

Article

Biomass Energy from Agricultural Waste at Peninsula de Santa Elena: A Sustainable Opportunity for Local Development

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Abstract

This study evaluates the technical, environmental, and economic feasibility of converting plantain and banana biomass (PBB) into renewable energy in the Santa Elena province, Ecuador. Through GIS-based assessment, empirical correlations for heating value estimation, and energy/exergy analyses, our work identifies 253,389.98 tons/year of field residues with a theoretical energy potential of 382.79 GWh/year. Passive solar drying and mechanical grinding enable low-energy pre-treatment, yielding a net energy output of 12.41 MJ/kg and an exergy efficiency of 51.2%, confirming the system's thermodynamic viability. If implemented at scale with a 20% plant factor, the energy recovered could meet 17% of the province's current electricity demand. Economic projections estimate a potential annual revenue of USD 18.95 million based on current electricity prices, supporting the profitability of decentralized combustion systems. The integration of PBB into the regional energy matrix contributes to reducing fossil fuel reliance, enhancing energy security, and promoting sustainable rural development. These findings align with Sustainable Development Goals (SDGs) 7 and 13, positioning biomass energy as a viable solution to Ecuador's decarbonization goals and rural energy challenges.

Keywords: biomass; energy; agricultural waste; waste to X; sustainability



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1. Introduction

The increasing global demand for sustainable energy sources has spurred significant interest in biomass energy, which involves converting organic materials into renewable energy. Biomass, particularly from agricultural waste, offers a promising solution to energy security challenges and environmental sustainability [1]. According to the International Renewable Energy Agency (IRENA), biomass could account for up to 17% of the world's total energy supply by 2030, significantly contributing to reducing greenhouse gas emissions and supporting a transition to a low-carbon economy [2]. This energy source not only helps to mitigate greenhouse gas emissions but also promotes waste management and economic development, particularly in rural and agricultural areas [3–5]. Among the various forms of biomass, agricultural waste from banana cultivation presents a unique opportunity as an

energy vector. Bananas, a major global agricultural product, generate substantial organic waste in the form of plant residues and peels, accounting for approximately 60% of the total plant weight [6]. For every ton of bananas produced, an estimated 2 tons of residual biomass, including leaves, pseudostems, and peels, is generated [7,8].

This waste, rich in lignocellulosic materials, can be converted into biofuels such as methane gas and bioethanol through processes like pyrolysis, anaerobic digestion, and fermentation [7,9–11]. For instance, one ton of banana waste can produce approximately 100 cubic meters of biogas, which is equivalent to about 60 cubic meters of natural gas [12,13]. The efficient use of banana waste for energy production not only addresses waste disposal issues but also contributes to the circular economy, transforming waste into a valuable resource [4].

In South America, countries with significant agricultural activities, including banana cultivation, are actively exploring various methods to extend the life cycle of biomass from agricultural waste. These initiatives focus on converting agricultural residues into valuable energy resources, emphasizing the potential of biomass energy [14,15]. The region's favorable climatic conditions and extensive agricultural lands, which contribute to about 30% of the world's banana production, make it an ideal candidate for biomass energy production [16]. These initiatives highlight the region's commitment to leveraging agricultural waste for energy, reducing carbon footprints, and stimulating rural economies.

Ecuador, a leader in banana exports, faces both challenges and opportunities in managing agricultural waste. The country has made significant commitments to meet decarbonization goals by 2050, as outlined in its Nationally Determined Contributions (NDCs) under the Paris Agreement [17]. These commitments include increasing the share of renewable energy in the national energy mix, improving energy efficiency, and reducing greenhouse gas emissions by 20% by 2025 [18]. Developing a biomass-based energy industry in this region can significantly contribute to Ecuador's decarbonization, energy independence, and local economic growth.

It is important to mention that Santa Elena is a province with a relatively recent history in agriculture [19,20]. The nascent stage of agricultural development in the region presents a unique opportunity to integrate sustainable practices from the outset, allowing for the seamless adoption of policies and regulations that support biomass energy initiatives. In locations with geographical and geological features that imply limited and challenging access to water, as is the case of Santa Elena, extending the benefit from agricultural activities and reducing waste become crucial for the sustainable development of the region [20]. Furthermore, promoting local development and encouraging innovation and investment in renewable energy technologies perfectly align with the objectives of the country and the necessities of the planet.

Biomass from agricultural waste, such as bananas and plantains, is considered a renewable energy resource, since the plants themselves capture CO₂ by the process of photosynthesis, and this CO₂ will later be transformed into organic matter that will be turned into biomass. When these residues are used for energy production, the carbon retained in the biomass is expelled back into the atmosphere in the form of CO₂ by the biomass power plant. This CO₂ is captured by plants that use it to grow again. As a result, we have a closed cycle as shown in Figure 1. This cycle also integrates a socioeconomic dimension, where farmers are a key link, since they are the providers of banana crop waste. Then, the availability of agricultural waste is transformed into energy through technological conversion processes.

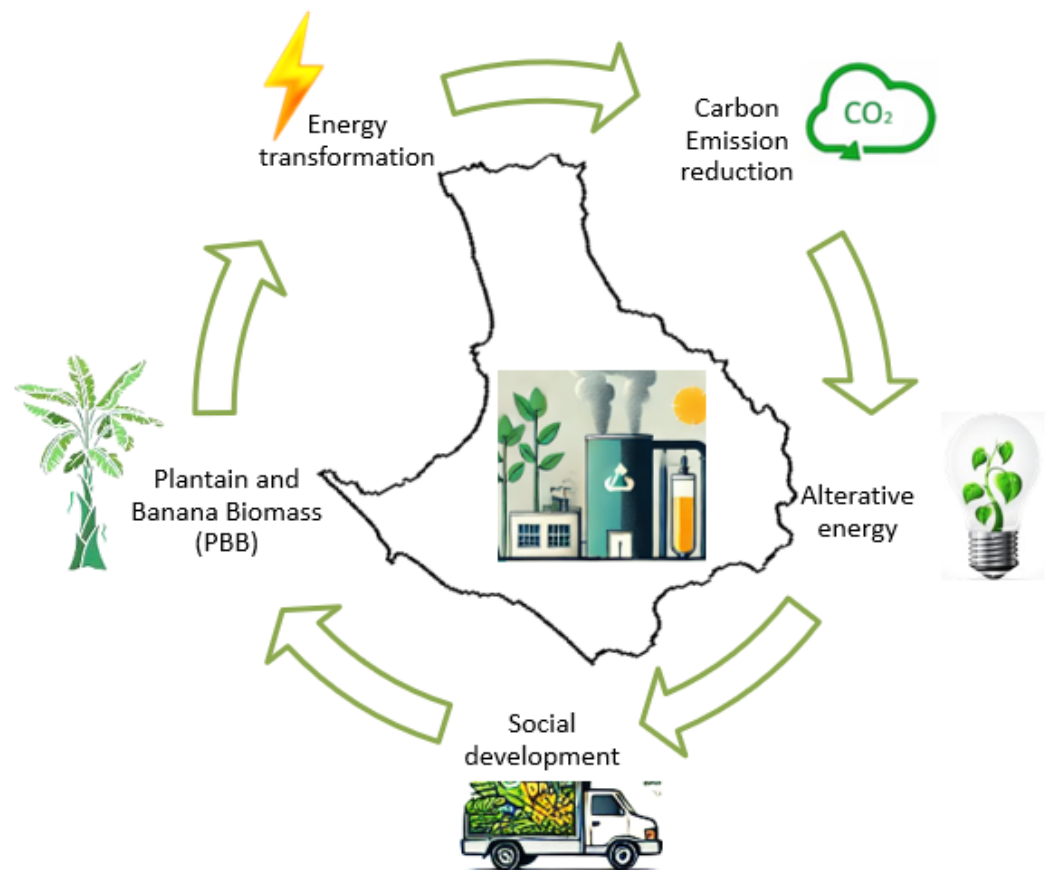


Figure 1. Banana and plantain biomass cycle on Santa Elena Peninsula.

This study aims to evaluate the potential of plantain and banana biomass (PBB) as a renewable energy source in Santa Elena province, Ecuador, and assess its viability for contributing to local energy needs. In the province of Santa Elena, plantain and banana biomass (PBB) residues offer a high potential for biomass energy production [21]. Additionally, the study explores how biomass energy can stimulate the local economy and improve environmental sustainability, thus supporting comprehensive local development.

The methodology involved estimating the energy potential of PBB through a combination of a literature review and empirical analysis, including the estimation of higher heating values (HHVs) from empirical correlations and the calculation of annual energy yields. The analysis confirms that PBB can serve as a reliable and sustainable energy source capable of supporting local energy demands and contributing to broader sustainability goals. The viability of incorporating PBB into the local energy framework of Santa Elena highlights its potential to contribute to energy diversification, economic growth, and environmental sustainability within the region, allowing Ecuador to make significant strides toward achieving its decarbonization goals.

2. Materials and Methods

This study utilizes a comprehensive methodology to assess the potential of biomass energy derived from agricultural waste in the Peninsula de Santa Elena, Ecuador. The research approach begins with a systematic literature review to compile existing knowledge and pinpoint gaps in the current research.

2.1. Biomass Selection

The literature shows several methods for the selection criteria of biomass, where some are based on provenance, availability, accessibility uses, and policies [22–25].

