	0.81	646.91
ORFW ^b	0.77	680.52
Avocado Seeds	0.92	569.57
Avocado Peels	0.90	582.22

ORFW organic retail food waste

*RM Raw Material

Table 7 Economic metric of fast pyrolysis route

Indicator	Unit	Raw material			
		Cassava stem	Subverified cassava stem	Rice Husk	Corn cobs
NPV	MUSD	1.86	2.37	0.95	1.22
Payback period	Year	7	5	12	10
Turnover ratio	-	3.64	4.51	2.93	3.05
MPSEF	Tonne/year	0.52	0.46	0.74	0.68
Equilibrium point	Tonne/year	0.47	0.33	0.59	0.52
EBIT	MUSD	2.85	3.64	1.56	2.09
EBITDA	MUSD	3.69	4.57	2.82	2.97

NPV net present value, MPSEF minimum processing scale for economic feasibility, EBIT earnings before interest and taxes, EBITDA earnings before interest, taxes, depreciation, and amortization

installation, electrical, service facilities), indirect (e.g., construction and legal expenses), and as functional of total direct and direct (e.g., contingency) costs of plant were 23%, 56%, 18%, and 3% respectively. 98.58% of the equipment costs were from the pyrolysis plant. The raw material conditioning stage (i.e., drying and grinding) contributes 9.42% to the equipment costs. The lower cassava stem was the raw material that presented the best economic indicators. The high mass yields in bio-oil generation in the fast pyrolysis of lower cassava stem improved economic viability. The higher cassava stem had a payback period of 7 years and an NPV of 21.52% lower than the lower cassava stem. The equilibrium point for fast pyrolysis reflects the scale which the plant operates without profit or loss. That is, the product sale (bio-oil) covers the OpEx. This scenario for a decentralized energy context is promising because it covers a basic need in a region. In this sense, scales between 0.33 and 0.59 ton/h of agricultural and agro-industrial waste such as cassava, rice, and corn can be applied in this context. The MPSEF was between 0.46 and 0.74 ton/h, which reflects that at higher scales, there are gains in the rapid pyrolysis of the analyzed waste. These scales can be achieved by covering 11.64–36.87% of waste generation in the department of Sucre. The equilibrium point and MPSEF for rice husk

were 0.59 and 0.74 ton/h. The raw material with the lowest economic performance was rice husk. The mass intensity of husk rice use was the lowest, with lower bio-oil production yields. In the rapid pyrolysis of corn cobs, the MPSEF and the equilibrium point were 8.11% and 11.86% lower than that of rice husk. Finally, in terms of EBIT and EBITDA, the trend in economic behavior was the same, where the pyrolysis of the waste generated by cassava had a better performance than corn cobs and rice husks. Capital depreciation, insurance, and tax costs ranged between 10 and 23% of the OpEx for all raw materials analyzed. Administrative and labor costs were the ones that contributed the most to the OpEx of fast pyrolysis.

The capital investment results are in agreement with the capital investment reported in the open literature. Indeed, the processing scales (i.e., 1 ton/h on a dry basis) is lower than several processing scales [71–73]. Most pyrolysis plants are designed and simulated considering a high scale (e.g., 72 tonnes/day). Then, the capital investment is higher than 10 M.USD. The economy of scale allows elucidating the correspondence between the data obtained and the literature reports. The bio-oil and biochar selling prices were sufficient to reach a positive economic behaviour. Nevertheless, the biochar selling price can be lower since the bio-oil selling

Table 8 Economic metric of anaerobic digestion route

Indicator	Unit	Raw material			
		Food waste	Cassava leaves	Avocado peel	Avocado seed
NPV	MUSD	0.39	0.28	0.44	0.67
Payback period	Year	15	18	11	11
Turnover ratio	–	0.61	0.44	0.76	0.93
MPSEF	Ton/year	0.72	0.84	0.62	0.49
Equilibrium point	Ton/year	0.65	0.71	0.48	0.33
EBIT	MUSD	1.54	1.37	1.67	2.01
EBITDA	MUSD	4.06	3.95	4.69	5.16

NPV net present value, MPSEF minimum processing scale for economic feasibility, EBIT earnings before interest and taxes, EBITDA earnings before interest, taxes, depreciation, and amortization

price can be higher. The results of the economic analysis demonstrated the influence of commercializing biochar and bio-oil as an alternative to increase pyrolysis plant profits. The same conclusion has been described by several authors [71–73].