The selection process of the biomass herein followed the process criteria described in Figure 2. It consisted of analyzing the national and local legal framework implemented in the province, the waste collection system, provenance, and the possible or current uses given to the biomass before its later transformation into energy. From our analysis, we found that the biomass derived from rural areas, especially from the banana agroindustry, was the most promising source of energy. The information used for the analysis was collected from national databases, agricultural records, and official governmental websites.

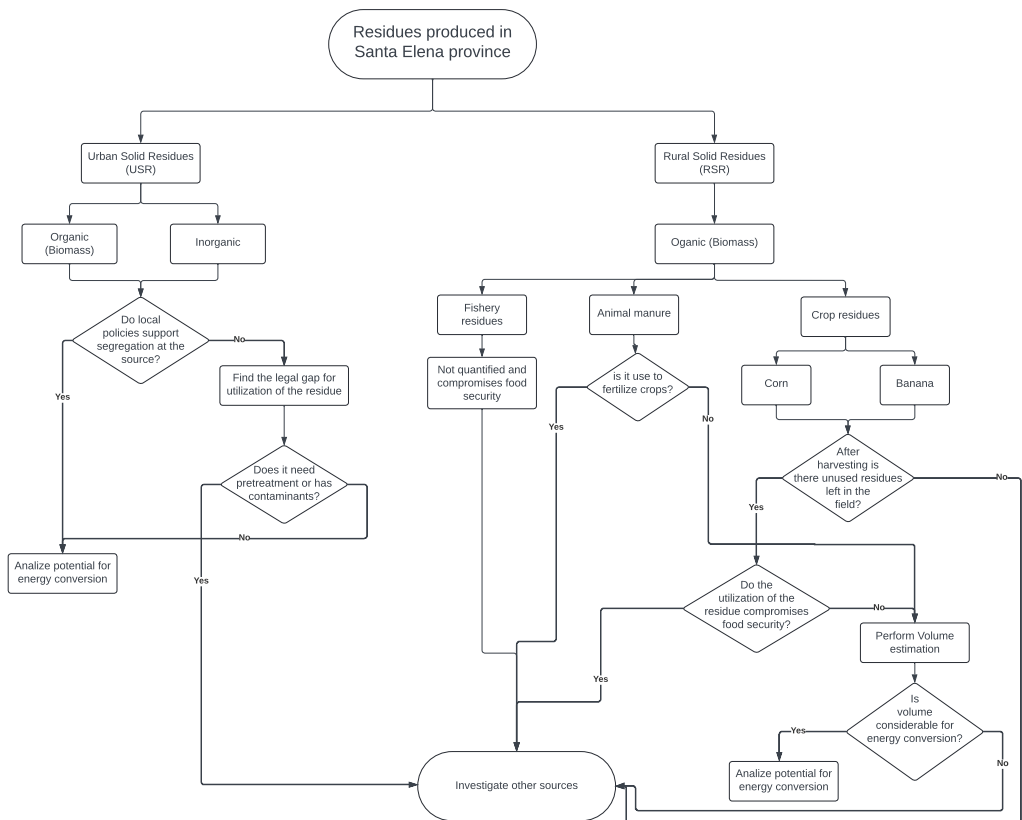


Figure 2. Flowchart explaining the applied biomass selection process based on availability, uses, and policies.

2.2. Biomass Waste Quantification

Estimating the total cultivated area of banana and plantain in the province of Santa Elena is crucial for determining the available waste biomass volume. The waste volume quantification was achieved by combining satellite images with high temporal resolution and the latest national land registry data from the Ministry of Agriculture in Ecuador. The GIS-based approach was used to interpret and analyze the collected data. This tool has been successfully used for quantification purposes similar to the one presented in this work [26–28]. The method allowed for an up-to-date and accurate calculation of the total cultivation area in the province. Samples of different varieties of banana and plantain were weighed to determine the biomass generated per plant unit.

2.3. Estimation of the HHV and PBB

The HHV is a measure of the energy that a substance can generate per unit mass, specifically indicating how much energy a substance produces when burned under standardized conditions [29]. Understanding the composition of PBB is fundamental for estimating its energy potential as a residue. Various correlations based on the structural composition of PBB were found and selected to estimate the HHVs, with a maximum 10% error. The se-

lected correlations are presented in Table 1 and were evaluated and compared using Python programming language, version 3.13.0.

Table 1. Correlations used to estimate the HHV.

Base Polymer for Correlation	Symbol	Correlation	Reference
Lignin	L	$HHV = 18.0124 - 0.0041L$	[30]
Hemicellulose	H	$HHV = 16.5917 + 0.0191H$	[30]
Cellulose	C	$HHV = 16.9961 + 0.0198C$	[30]
Lignin + Cellulose	L-C	$HHV = 15.9391 + 0.0210L + 0.0250C$	[30]
Lignin + Hemicellulose	L-H	$HHV = 14.2252 + 0.0424L + 0.0295H$	[30]
Lignin + Hemicellulose + Cellulose	L-H-C	$HHV = 14.2193 + 0.0425L + 0.0305H - 0.0015C$	[30]
Demirbas for non woody residues	L	$HHV = 0.0877L + 16.4951$	[31]

Table 2 presents various characterizations of PBB conducted by several authors, including Ecuadorian studies. The table shows the structural characterization of different banana residues that serve to test the equations presented in Table 1. NR stands for variety not reported and (a) pseudostem, and (b) leaves. LHV is the low heating value. It is important to note that the percentages indicate the fraction of polymer mass relative to the dry sample mass. Both the pseudostem and the leaves show very similar values for cellulose, hemicellulose, and lignin. In all cases analyzed, cellulose stands out as the main component of PBB, followed by hemicellulose, and lastly lignin.

Table 2. Structural characterization for different banana field residues.

Musa Variety	Hemicelulose %	Celulose %	Lignin %	LHV	HHV	Reference
NR	14.98 ± 2.03 a, 17.08 ± 1.11 b	31.27 ± 3.61 a, 25.75 ± 1.42 b	15.07 ± 0.66 a, 24.84 ± 1.32 b	12.2	17.4 a, 17.62 b	[32]
<i>Musa</i> spp.	25.36 a, 23.46 b	38.48 a, 35.58 b	5.77 a, 10.58 b	13.63 a, 16.16 b	15.04 a, 17.57 b	[33]
<i>Musa Cavendish</i>	24.9 a, 27.39 b	35.3 a, 36.3 b	5.2 a, 8.5 b	-	17.62 b,	[34]
<i>Musa Sapientum</i>	18.07 a	55.83 a	28.15 a	-	-	[35]
<i>Musa acuminata</i>	24.9 a	35.3 a	5.2 a	-	-	[36]
NR	23.28 a, 21.88 b	34.15 a, 30.51 b	30.07 a, 29.61 b	-	-	[37]
NR	18 a, 25.8 b	44 a, 26.1 b	8.07 a, 17 b	-	-	[38]

Note: the table shows the structural characterization of different banana residues that serve to test the equations presented in Table 1. NR stands for variety not reported, (a) pseudostem, and (b) leaves. LHV is the low heating value.

To calculate the energy potential of the PBB estimated, it is necessary to evaluate the higher heating value. Guzmán-Bello et al. [39] established an empirical method to estimate the energy potential of various biomass types. This method integrates key factors, including annual agricultural production M_i , the residue-to-product ratio RRP_i , the higher heating value HHV_i , and the residue's dry matter content DMC_i , into a systematic framework for comprehensive assessment. This adaptable equation can be applied to different agricultural products (n).

$$[H]BEP = \sum_{i=1}^n (M_i \cdot RRP_i \cdot HHV_i \cdot DMC_i) \quad (1)$$

The potential energy yield was assessed to determine its contribution to local electricity capacity and its impact on local development. This includes calculating how much biomass-derived energy can enhance energy security, reduce fossil fuel dependence, and promote economic growth. The RRP was estimated by dividing the total amount of field residues by the average weight of product (206) produced per hectare in Santa Elena.

2.4. Energy and Exergy Calculations

The higher heating value (HHV) of plantain and banana biomass (PBB) was determined experimentally by bomb calorimetry according to ASTM D5865. Proximate and ultimate analyses followed ASTM D3172 and ASTM D5373 standards, respectively. HHVs were also estimated from ultimate analysis using published correlations to validate the measurements [40,41].

The specific chemical exergy of biomass was estimated from its HHV using the correlation proposed by Song et al. [42]:

$$e_{chem} = k_{ex} \cdot HHV$$

where k_{ex} is the exergy-to-energy ratio reported for lignocellulosic biomass (typically 1.03–1.06).

The exergy of useful heat was calculated using

$$Ex_Q = Q \left(1 - \frac{T_0}{T_{av}} \right)$$

where Q is the thermal energy released, T_0 the reference ambient temperature (298 K), and T_{av} the average temperature of the useful heat stream.

The overall exergetic efficiency was computed as

$$\eta_{ex} = \frac{Ex_{outputs}}{m_{fuel} \cdot e_{chem}}$$

2.5. Carbon Footprint Estimation

Greenhouse gas emissions were estimated following IPCC Guidelines [43,44]. Activity data (MJ or kWh) were multiplied by the corresponding emission factor (EF):

$$\text{Emissions} = \text{Energy input} \times EF$$

Diesel-related emissions applied IPCC default EFs, while electricity used the Ecuadorian grid emission factor [45]. Biogenic CO₂ from biomass combustion was reported separately.

3. Results

3.1. Estimation of the PBB in Santa Elena Province

According to the Ministry of Agriculture (2022), the Santa Elena canton has 2591 hectares of banana crops, representing 1.39% of the total national area dedicated to this cultivation [46]. These plantations are in southern areas such as El Azúcar, Chanduy, Las Juntas, and Limoncito, managed by producers of various scales and directly benefiting from the El Azúcar dam. Banana-producing farms were vectorized using polygons in georeferenced systems, allowing for the estimation of the total area dedicated to cultivation in the Santa Elena province, which yields 3329.54 hectares as of the date of publication. Figure 3 displays a map identifying banana crops in the province of Santa Elena at a scale of 1:300,000 from the year 2023.

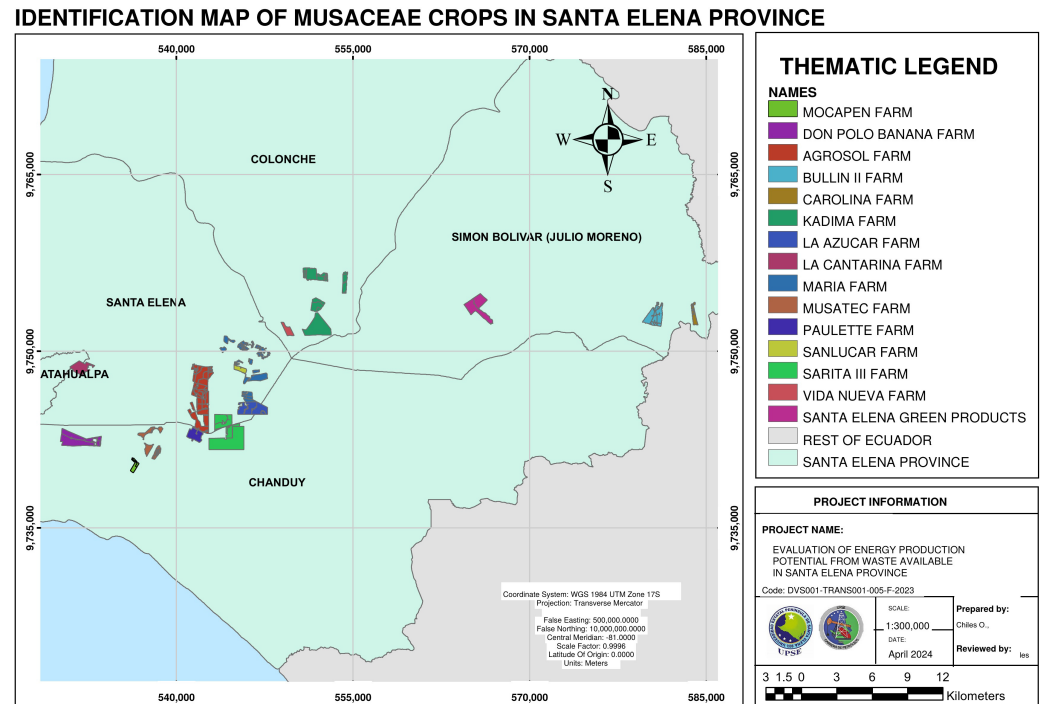


Figure 3. Map of identification of banana farms in Santa Elena province, scale 1:300,000.

It is important to note that Google Earth's temporal resolution corresponds to the year 2023, providing a more precise approximation of the area dedicated to this crop. However, to ensure the quality of the mapping, in situ verifications are indispensable—a task that falls to the relevant state authority. To certify the geographic accuracy of the study, the coordinates (WGS84) of each site are presented in Table 3. The data obtained in this study will serve as a reference and will allow for the future analysis of the feasibility of utilizing and converting selected residues into energy. It is worth mentioning that the most common varieties of PBB found in Santa Elena are Musa Cavendish and Dwarf Cavendish, which are destined for exportation.

Table 3. Coordinates of the farms on the Santa Elena Peninsula (WGS84).

Name	Lon	Lat
HACIENDA MARIA	546,981.2112	9,748,039.307
HACIENDA MUSATEC	537,773.2413	9,742,027.917
HACIENDA VIDA NUEVA	549,539.4591	9,751,682.967
HACIENDA CAROLINA	583,969.0956	9,752,948.868
HACIENDA SANLUCAR	545,249.2974	9,748,526.457
AGRICOLA MOCAPEN	536,415.1537	9,740,167.592
HACIENDA PAULETTE	541,376.9992	9,742,898.073
HACIENDA LA AZUCAR	546,314.5474	9,745,222.971
HACIENDA SARITA III	543,807.6153	9,744,396.147
HACIENDA AGROSOL	541,823.6773	9,743,781.871
HACIENDA LA CANTARINA	531,713.2665	9,748,564.225
HACIENDA BULLIN II	580,101.0247	9,752,797.566
HACIENDA KADIMA	551,955.1226	9,752,050.382
BANANERA DON POLO	530,891.6013	9,742,300.466
SANTA ELENA GREEN PRODUCTS	564,902.2032	9,753,823.094

Regarding the plant density per hectare, based on the experience of local agriculture, the banana and plantain are set in a common distribution of 3.0×3.0 m per unit, giving

1111 plants per unit of area. This information was contrasted with published information and with satellite images [47,48].

The national average yield reported by the Ministry of Agriculture (38.18 T/ha) was used for provincial scaling [49]. To check for consistency, these values were compared with provisional FAO/FAOSTAT data [50]; the differences were minor and do not affect the estimate of regional potential show in Figure 4.

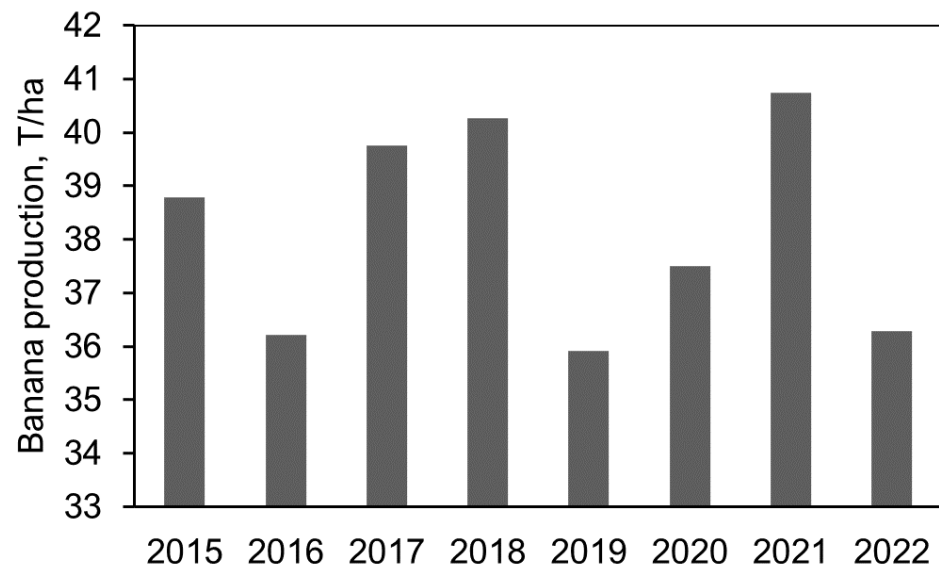


Figure 4. Average annual banana production per hectare in Ecuador (T/ha). Data and reference year: Ministry of Agriculture (MAGAP)/National Statistics 2022; provisional data from FAO/FAOSTAT 2023.

3.2. Justification of Feedstock Selection

The selection of plantain and banana biomass (PBB) as the primary feedstock for this study is based on its abundant availability and current underutilization in the Santa Elena province. According to regional agricultural statistics, banana and plantain cultivation represents one of the largest sources of crop residue in the area, with significant volumes of leaves and pseudostems discarded after each harvest cycle [51]. Although PBB presents a high moisture content (up to 68%), this limitation is addressed through the implementation of passive solar drying systems, which are feasible given the high solar radiation levels in the region. The use of solar energy enables moisture reduction without fossil fuel dependency, thereby minimizing energy penalties and improving the overall efficiency of biomass utilization.

While the focus of this study is on PBB, it is important to acknowledge that other agricultural residues present in the region—such as sugarcane bagasse, corn stalks, and rice husks—typically contain lower moisture levels and may offer advantages in terms of preprocessing energy requirements. Future research will incorporate these alternative feedstocks to perform comparative assessments and explore potential feedstock diversification strategies that enhance energy performance and operational flexibility.

3.3. Biomass and Energy

Table 4 summarizes the averaging process of the biomass residues. Furthermore, the table presents the average weight per sampled plant, differentiating between field residues and processing residues. The percentage of the total corresponds to the weight of the field residues excluding the fruits.

Table 4. Average weight of PBB per unit.

Residue Classification	Plant Part	Sample 1 (kg)	Sample 2 (kg)	Sample 3 (kg)
Field residues	Pseudo stem	41	50	68
	Leaves	8	15	21
Processing residues	Rachis	1	2	2.5
	Fruit bunch	15	33	33
	Total weight of field residues	49	65	91.5
Percentage over total		75%	65%	73%

The mass of the fruits, including rejected fruits and the rachis, is not considered. Rejected fruits are those that do not meet specifications, are imperfect, or are contaminated, and are usually used to feed livestock. These are considered processing residues, and their primary use is for feed. As an additional note, the maximum weight of the banana bunch is reached approximately 12 weeks after the appearance of the floral primordium, varying according to the Musa variety.