The economic metrics for the anaerobic digestion route are presented in Table 8. The CapEx of the anaerobic digestion route was 700,800 USD for 1 ton/h of raw material. The equipment cost was 163,700 USD without considering VAT and freight costs (8% of the equipment cost). The digester costs contributed 62.56% of the equipment cost. The raw material conditioning stage contributed 3.62%. The generation of electrical energy was 33.82% of the equipment cost. The best economic indicators were for avocado waste. The payback period was the same for the avocado seed and peel waste. However, the NPV for avocado seed was 12.36% higher than that of avocado peel due to the higher biogas production yield. Regarding MPSEF, an equilibrium point, the avocado seeds were 0.49 and 0.62 ton/h. These scales demonstrate that it is possible in the context of the Department of Sucre to apply anaerobic digestion as a route for producing non-centralized bioenergy. For food waste, the payback period was 15 years, 26.67% greater than for avocado waste despite presenting higher biogas production yields. The acquisition costs of food waste are significantly higher than those of cassava leave and avocado residues. Among the main reasons is the decentralization of food waste. This factor considerably reduces the economic viability of the anaerobic digestion of food waste compared to the other waste analyzed. Regarding EBIT and EBITDA, the trend in economic metrics was the same, where avocado waste presented better results. The costs of capital depreciation instrumentation and taxes ranged between 3 and 8% for

all scenarios. Raw material costs for the anaerobic digestion route were between 30 and 63% for all raw materials analyzed.

In comparative terms, fast pyrolysis presented better economic indicators than the anaerobic digestion route. However, the EBIT and EBITDA results were similar for the two energy production routes because the capital depreciation costs and insurance and taxes were lower for anaerobic digestion than for fast pyrolysis. In this sense, the selection of routes for bioenergy production allows us to find the best waste recovery. The turnover ratio for fast pyrolysis was much higher for fast pyrolysis than for anaerobic digestion, which indicates better turnover for the first energy production route. The highest values of the turnover ratio were reflected in the NPV for rapid pyrolysis and anaerobic digestion. In fast pyrolysis, the NPV was significantly higher than in anaerobic digestion, which implies greater gains.

Environmental Assessment

The environmental impact of the raw materials evaluated by the pyrolysis route is presented in Fig. 2a. The environmental impact for the pyrolysis route was 61–129 gCO₂eq/MJ. The raw material with the lowest environmental impact was cassava stem because the process had greater mass and energy efficiency. In the rapid pyrolysis of the lower cassava stem, the largest amount of bio-oil and biochar was produced compared to the other raw materials, which implies a higher mass intensity. The cassava stem superior had a greater environmental impact than the cassava stem inferior. Corn cobs and rice husks had a higher environmental impact, implying a lower mass yield. This is corroborated by the calculated technical indicators. Finally, the environmental impact of using rice husk to produce biochar and

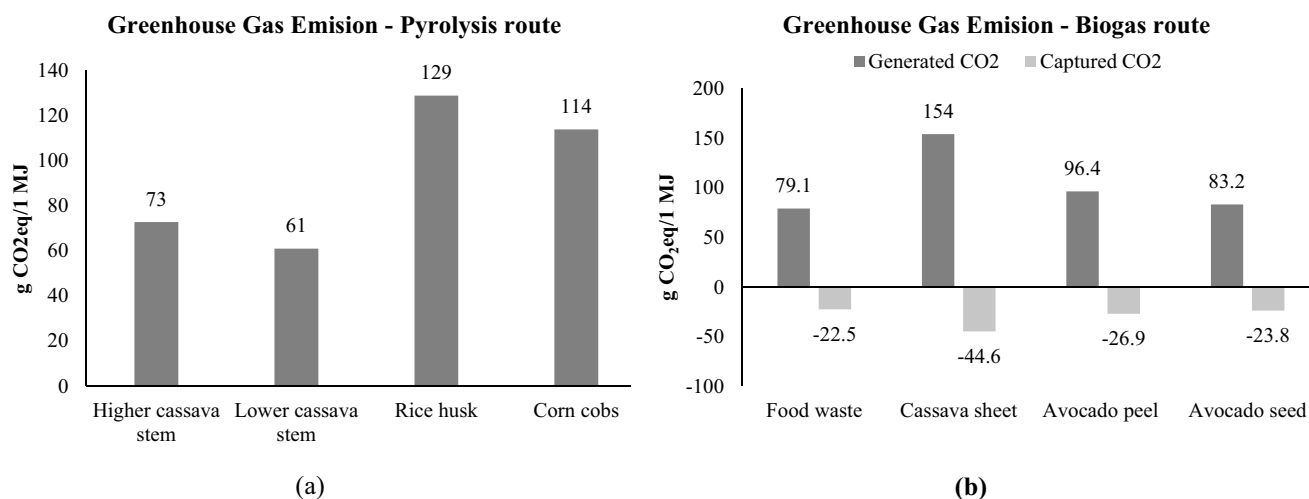


Fig. 2 Greenhouse Gas Emission of **a** pyrolysis and **b** biogas routes

bio-oil was the greatest. In this sense, the fast pyrolysis of rice husk had lower mass yields and mass intensity. The gases (emissions) generated in rapid pyrolysis contribute the most to the environmental impact. Energy consumption in the pretreatment stages (e.g., drying and grinding of raw materials) does not significantly impact greenhouse gas emissions. The generation of greenhouse gases measured in CO_2eq for the fast pyrolysis of different feedstocks has been widely evaluated in the literature. For example, Lan et al. [74] valued the environmental impact of the rapid pyrolysis of wood waste (pine patula waste), obtaining $111.8 \text{ gCO}_2\text{eq/MJ}$, where the gas emissions profile generated is the most polluting factor. However, using biochar generated in slow pyrolysis as a soil amendment reduces greenhouse gases to $19 \text{ g CO}_2\text{eq/MJ}$. Longwen and Hao [75] evaluated the effect of moisture content and particle size of pine residues on the generation of greenhouse gases in predatory pyrolysis, resulting in emissions between 22 and $40 \text{ g CO}_2\text{eq/MJ}$ where the drying stages and Grinding of the raw material has a significant effect on bio-oil production yields and greenhouse gas emissions. In this sense, reducing humidity and particle size increases bio-oil production performance, reducing the generation of greenhouse gases from the process but increasing energy consumption. Therefore, it is necessary to consider the source of energy generation to reduce the environmental impact. Steele et al. [76] demonstrated that changing fuel for energy generation in the pyrolysis processes can reduce emissions by up to 70%. The environmental impact of rapid pyrolysis of agricultural waste has been reported between 520 and $616 \text{ g CO}_2\text{eq/MJ}$, where the generation of greenhouse gases is much higher than those obtained in this research due to low yields of the process (i.e., lower mass intensity) [77].

The results of the environmental impact of biogas production routes for the selected raw materials are presented in Fig. 2b. The environmental impact of the biogas route was between 79.1 and $154 \text{ gCO}_2\text{eq/MJ}$. The greenhouse gas results for the two energy production routes were similar. However, in anaerobic digestion, the waste neutralization in terms of generating greenhouse gases presents a negative value of emissions that implies an advantage in mitigation. In this sense, anaerobic digestion presents an environmental advantage over pyrolysis. Among the raw materials considered for anaerobic digestion, cassava leaves had the greatest environmental impact. The main reason was the low anaerobic digestion performance in biogas production. The valorization of food waste by anaerobic digestion presented the lowest environmental impact. This is due to the biogas production yields. Avocado waste (peel and seed) had an environmental impact of 96.4 and $83.2 \text{ gCO}_2\text{eq/MJ}$. The avocado seed has a lower environmental impact because it has a high content of starch and fats that contribute to increased biogas production performance. As in pyrolysis, the raw materials