The thickness of the leaf blade and the fruit caliber are directly influenced by the agronomic management of the crop, especially by the appropriate dosage of phosphorus. These details have been corroborated through consultations with crop management experts, who emphasize the importance of these variables in maximizing banana productivity and quality. Table 5 shows the total plantation surface, plants per unit area, average residue weight, and total average PBB (76.10 T/ha per year).

Table 5. Average PBB available in Santa Elena.

Plantation Surface (Ha)	Plants per Unit of Area (u/Ha)	Average Residue Weight (kg)	Total Average PBB (T/Year)
3329.54	1111	68.5	253,389.98

The average humidity was obtained experimentally, averaging 67.8% over total mass; therefore, the total dry PBB averages 24.5 tons/ha per year. It is important to highlight that, according to Ecuador's bioenergy atlas, it is estimated that there is an availability of 22.21 tons of dry biomass residues per hectare of banana cultivated per year, considering both field and processing residues at the national level [52].

Various studies conducted by different authors in provinces with a significant history of banana cultivation, such as Los Ríos, El Oro, and Guayas, have reported biomass values close to 418 ± 102 T/ha, 544 ± 96 T/ha, and 513 ± 111 T/ha, respectively, with variations around 20%.

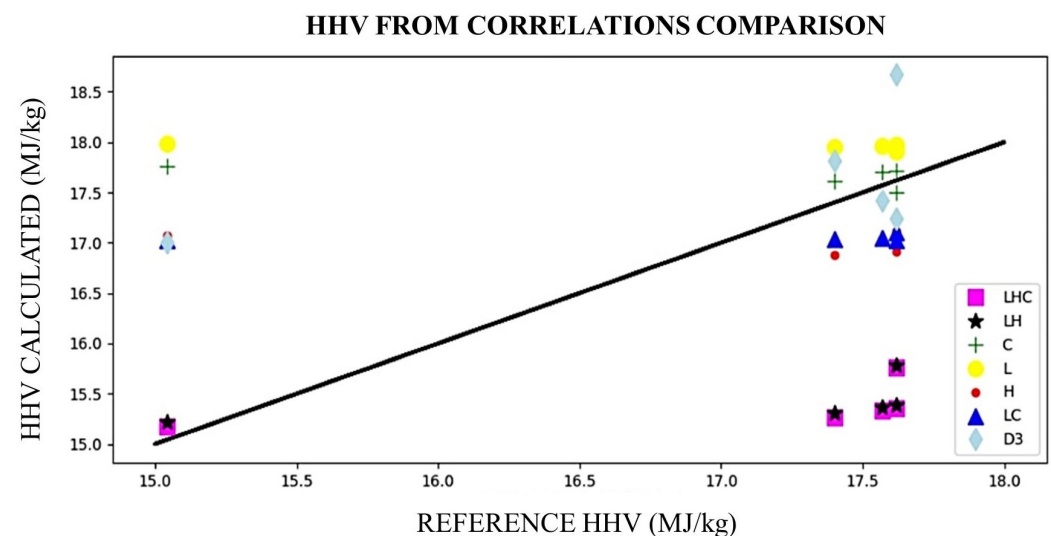
Additionally, a study conducted by Tock et al. revealed that, in Malaysia, a banana crop can generate approximately 50 T/ha of biomass, while a plantain crop produces around 40 T/ha. Finally, other authors mention that the biomass produced by each hectare of banana is about 200 T/year in wet weight [32,48,52–54].

3.3.1. Estimation of HHV

The structural compositions of PBB show that it can exhibit higher HHVs with increased lignin content (Table 2). Lignin imparts a woody characteristic to PBB, leading to samples with high lignin content producing a greater amount of carbonaceous residues upon combustion [37]. For PBB in the Santa Elena Province, the HHV was evaluated and compared using equations in Table 2 and an automated table programmed in Python. The results are presented in Figure 5 and Table 6. Furthermore, a total of 40 different HHVs were computed and compared with various authors' experimental values cited in Table 2.

Table 6. HHVs calculated with different empirical correlations.

	ST1	LV1	ST2	LV2	LV3
HHV Reference	17.4	17.62	15.04	17.57	17.62
● L	17.95	17.91	17.99	17.97	17.98
● H	16.88	16.92	17.08	17.04	17.11
+ C	17.62	17.51	17.76	17.70	17.71
▲ L-C	17.04	17.10	17.02	17.05	17.03
* L-H	15.31	15.78	15.22	15.37	15.39
■ L-C-H	15.27	15.76	15.18	15.33	15.36
◆ D-3	17.82	18.67	17.00	17.42	17.24

**Figure 5.** Calculation and comparison of HHVs using empirical correlations.

In general terms, correlations that include the hemicellulose percentage tend to have higher error margins, deviating more from the reference line. In addition, the distribution of the different probable values for HHVs was plotted, including those acquired from the literature, and are presented in Figure 5. The best estimation of the average heating value was obtained through observation and analysis of the information presented. Consequently, the HHV used for subsequent calculations is approximated to be 16.89 MJ/kg.

The calculated HHVs were compared with experimental data from the literature using regression analysis. The correlation coefficients ($R^2 > 0.92$) confirm a strong agreement between empirical correlations and reference HHVs. Deviations were within $\pm 10\%$, consistent with the reported uncertainty of the correlations.

It is important to emphasize that HHVs were calculated on a dry basis. The experimentally measured average moisture content of 67.8% was incorporated into the biomass energy potential estimation, ensuring a realistic assessment of the usable energy under actual processing conditions. The inclusion of dry matter content (DMC = 0.32) in the energy potential formula reflects this correction.

3.3.2. Estimation of BEP

The amount of biomass produced per hectare of banana or plantain (PBB) varies significantly depending on local cultivation conditions and applied agronomic management. This includes factors such as soil type, plant density per unit area, climate, fertilization practices, pest and disease management, harvest time, Musa variety, etc. For conditions

of the PBB produced per hectare in Santa Elena, field residues constitute approximately 67% of the total plant biomass, significantly exceeding the amount of processing residues used by different consulted authors [39,55]. A higher RRP indicates a greater availability of biomass residues for energy production, which is advantageous for generating biomass energy. The values of all variables were used to estimate the BEP, and the final results are presented in Table 7.

Table 7. Estimation of the BEP from the PBB produced in the province of Santa Elena.

Product Evaluated	M (T/Year)	RRP	HHV	DMC	BEP (GJ/Year)
PBB	103,215.74	2.45	16.89	0.32	1,378,079.87

The energy potential estimated is 1,378,079.87 GJ/year, which is equivalent to 382.79 GWh in the same period. These findings help to identify investment opportunities in biomass conversion technologies, particularly fostering local growth by establishing a new commercial sector for local farmers and agro-industrial companies in Santa Elena. Nonetheless, there is still significant untapped potential in other agricultural residues that could further enhance the country's and especially the province's renewable energy capacity.

Compared to other countries, such as the Dominican Republic, which reports an energy potential of 1,798,492.60 GJ (499.58 GWh) per year from processing residues representing a lower volume of biomass, field residues like pseudostems and leaves generally have a lower higher heating value (HHV). This difference in HHV is a significant factor contributing to the variance in results [39].

3.4. Potential Energy Generation from Residues

Based on the estimated 100,000 tons of banana and plantain residues available annually in Santa Elena province (dry basis), the potential energy generation is approximately 1.66 PJ/year. This is equivalent to about 460 GWh of electricity assuming a 30% conversion efficiency. Such production could cover nearly 8% of the current annual electricity demand of the province [45], highlighting its significance for local energy security.

For comparison, rice-husk-based projects in Vietnam have demonstrated generation potentials of 250–300 GWh/year [56], while sugarcane bagasse cogeneration in Brazil contributes over 20,000 GWh/year to the national grid [57]. Although the absolute potential in Santa Elena is smaller, the relative contribution to the provincial energy mix is substantial, and the use of residues would simultaneously reduce open-field burning and provide socioeconomic benefits to local communities.

The biomass matrix can be diversified with the waste of other crops that we can also find a significant amount of within the Santa Elena peninsula. According to statistics from INEC [58], dry corn contributes about 25,291 tons of grain; if we consider that the stems and leaves are equivalent to 120–150% of the weight of the grain, more than 30,000 tons of waste is generated that can be used for bioenergy. INEC [58] reports 956 tons of cacao (dried almond), where the shells and residues are equivalent to approximately 70% of the fruit, representing about 670 tons of biomass. Avocado and passion fruit also report significant production, with 362 and 1179 tons, respectively, but the discarded material has a smaller volume. Together, they are an excellent alternative for strengthening the use of energy from biomass in the province.

3.5. Energy and Exergy Balance

The experimental HHV obtained by bomb calorimetry was 16.62 MJ/kg (dry basis). The estimated HHV from elemental correlations was 16.45 MJ/kg, confirming good agree-

ment. Using the correlation from Song et al. [42], the corresponding chemical exergy was calculated as $e_{chem} = 1.047 \times HHV = 17.40$ MJ/kg.

Assuming 75% combustion efficiency, the useful thermal energy was 12.67 MJ/kg. At an average temperature of $T_{av} = 573$ K, the exergy of heat was 6.08 MJ/kg. The resulting exergetic efficiency was 51.2% in Table 8.