with the lowest mass yield of biogas production had the greatest environmental impact. In anaerobic digestion, thermal and caloric energy consumption was the activity that had the greatest influence on the generation of greenhouse gases. The cassava leave presented a higher CO_2 capture value than the other raw materials analyzed in the anaerobic digestion route. The amount of digestate obtained per functional unit (i.e., 1 MJ of energy from biogas) is greater due to the low mass yields of the process. Therefore, the cassava leaves has a low degradation time, generating more solid digestate. Different authors have evaluated the environmental impact of anaerobic digestion considering different raw materials and process configurations (different biogas use routes such as energy or heat). Feiz et al. [78] evaluated the environmental impact of anaerobic digestion of food waste, obtaining between 9 and $83 \text{ gCO}_2\text{eq/MJ}$ for different heat generation configurations. Shinde et al. [39] obtained an environmental impact of $14.3 \text{ gCO}_2\text{eq/MJ}$ in the anaerobic digestion of organic waste, where the upstream stage of biogas contributed 7% to the generation of greenhouse gases. The anaerobic digestion of corn residues and perennial wild plants has an environmental impact in terms of greenhouse gas generation of 280– $849.6 \text{ gCO}_2\text{eq/MJ}$. Most methane emissions are attributed to the addition of agrochemicals in corn cultivation. Indeed, these agrochemicals are the most important sources of GHGs [79]. Siegl et al. [80] evaluated the anaerobic digestion of 40 types of Austrian plants, resulting between 428.4 and $2599.2 \text{ gCO}_2\text{eq/MJ}$. In this sense, the results of this work related to a lower environmental impact for food waste coincide with what is reported in the literature. Kral et al. [2] evaluated biogas production from grassland biomass using a steam explosion pretreatment stage, obtaining an environmental impact of $1828.8 \text{ gCO}_2\text{eq/MJ}$. In this sense, including a pretreatment stage to increase the biogas production yield increases the generation of greenhouse gases.

Policies and Impacts of Energy-Driven Processes in Sucre, Colombia

The selection of promising energy-driven alternatives to upgrade lignocellulosic residues in rural zones of Sucre, Colombia (or any other place), needs more than technical, economic, and environmental indicators. Policies and governmental support are needed to encourage a reliable energy transition. The Colombian government has developed an energy transition framework to improve the current situation in rural regions. For instance, the law 1715 of 2014 is the “spine” of renewable energy production using non-conventional energy sources (e.g., biomass, wind, and sunlight). Resolution 281 of 2015, given by the Energy Mining Panning Unit (UPME), establishes 1 MW of electricity as the minimum electricity capacity generation to classify

large-scale and small-scale self-generators. The electricity self-generators have financial support to develop decentralized projects. Finally, law 2099 of 2021 promotes the energy transition, the revitalization of the energy market, and the economic reactivation of the country. More policies have been developed based on the use of renewable energy sources. Thus, Colombia has all the required support to implement energy-driven transition projects in rural zones. This statement can boost rural regions' socio-economic development based on biomass upgrading and sustainable use of renewable resources. The impact of implementing the technologies mentioned above is related to (i) improving quality of life, (ii) promoting socio-economic development, (iii) encouraging research and development of new strategies to upgrade renewable resources, and (iv) diversifying the energy matrix based on renewables. Finally, implementing energy-driven processes promotes a global economy since the value chains based on agricultural products can increase sustainability. This statement was confirmed based on previous studies in the same region [1]. For instance, producing marketable products and energy vectors can improve the socio-economic development of the Sucre region by creating jobs, more income for families, new market opportunities, and the development of high-quality products with the designation of origin stamps [81, 82].