Table 8. Energy and exergy balance of banana and plantain biomass (per kg dry matter).

Parameter	Value	Unit	Source/Notes
HHV (measured)	16.62	MJ/kg	Bomb calorimetry
HHV (estimated)	16.45	MJ/kg	[40]
Chemical exergy e_{chem}	17.40	MJ/kg	$1.047 \times HHV$ [42]
Useful heat Q	12.67	MJ/kg	Assuming 75% combustion efficiency
Exergy of heat Ex_Q	6.08	MJ/kg	$T_{av} = 573$ K
Exergy efficiency η_{ex}	51.2	%	Calculated ratio

3.6. Carbon Footprint Analysis

Table 9 summarizes the emission factors applied. Diesel-related emissions were estimated with the IPCC default factor of 74 t CO₂/TJ [44], while electricity-related emissions used the Ecuadorian grid factor of 0.40 t CO₂/MWh reported by CENACE [45]. Biogenic CO₂ from biomass combustion was reported separately.

Table 9. Emission factors applied for carbon footprint estimation.

Input	Emission Factor	Source
Diesel (transport, machinery)	74 t CO ₂ /TJ	[44]
Electricity (Ecuador grid)	0.40 t CO ₂ /MWh	[45]
Biomass combustion	Biogenic CO ₂	Reported separately

4. Discussion

The findings of this study underscore the significant potential of utilizing plantain and banana biomass (PBB) as a renewable energy resource in the Santa Elena province of Ecuador. The estimation of 382.79 GWh per year from PBB highlights the substantial contribution that agricultural waste can make toward local energy needs. This energy potential is not only considerable in terms of volume but also crucial for enhancing the sustainability and resilience of the regional energy matrix. It is important to note that the actual energy output will ultimately be influenced by the plant factor, which depends on the efficiency of the exploitation or power conversion method selected. The most observed plant factor for such applications is approximately 20% and corresponds to the thermal conversion process. This factor highlights the theoretical energy potential that can be realistically achieved; therefore, the selection of an optimum conversion technology is necessary to maximize the utilization of this promising renewable resource.

4.1. Analysis of the Biomass Pre-Treatment Process

Biomass pre-treatment plays a fundamental role in the feasibility and energy performance of bioenergy systems. For plantain and banana biomass (PBB), the two most critical pre-treatment steps are moisture reduction (drying) and particle size reduction (grinding). This section presents an energy-based analysis of both processes using local environmental data and the technical literature.

4.1.1. Solar Drying Potential in Santa Elena

Due to the high initial moisture content of PBB (approximately 67.8%), drying is essential before energy conversion processes. In this study, solar drying is proposed as the primary moisture removal method as it offers a zero-fossil-fuel solution under the region's high solar availability.

The average global solar radiation in the Santa Elena province is approximately 4575 Wh/m²/day, equivalent to 16.47 MJ/m²/day. Assuming a thermal efficiency of 20% for open-air drying systems [59,60], the usable energy for moisture evaporation is estimated at 3.29 MJ/m²/day. Considering that the latent heat of vaporization of water at typical drying temperatures is around 2.5 MJ/kg [61], this yields an evaporation capacity of approximately 1.32 kg H₂O/m²/day.

Using the available drying area in the project zone, the system is capable of removing enough water to process up to 73,104.84 metric tons of biomass per day. This confirms the technical feasibility of decentralized solar drying infrastructure at a large scale in the region as shown in Table 10.

Table 10. Solar drying performance estimation for PBB.

Parameter	Value
Solar radiation (average)	4575 Wh/m ² /day
Equivalent in MJ	16.47 MJ/m ² /day
Thermal efficiency (solar drying)	20%
Usable energy for drying	3.29 MJ/m ² /day
Latent heat of vaporization	2.5 MJ/kg
Water evaporated per m ² /day	1.32 kg
Total drying capacity (project area)	73,104.84 tons/day

4.1.2. Energy Requirement for Biomass Grinding

After drying, PBB must be ground to a uniform particle size to enhance the efficiency of combustion or digestion. Hammer mills are the most commonly used equipment for lignocellulosic materials. The energy requirement for size reduction varies based on feedstock structure, screen mesh size, and machine efficiency.

According to Manzone et al. (2019), the specific energy consumption for hammer-milling dry agricultural residues ranges from 50 to 120 kWh per metric ton [62]. Given the fibrous nature of PBB and a target particle size of <10 mm, an average value of 70 kWh/ton is considered reasonable for this case, equivalent to 0.252 MJ/kg.

$$E_{\text{grinding}} = 70 \text{ kWh/ton} = 0.252 \text{ MJ/kg} \quad (2)$$

This energy input accounts for approximately 1.5% of the biomass HHV (16.89 MJ/kg), and can be supplied using grid electricity or on-site renewable energy systems. Combining solar drying and efficient grinding enables a low-carbon, locally optimized biomass preparation process.

4.1.3. Biomass Collection

Plantain and banana biomass (PBB) is typically left in the field after harvest, making its collection a relatively low-cost process compared to other lignocellulosic feedstocks. In this study, it is assumed that biomass is collected manually or semi-mechanically from plantations within a 5 km radius of the processing facility. The collection process involves stacking and bundling residues such as pseudostems and leaves, followed by short-distance hauling using light agricultural vehicles. Based on data from small-scale agricultural logistics studies, the energy consumption for manual-to-mechanized collection is estimated

at approximately 0.015 MJ/kg [63]. This value considers fuel use for small tractors or collection carts operating over flat terrain and short intervals typical of banana plantations in the region.

4.1.4. Summary of Pre-Treatment Energy Balance

The Table 11 shows the total pre-treatment energy requirement per kilogram of dry biomass is estimated at 0.252 MJ, which represents only 1.5% of the higher heating value (HHV) of PBB. This confirms the technical viability and energy efficiency of the proposed solar-assisted pre-treatment approach in Santa Elena.

Table 11. Energy requirements for PBB pre-treatment.

Process	Energy Input (MJ/kg)
Solar drying	0 (passive)
Grinding (hammer mill)	0.252
Collection	0.015
Total pre-treatment input	0.267
Balance	$16.89 - 0.267 = 16.623$

4.2. Suitability of PBB for Thermochemical Energy Recovery

Given the physicochemical properties of plantain and banana biomass (PBB), including its moderate calorific value and fibrous structure, the most suitable conversion technology proposed in this study is direct combustion in fixed-bed systems. This thermochemical route is favored for its simplicity, low capital cost, and compatibility with decentralized rural applications. Under optimized conditions, combustion systems can reach efficiencies of 70–80% in converting the higher heating value (HHV) of the feedstock into usable thermal energy [64].

A preliminary net energy analysis was conducted to evaluate the viability of this approach. The gross energy yield of dried PBB, based on its HHV of 16.89 MJ/kg and assuming 75% conversion efficiency, is approximately 12.67 MJ/kg. On the input side, energy requirements for biomass preparation include 0.252 MJ/kg for grinding (as previously estimated), and an additional 0.011 MJ/kg for transportation, assuming a 30 km average hauling distance and diesel consumption of 0.3 L/ton-km. Since drying is performed passively using solar radiation, no direct energy input is required for that stage. Therefore, the total preprocessing energy input is approximately 0.263 MJ/kg.

Subtracting these inputs from the output, the resulting net energy balance is approximately 12.41 MJ/kg, which represents over 95% of the gross energy value. This confirms that the proposed system configuration yields a strong positive net energy return, especially when low-cost passive drying is used. While future studies should validate this outcome with life-cycle analysis and pilot-scale trials, the current results support the technical feasibility of thermal energy recovery from PBB under local conditions.

4.3. Comparative Analysis with Existing Literature

The energy potential estimated for Santa Elena aligns with similar studies conducted in other regions, demonstrating the broader applicability of biomass energy solutions. For instance, the energy potential of banana biomass in the Dominican Republic was reported to be 1,798,492.60 GJ per year, which, despite being higher, underscores the variability in biomass energy yield due to differing agricultural practices, local conditions, and biomass compositions [39]. The variation in HHV reported across various studies, ranging from 15.04 to 17.62 MJ/kg, reflects the impact of lignin, cellulose, and hemicellulose

content on energy potential. This variability highlights the importance of conducting localized assessments to accurately estimate the energy potential of biomass resources.

The empirical correlations and experimental data presented in this study suggest that higher lignin content in banana residues generally correlates with higher energy yield. This finding supports previous research indicating that lignin-rich biomass tends to produce more energy per unit mass.

The observed discrepancy in HHVs among different studies can be attributed to factors such as sample preparation, biomass composition, and experimental methodologies, highlighting the importance of standardizing these variables in future research.

4.4. Implications for Local Energy and Economic Development

The province's current energy demand and generation capacity, dominated by thermo-electric plants, indicate a reliance on non-renewable sources. The introduction of biomass as a base energy source could provide a more stable and reliable supply, mitigating the risks associated with energy shortages and price fluctuations in fossil fuels. Furthermore, the development of a biomass energy sector in Santa Elena could stimulate economic growth by creating new job opportunities and fostering investment in renewable energy technologies. This aligns with Ecuador's broader decarbonization goals and the global shift toward sustainable energy practices.

Local farmers who participate in the exchange of raw materials for biomass energy generation will find an opportunity to expand and diversify their income. They would use a product that the market does not value and add an economic purpose to it by establishing a waste purchasing and collection system, reducing their exclusive dependence on the exportation market, and transforming a byproduct into an energy resource with growing demand.

This scheme not only contributes to the sustainability of the province but also supports regional socioeconomic development by improving the local economy. The various stages of the process (collection, transportation, treatment, and plant operation) promote job creation. According to the Food and Agriculture Organization 2020, rural bioenergy projects can generate between three and five jobs per GWh, primarily linked to maintenance and logistics services.

Carbon Footprint and Emissions

The 2022 CO₂ Emission Factor report for Ecuador's National Interconnected System (SIN) analyzes the carbon dioxide (CO₂) emissions generated by this diverse network, including thermal and hydroelectric plants, biomass, and non-conventional renewable energy. We will use the information provided by this report and the information provided by the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories to compare biomass with other energies in terms of emissions and explore the relationship between the carbon footprint and the use of banana waste in the energy sector of the Peninsula de Santa Elena.

CO₂ emission factors are expressed in tons of CO₂/TJ. For liquid fuels, the IPCC default factors were used, and for the electricity grid factor, the CENACE/Ministry report was used when applicable [44,45].

As we have mentioned, thermoelectric plants dominate the energy production in Santa Elena. These units use diesel and fuel oil to operate. It is known that diesel is one of the most polluting fossil fuels, emitting around 74 tons of CO₂/TJ of energy generated.

In addition to this, diesel and fuel oil are less efficient and more costly than biomass. Biomass direct combustion produces a carbon footprint of about 100 tons of CO₂/TJ of energy generated [44]. Given the urgent need for cleaner energy, the cost of production

remains significantly higher due to the availability of domestic fuels. Ecuador relies on imported fuels to operate these plants, further increasing expenses and dependency on external sources.

On the other hand, renewable energy sources such as solar and wind have a much lower carbon footprint. Solar energy emits approximately 13.8 tons of CO₂/TJ of energy generated, with most emissions occurring during the manufacture of the solar panels. Wind energy emissions are even lower, emitting only 5.5 tons of CO₂/TJ, mainly derived from turbine construction and maintenance. Hydroelectric power generates minimal emissions during its operation, but there may be indirect emissions associated with the construction of infrastructure such as dams. These values underscore the efficiency and environmental superiority of solar, wind, and hydroelectric energy compared to fossil fuels and direct biomass combustion [65].

From an emissions and energy efficiency perspective, direct combustion may not be the most optimal option [53,66–68]. However, it is possible to explore the transformation of biomass through fermentation, gasification systems, pyrolysis, biodiesel, or other biomass-derived biofuels to reduce the carbon footprint [53,66,68]. By transforming biomass, we acquire a less impactful option compared to fossil fuels, as biofuels can generate between 54 and 70 tons of CO₂/TJ, which is lower than the 74 delivered by the diesel currently used in the thermoelectric plant. However, the sustainability of biomass-derived fuels depends on the development of proper policy frameworks and the market to support their adoption.

Despite the environmental benefits of chemical conversion processes, these technologies remain relatively expensive compared to direct combustion [69]. Additionally, Ecuador lacks clear regulations for the use of biomass for energy generation, and the local carbon market is not well established yet. These regulatory gaps present a significant barrier to promoting the application of more efficient green technologies.

Also, the conversion of agricultural waste to biomass energy represents an ideal solution to the common practice of the open burning of waste. Open burning has an atmospheric impact due to fine particle material emission (PM_{2.5}), nitrogen oxides (NO_x), and organic volatile compounds [70], which deteriorate air quality and cause serious harm to the health of nearby communities. Bioenergy systems will allow this burning to be a controlled combustion and conversion process, reducing local atmospheric contamination.

Biomass energy use helps to mitigate greenhouse gases. Agricultural waste under natural decomposition or uncontrolled burning liberates gases such as carbon dioxide (CO₂) and methane (CH₄). When integrated with a renewable energy system, CO₂ emissions are part of a biogenic cycle, reducing greenhouse gas net emissions. Segun [71] suggests that fossil fuels for bioenergy can reduce 60 to 80% of CO₂ emissions.

The current advantage of biomass relies mostly on the economic side of the feedstock, with values of between approximately USD 0.10 and USD 0.20 per kg of biomass, which can vary depending on the type of biomass [72,73]. This makes biomass an attractive option for energy generation in regions with vast agriculture like Ecuador.

4.5. Biomass-Derived Energy Sources and Emissions

The data obtained on CO₂ emissions for various types of biomass energy sources are summarized in Figure 6. Among solid biomass, it contributes the most, with 100 tons CO₂/TJ, while biogas is the most favorable option due to its lower environmental impact at 54.6 tons CO₂/TJ. Biodiesel takes a middle position, being made from agricultural waste at 70.8 tons CO₂/TJ, and charcoal is the most polluting fuel at 112 tons CO₂/TJ.

These results also show that biogas is the cleanest and most environmentally efficient option; hence, it is a promising technology for the region if its economic challenges could be surmounted. However, solid biomass is not a bad option either since the associated

emissions are much lower compared to those from fossil fuels such as diesel used in thermal power plants. This all but renders it far more feasible, especially when comparing it to regional infrastructural constraints, making solid biomass a more feasible option for immediate implementation [44,74].

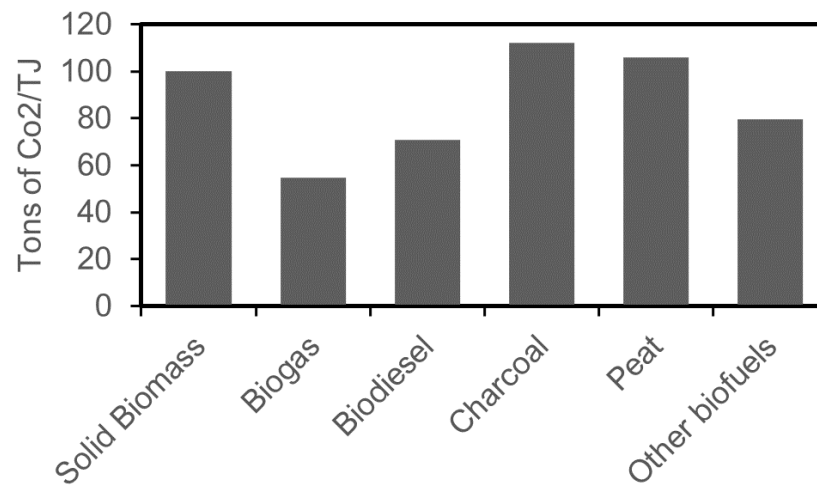


Figure 6. CO₂ emissions from biomass-derived energy sources.

These alternatives will strengthen the agricultural value chain by utilizing locally sourced crop residues as feedstock, providing an additional revenue stream for farmers. Furthermore, they would stimulate rural economies by creating employment opportunities in the collection and processing of agricultural waste, as well as in the operation and maintenance of biomass power plants. This approach not only enhances energy security but also fosters sustainable development by integrating the agricultural and energy sectors.

4.6. Exergy Efficiency Analysis

The chemical exergy of PBB was estimated using a representative exergy-to-energy ratio of 0.35, applied to its measured HHV of 16.623 MJ/kg, yielding an exergy input of 5.91 MJ/kg. The useful thermal energy output, derived from an assumed 75% combustion efficiency, is approximately 12.67 MJ/kg. However, since thermal energy has a lower exergy content compared to mechanical or electrical energy, a quality factor of 0.25 was applied, resulting in a usable exergy output of 3.17 MJ/kg. Energy inputs for biomass collection, local transport, and grinding were previously estimated at 0.015 MJ/kg, 0.011 MJ/kg, and 0.252 MJ/kg, respectively. These values were adjusted using appropriate exergy factors from the literature: 1.00 for electricity and manual collection, and 1.04 for diesel-based transportation [75].

The total exergy input to the system, combining biomass and processing stages, is therefore 6.1884 MJ/kg. This includes 5.91 MJ/kg from the biomass and 0.2784 MJ/kg from auxiliary processes. Table 12 presents a summary of the main input and output flows considered in the calculation.

Based on these values, the exergy efficiency of the system is calculated as follows:

$$\eta_{ex} = \frac{3.17}{6.1884} = 0.512 \Rightarrow 51.2\% \quad (3)$$

This result indicates that approximately half of the total exergy input is effectively converted into usable thermal exergy. Such a value is considered favorable for low-complexity combustion systems operating in rural environments, especially when passive solar drying is employed and transport distances are minimized. The remaining exergy losses are primarily associated with the inherent irreversibility of combustion processes and the

low thermodynamic quality of thermal energy. Nonetheless, the system exhibits robust performance, supporting the suitability of banana and plantain biomass as a viable local resource for decentralized energy production.

Table 12. Exergy input and output values for PBB combustion system.

Flow	Exergy (MJ/kg)
Chemical exergy of biomass	5.910
Collection (manual/tractor)	0.015
Transport (diesel-based)	0.0114
Grinding (electricity)	0.252
Total exergy input	6.1884
Useful exergy output (thermal)	3.170

4.7. Role of Banana and Plantain Biomass in the Energy and Bioeconomy Transition of Santa Elena

The province of Santa Elena has experienced sustained growth in its energy demand in recent years, reaching 446 GWh in 2022, representing an increase of 4.2% compared to 2021 [76]. The 2023 Electricity Master Plan highlights that the province's generation capacity is dominated by two main thermoelectric plants, Santa Elena II and Santa Elena III, which together provide an effective capacity of 105 MW, translating to approximately 920 GWh/year. Additional power is supplied through the National Interconnected System (SNI).