Limitations and Practical Implications of the Study

The methodological approach for linking lignocellulosic residues with energy-driven and product-driven applications proposed in this study can be applied to upper-middle-income, lower-middle, and low-income countries such as Colombia, Brazil, Peru, and India (among others). These countries have rural regions without an affordable, continuous, and reliable energy supply. These regions are denominated non-interconnected zones (NIZ) with a weak energy matrix (i.e., these areas mostly depend on fossil fuels). The proposed methodological approach has limitations and practical implications. The limitations are related to geographical and economic aspects.

The geographical areas where the methodological approach can be applied are upper-middle-income, lower-middle, and low-income countries such as Colombia, Brazil, Peru, and India. These regions produce a lot of lignocellulosic residues without any specific application. In addition, these regions have different issues related to the energy transition and supply in rural regions. Indeed, there are non-interconnected zones (NIZ) with a weak energy matrix (i.e., these areas depend on fossil fuels in most cases). Specifically in these regions (NIZ), lignocellulosic biomass is the most promising option to encourage rural development. The

geographical restrictions of this research study are delimited to (i) biomass scale and availability and (ii) biomass chemical composition and physical state. Most rural regions in Colombia and Latin American countries do not produce sufficient residues to propose a large-scale facility. Then, medium-scale and small-scale upgrading processes are possible to implement. The economic limitations of the methodological approach are (i) the Technological Readiness Level (TRL) of the biomass upgrading processes proposed, (ii) Capital investment, and (iii) Energy transition policies. The proposed processes (i.e., pyrolysis, combustion, anaerobic digestion) have a high TRL. These processes are easier to implement than processes such as methanol, bioethanol, and butanol. Capital investment (CapEx) is another economic limitation since implementing these processes requires an initial investment based on the scale. Finally, policies and energy transition support are limitations because not all countries have sufficient budgets to support the development of these technologies until they reach an equilibrium point and generate profits. There are several social, technical, and economic challenges to ensure a reliable energy transition. For instance, the social challenges are related to (i) public acceptance and engagement, (ii) public education and awareness, (iii) behaviour change and resistance, (iv) energy justice, (v) labor transition, and (vi) energy security. Instead, economic challenges are related to (i) incentives and investment risk, (ii) mitigation and adaptation costs, and (iii) subsidies [83]. These factors are key to promote energy transition policies to develop and implement biomass upgrading processes in new contexts.

The practical implications of the proposed methodological approach are related to (i) identifying energy-driven applications based on biomass composition, (ii) elucidating the best energy-driven alternative based on the context conditions, and (iii) proposing potential lignocellulosic biomass upgrading routes. These implications can be applied to any context considering biomass composition. The spectrum of lignocellulosic biomass residues is representative since different residues can be involved. Finally, the methodological approach can be applied to any other lignocellulosic residue based on the chemical composition and proximate analysis.

Conclusions

Agricultural and agroindustrial residues have a high potential to be upgraded into a series of value-added products and energy vectors. Nevertheless, the correct management of these residues can make a difference in the energy and productive transition of a region/country. The bioenergy and biorefining approach for selecting suitable technologies serves to screen those raw materials with high availability

to produce decentralized energy and solve energy supply issues in rural regions. The Sucre region has a wide range of residues without any specific use. A systematic approach to defining near-future and prospective applications was essential to determine the potential of these residues to produce bioenergy and value-added products. Corn cobs, rice husk, cassava stem, and subverified cassava stem were the most suitable raw materials for thermochemical upgrading based on their fuel properties. Avocado seeds, avocado peels, and cassava leaves were selected as the most suitable raw materials for biogas production based on the biogas production potential. Finally, plantain peel, rachis, and organic food waste were selected as potential and prospective raw materials for feedstock in biorefinery systems to produce high-value-added products. This selection was based on the chemical composition of the raw materials (i.e., cellulose, starch, and hemicellulose content).

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they do not have competing interests.

Ethical Approval This paper has not been published previously. It is not under consideration for publication elsewhere. The will not be published elsewhere in substantially the same form, in English or any other language, without the written consent of the Publisher. The authors of the manuscript involve only those who have made significant contributions to the conception, design, execution, and analysis of the present manuscript. Finally, the authors ensure that they have written the submitted manuscript entirely, and the references of other works have been correctly cited.

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