According to the 2022 annual report from the National Electricity Operator (CENACE) [45], Santa Elena II contributed 5.41% of the national thermoelectric generation, producing 192.3 GWh in that year. These developments align with Ecuador's Nationally Determined Contributions (NDCs), which promote renewable energy as a strategy for climate action. Although hydropower remains the country's main electricity source [45] recurring droughts and infrastructure limitations have revealed the urgency of diversifying the energy matrix with sustainable, dispatchable alternatives.

Among these, agricultural biomass, particularly plantain and banana biomass (PBB), emerges as a promising option for the Santa Elena region. Unlike solar and wind, biomass can be stored and used continuously, allowing it to function as a stable base load supply. This study identified an energy potential of 382.79 GWh/year from agricultural residues, a quantity theoretically sufficient for covering 86% of the province's annual demand. Under a conservative 20% plant factor, the usable energy would reach 76.56 GWh/year, covering 17% of the current demand or nearly 40% of the output from Santa Elena II, all through a low-carbon, renewable source.

Beyond energy security, the development of a biomass sector can stimulate rural employment and create economic opportunities across the agricultural and logistics sectors. It also provides a productive use for post-harvest residues that are typically discarded, contributing to sustainable waste management practices.

In addition, the biomass-to-energy system directly supports several Sustainable Development Goals (SDGs). By providing renewable electricity, it contributes to Affordable and Clean Energy (SDG 7). By creating local jobs in collection, transport, and plant operation, it supports Decent Work and Economic Growth (SDG 8). Finally, by reducing open-field burning and fossil fuel dependence, it strengthens Climate Action (SDG 13). Aligning residue valorization with these global goals underscores the broader sustainability value of the project.

4.8. Economic Assessment

A refined economic assessment based on exergy values provides a realistic perspective on the system's viability. Considering an exergy output of 3.17 MJ/kg and an available biomass supply of 253,389.98 tons/year, the total usable exergy is as follows:

$$E_{ex,total} = 253,389.98 \times 1000 \times 3.17 = 802,242,126 \text{ MJ/year} \quad (4)$$

This corresponds to

$$E_{ex,kWh} = \frac{802,242,126}{3.6} = 222,845,035 \text{ kWh/year} \quad (5)$$

At a market price of 0.09 USD/kWh, the annual gross revenue is estimated at

$$R = 222,845,035 \times 0.09 = 20.06 \text{ million USD/year} \quad (6)$$

To determine economic viability, this revenue must be compared to biomass acquisition costs. According to field-level studies, the cost of banana and plantain biomass residues at the collector level ranges between 6.3 and 6.5 USD/ton [77]. Using the upper bound for a conservative estimate, the annual feedstock cost becomes

$$C_{biomass} = 253,389.98 \times 6.5 = 1.65 \text{ million USD/year} \quad (7)$$

Subtracting this from the gross revenue yields an annual net income of approximately

$$\text{Net income} = 20.06 - 1.65 = 18.41 \text{ million USD/year} \quad (8)$$

In summary, the economic evaluation was based on electricity market prices in Ecuador (0.09 USD/kWh), estimated revenues from exergy-based energy production (20.06 million USD/year), and biomass feedstock costs (6.5 USD/ton, 1.65 million USD/year). The resulting net annual income is USD 18.41 million.

This substantial margin demonstrates the economic viability of using PBB residues for bioenergy under realistic cost conditions in Santa Elena province. These results are especially promising considering that no co-benefits from carbon credits, heat recovery, or byproduct valorization were included in the calculation.

Moreover, while this work focuses on energy recovery, biomass can also be used to generate high-value products such as biofertilizers, pigments, organic acids, or enzymes [78]. Table 13 compares the estimated revenue per ton of PBB across different valorization pathways based on regional process data and market-based cost estimates.

Table 13. Estimated revenue per ton of PBB for different valorization pathways.

Use of Biomass	Value (USD/ton)	Source
Electricity (this study)	81.30	-
Biogas (anaerobic digestion)	55–65	[79]
Biochar	400–700	[80,81]
Cellulase enzyme extracts	200–300	[82]

4.9. Complementary Factors Influencing Feedstock Utilization

In addition to the calorific value and composition of plantain and banana biomass (PBB), its effective utilization for bioenergy requires considering broader environmental and logistical variables. In the Santa Elena province, seasonal variation in agricultural production influences biomass availability. Although banana and plantain are perennial

crops, official data indicate that harvest peaks between April and August, while a drop of up to 25% in yield occurs from December to February [51]. This fluctuation may challenge supply continuity for energy systems unless supplemented by biomass storage or alternative feedstocks.

PBB also presents natural variability in composition, depending on plant part, maturity, and cultivation conditions. Lignin content, for example, tends to be higher in pseudostems than in leaves, affecting combustion behavior and residue generation [64]. These differences require regular monitoring to maintain system efficiency and process stability.

A further concern is the presence of agrochemical residues in the biomass. In Ecuador, banana cultivation commonly involves substances such as chlorpyrifos and mancozeb, which may remain in plant residues after harvest [83]. When subjected to thermochemical conversion, these compounds can release hazardous pollutants like dioxins or heavy metals, requiring mitigation strategies such as emission control systems or low-cost alternatives like washing or natural degradation.

Seasonal variation is a key factor for evaluating the availability of biomass as an energy resource. Santa Elena's climate is semi-arid from June to November, and rainy from December to May. Naturally, most crops, including banana and plantain, are concentrated in the rainy season, generating biomass throughout the year with higher peaks between December and May. This is relevant for planning the collection, storage, and drying of the waste available per month.

Lastly, the viability of a biomass-to-energy system depends on access to collection sites and community involvement. Transport infrastructure and distance affect recovery costs, while participation from farmers and cooperatives ensures supply stability and fosters social acceptance. These factors, summarized in Table 14, must be addressed holistically to guarantee a sustainable energy transition based on agricultural waste.

Table 14. Key factors influencing PBB utilization for bioenergy.

Factor	Impact on Biomass Utilization
Seasonal availability	Fluctuating supply; affects plant operation continuity
Chemical variability	Alters energy yield and conversion efficiency
Agrochemical residues	Requires emission control or pre-treatment
Logistics and access	Influences transport costs and residue recovery rates
Community engagement	Essential for collection, sustainability, and acceptance

A critical barrier to biomass energy development in Santa Elena is the scattered and seasonal nature of agricultural residues. Efficient collection systems must be designed, ideally organized around farmer cooperatives or decentralized collection points. Storage infrastructure is also necessary to smooth seasonal fluctuations, such as low-cost covered sheds or silage bags that preserve biomass quality. Transport logistics remain particularly relevant, as studies suggest that transportation may account for 20–30% of total biomass costs [84]. Clustering feedstock supply within a 20–30 km radius of conversion facilities could minimize these costs and enhance project feasibility.

4.10. Policy Implications

Successful implementation of biomass projects requires targeted policy interventions. Local and regional governments could introduce feed-in tariffs for renewable electricity, fiscal incentives for biomass-based power plants, or credit lines for farmer associations engaged in residue collection. Public–private partnerships may also accelerate deployment by reducing upfront risks. Experiences from India and Brazil show that long-term power

purchase agreements and residue collection subsidies have been crucial in enabling biomass projects to scale [85].

In addition to policy frameworks, infrastructure investment is necessary to make biomass energy economically viable. This includes rural road improvement for efficient transport, establishment of decentralized storage hubs, and financing schemes for pre-processing equipment. Access to concessional loans or blended finance instruments could significantly reduce the capital burden of small-scale plants, allowing farmer cooperatives or local entrepreneurs to participate in the value chain. International experience shows that financial de-risking mechanisms are often decisive for biomass energy adoption in developing regions [86].

4.11. Challenges and Future Research Directions

The potential of plantain and banana biomass (PBB) as an energy feedstock presents both strengths and limitations. On the one hand, PBB is abundantly available in the Santa Elena province, offers a low-cost raw material, and provides socio-environmental benefits such as reducing open-field burning and supporting rural income generation. On the other hand, its relatively high moisture content, seasonal variation, and lower energy density compared to fossil fuels introduce technical and logistical challenges. Additionally, the possible presence of agrochemical residues requires careful handling and disposal strategies. Table 15 summarizes the main advantages and disadvantages identified in this study.

Table 15. Advantages and disadvantages of plantain and banana biomass (PBB).

Advantages	Disadvantages
Abundant local availability	High moisture content (~68%)
Low cost of feedstock	Seasonal variation in yields
Reduces open-field burning	Possible agrochemical residues
Supports rural economy and income generation	Lower energy density than fossil fuels
Potential to contribute to renewable energy goals	Requires logistics for collection and storage

While the potential benefits are significant, several challenges must be addressed to realize this potential. These include optimizing biomass collection and processing methods, ensuring consistent quality and energy yield, and addressing logistical and economic barriers to implementation. Future research should focus on developing efficient technologies for biomass conversion, assessing the long-term environmental impacts, and exploring the economic feasibility of large-scale biomass energy projects. Promising technologies for future deployment include anaerobic digestion for biogas production, gasification for syngas, pyrolysis for bio-oil and biochar, and fermentation for bioethanol. These pathways can reduce the carbon footprint compared to direct combustion, albeit requiring higher capital investment.

It is estimated that the development of bioenergy in the Santa Elena Peninsula will keep growing; therefore, the optimization of the use of biomass will increase the resilience of the energy system, in addition to diversifying the use of different agricultural waste. In Santa Elena, the three most feasible bioenergy technologies are as follows: (A) anaerobic digestion, which treats waste with higher moisture content, the process generating, in addition to thermal and electrical energy, a byproduct called digestate [87], which can be used as fertilizer, benefiting local agriculture. Although this technology requires greater technical management, implementing it in banana plantations can reduce dependence on chemical fertilizers. (B) Direct combustion is viable due to the high availability of lignocellulosic residues from bananas and plantains. It can be used on a small or medium

scale for decentralized electricity generation; its approach requires a moderate investment and lower costs, which places it as a viable, immediate, and ideal option for the province. (C) Pellets: this type of biofuel uses different types of biomass that determine its color. They are cylindrical in shape, approximately 6 mm in diameter, and 40 mm in length. To obtain a quality bioproduct, the calorific value must be ≥ 16 MJ/kg and the humidity percentage $\leq 10\%$ [88]. The combination of these technologies will make biomass energy a feasible product, thus projecting a cleaner future for the peninsula.

In addition to banana and plantain residues, other agricultural by-products in Santa Elena province represent potential complementary feedstocks. Sugarcane bagasse, rice husks, and maize stalks are locally available in smaller but significant quantities, often with lower moisture content and different harvesting seasons. Their co-processing with PBB could reduce the overall supply variability and improve the stability of biomass-based energy systems. Future studies should therefore evaluate these residues to design more diversified and resilient feedstock supply chains.

These types of technologies are not new worldwide. Thermochemical and biochemical technologies have been implemented in Asia and India, where biofuels are derived from various biomasses such as coconut shells, palm residues, and sugarcane bagasse. These regions, like Ecuador, face two common problems: access to energy in rural areas and the accumulation of agricultural waste [78]. The successful example of these decentralized biogas plants in different parts of the world is a valuable reference for initiatives in countries where this technology is young and growing. The adoption of this revolutionary method of energy generation and the management of supply and demand have been key to the development of these rural areas; these steps can be replicated locally in Ecuador.

On the other hand, international experiences highlight the feasibility of agricultural residue-based energy systems under appropriate policy and logistical frameworks. In Brazil, sugarcane bagasse cogeneration has become a cornerstone of renewable electricity supply, supported by stable power purchase agreements [57]. In India, government incentives for rice husk gasification have enabled hundreds of decentralized power plants serving rural communities [85]. Vietnam has also leveraged rice husk combustion to produce electricity while reducing open burning [56]. These examples illustrate the potential role of banana and plantain residues in Santa Elena, provided that similar institutional and infrastructural support mechanisms are implemented.

The overall energy performance of biomass systems depends significantly on pre-treatment stages such as collection, transportation, drying, and size reduction. These steps can contribute substantial energy costs that affect the net energy balance of the system. Although not quantified in this study, future work should incorporate a detailed life-cycle energy analysis to determine the impact of each preparatory operation and identify optimization opportunities to maximize energy return on investment.

Furthermore, factors such as seasonal availability, agronomic practices, variability in chemical composition, and potential contamination from agrochemicals may affect the consistency and efficiency of biomass conversion. These aspects warrant consideration in future studies to refine the techno-economic assessment and ensure sustainability throughout the biomass supply chain.

To provide a clear overview of the challenges and future research directions, a conceptual scheme was developed (Figure 7). This flowchart summarizes the main stages of PBB utilization, from biomass generation to energy conversion, while highlighting key bottlenecks and opportunities for improvement.

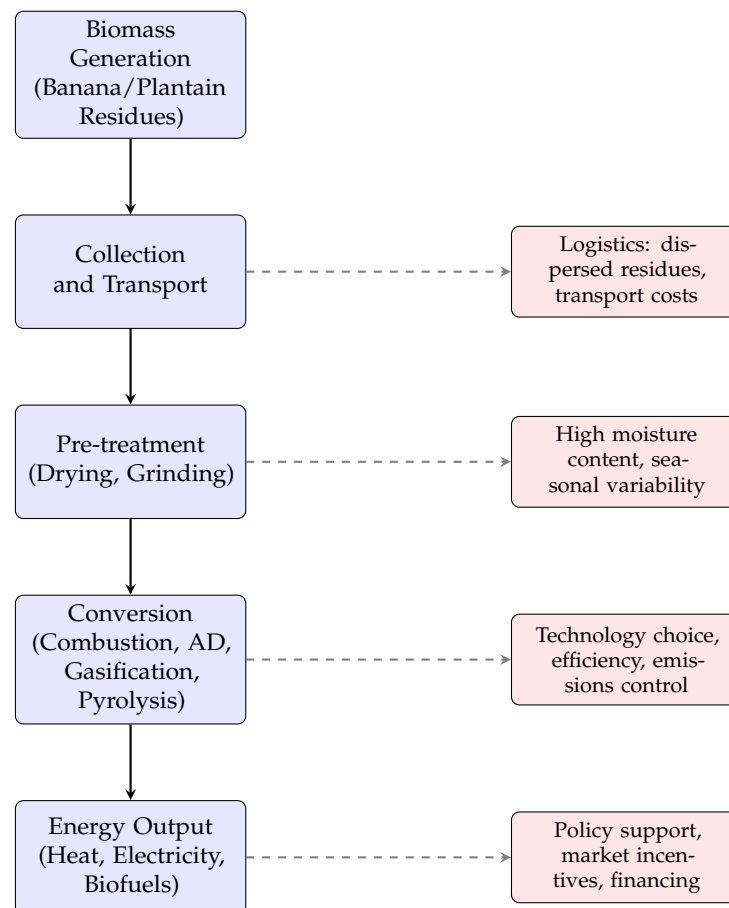


Figure 7. Conceptual scheme of plantain and banana biomass (PBB) energy pathway, highlighting key challenges and future research directions.

5. Conclusions

This study demonstrates the significant potential of plantain and banana biomass (PBB) in Santa Elena, Ecuador, as a renewable energy source, with an estimated energy generation potential of 382.79 GWh per year, which would help to meet local energy needs and support Ecuador's move toward cleaner energy transition. This energy potential could cover 17% of Santa Elena's annual energy needs, becoming a substantial contribution to the energy matrix and reducing fossil fuels reliance.

The ability to generate 76.56 GWh/year from PBB considering a conservative 20% plant factor emphasizes its contribution not only to the energy security of the province but also to the diversification of energy sources. Biomass, in comparison to intermittent energy sources like solar and wind, provides a consistent and reliable energy supply. This advantage also makes it a good option for isolated rural areas that cover much of the extension of Santa Elena.

It is noticeable that biomass could supply at least 17% of the local energy demand per year in Santa Elena, representing a significant contribution to the energy matrix. This potential not only reduces reliance on fossil fuels but also supports energy security by diversification of energy sources.

By integrating PBB into its energy matrix, Santa Elena can align with Sustainable Development Goals (SDG), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). This approach not only supports sustainable development but also strengthens the local community's resilience while benefiting the environment.

Finally, the adoption of banana and plantain biomass as a renewable energy source represents a promising option to meet Santa Elena's energy needs, reducing greenhouse

gas emissions and promoting local economic development. Internationally, diversification of the energy matrix is a strategy for sustainable development. Developing economies like Ecuador's should adopt this approach to enhance energy security, achieve sustainability goals, and meet the decarbonization goals outlined under the Paris agreement.

A net energy balance analysis confirmed that, under realistic assumptions, the energy recovered through direct combustion of pre-treated PBB exceeds the energy consumed during collection, preparation, and conversion by a wide margin, resulting in an estimated net energy output of 12.41 MJ/kg. This supports the viability of the proposed system from a thermodynamic perspective.

Additionally, an exergy analysis was performed to assess the thermodynamic quality of the energy conversion process. The results indicate an exergy efficiency of 51.2%, confirming that more than half of the exergy contained in the feedstock and support operations is effectively transformed into useful thermal energy. This performance is considered favorable for decentralized systems with low processing complexity, especially under passive drying and short-distance logistics.

In addition to the technical and environmental viability, an initial economic approximation suggests that solid biomass systems using PBB could be profitable under local market conditions. With a production cost of approximately 6.5 USD/ton for biomass and an average energy price of 0.09 USD/kWh in Ecuador, the total annual revenue would reach up to 18.95 million USD/year. Considering an average conversion efficiency of 75% and pre-treatment energy costs of less than 2% of the HHV, the system offers a favorable energy return on investment. Even when accounting for logistical, operational, and maintenance expenses, the low feedstock cost and infrastructure simplicity of fixed-bed combustion systems suggest that local deployment is economically viable. A more comprehensive techno-economic assessment will be necessary to quantify investment needs, the internal rate of return, and the payback period, but these preliminary indicators support the development of decentralized bioenergy systems based on agricultural residues in Santa Elena.

Nevertheless, future work should expand on this assessment by incorporating life-cycle energy modeling and pilot-scale demonstrations. These will help to refine the estimates, validate environmental impacts, and ensure replicability under different operational contexts. A more detailed techno-economic analysis is also needed to assess the long-term profitability and policy integration of biomass-based energy systems in rural Ecuador.

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