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Renewable Energy from Cocoa Waste Biomass in Ecuador's Coastal Region: Advancing Sustainable Supply Chains

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Abstract

Coastal regions of Ecuador, particularly Esmeraldas and Manabí, face significant challenges related to energy access, waste management, and sustainable agricultural development. This study evaluates the renewable energy potential of cocoa waste biomass generated by smallholder farms in these provinces. A total of 20 cocoa farms, either certified or in the process of certification under the Rainforest Alliance standard, were surveyed to quantify the volume of agricultural and agro-industrial residues. Residual biomass generation ranged from 50 to 6500 tons per year, depending on farm size, planting density, and management practices. Spatial analysis revealed that Esmeraldas holds the highest concentration of cocoa waste biomass, with some farms reaching a gross energy potential of up to 89.07 TJ/year. Using thermochemical conversion scenarios, effective energy potential was estimated, and 75% of the farms exceeded the viability threshold of 100 MWh/year. The results confirm the feasibility of cocoa biomass as a renewable energy source, mainly when managed collectively at the community level. Incorporating this waste into decentralized energy systems supports circular economy models, enhances energy self-sufficiency, and aligns with sustainable supply chain goals promoted by certification schemes. This study contributes to national efforts in energy diversification and provides a replicable model for integrating renewable energy into rural agricultural systems.

Keywords: cocoa biomass; agricultural residues; renewable energy; circular economy; Rainforest Alliance

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1. Introduction

Energy plays a fundamental role in driving economic growth and industrial development worldwide. While 91% of the global population has access to energy, approximately 61.4% of global energy production still comes from fossil fuels such as coal and oil [1]. The intensive use of these non-renewable sources has serious environmental consequences, including the emission of greenhouse gases (GHGs), the depletion of finite resources, and long-term contributions to air pollution.

To address these challenges, renewable energy sources—such as biomass, solar, and wind—have gained traction as cleaner alternatives. However, in many countries, their contribution to the national energy mix remains relatively small [2].

In Ecuador, the national energy matrix continues to rely heavily on fossil fuels, with 76% of the supply coming from oil (38%), natural gas (25%), and coal (13%) [3]. Nevertheless, the country has signaled its commitment to transitioning toward more sustainable energy sources, especially in rural areas, to strengthen energy security and achieve the Sustainable Development Goals (SDGs) [4].

Among renewable options, biomass has attracted increasing interest from researchers and industries alike due to its renewability and potential as a substitute for fossil fuels [5,6]. Biomass can reduce greenhouse gas emissions, support climate change mitigation, and offer a pathway to diversify Ecuador's energy sources.

Recent studies in Ecuador have focused on the energy potential of agricultural biomass, particularly in rural areas where crop production is prevalent [7]. Key crops contributing to biomass generation include banana, rice, cocoa, sugarcane, corn, African palm, pineapple, coffee, and palm heart. Additional sources include livestock waste from poultry, pigs, and cattle, as well as forestry byproducts [8]. According to the Bioenergy Atlas of Ecuador [9], cocoa (Theobroma cacao L.) is one of the top contributors to residual biomass, producing an estimated 2 million tonnes annually. This amount is roughly equivalent to 101 million gallons of diesel. However, despite this potential, cocoa biomass remains underutilized due to limited technical knowledge, insufficient technology, and a lack of strategic frameworks for recovery [7].

Despite the high biomass availability, coastal provinces like Manabí and Esmeraldas face unique socio-environmental challenges, including limited access to stable energy sources, vulnerability to climate change, and rural poverty. Many rural communities rely on traditional biomass or expensive fossil fuels for cooking and processing, leading to inefficiencies and environmental degradation. At the same time, these areas exhibit high agricultural productivity and a strong presence of cocoa cultivation, which presents an opportunity for decentralized, circular bioenergy systems that generate value locally while supporting sustainable agriculture [10].

International efforts have further demonstrated the viability of cocoa waste as an energy source. In leading cocoa-producing countries like Ghana and Nigeria, projects have explored the conversion of cocoa shells and mucilage into energy through combustion, gasification, and anaerobic digestion [10,11]. These cases highlight cocoa waste's potential to contribute meaningfully to rural bioenergy systems.

Historically, only cocoa beans have been commercially exploited—for chocolate production, cosmetics, and other products—while large quantities of agricultural waste (e.g., shells and mucilage) and industrial waste (e.g., husks) are discarded. These by-products account for approximately 70–80% of the fruit's total weight [2,12].

In Ecuador, the canton of El Carmen, located in the province of Manabí, functions as a key cocoa export hub, sourcing from farms in both Manabí and Esmeraldas. Many of these farms are currently pursuing Rainforest Alliance certification, which encourages the implementation of agro-industrial practices that make efficient use of agricultural residues. In this context, evaluating the energy potential of cocoa waste biomass is critical for reducing environmental impacts and advancing energy sustainability [13,14].

In this context, evaluating the energy potential of cocoa waste biomass is important for mitigating environmental impacts and promoting energy sustainability. This approach could also reduce dependence on fossil fuels, lower production costs for farmers, and support rural development by enhancing energy access and generating local employment opportunities. In areas like Manabí and Esmeraldas, characterized by dispersed agricultural settlements and limited infrastructure [15], decentralized solutions can play a pivotal role in strengthening energy resilience and promoting inclusive economic growth.

This study supports the United Nations Sustainable Development Goals, particularly SDG 7, which promotes clean and affordable energy, and SDG 12, which advocates responsible resource use and waste reduction [16].

The integration of residual cocoa biomass valorization into sustainable supply chains offers a significant opportunity to improve both environmental performance and local livelihoods. By transforming post-harvest waste into renewable energy, producers can reduce waste, generate added value at the source, and diversify their sources of income. This approach also promotes circularity and resilience throughout the cocoa value chain by linking primary production with energy generation, thereby reinforcing sustainability objectives beyond the farm level [17].

The goal of this research is to evaluate the energy potential of cocoa waste biomass produced by farms in the provinces of Esmeraldas and Manabí, Ecuador. The aim is to support sustainable supply chains and promote the use of renewable energy through agroecological practices.

2. Materials and Methods

2.1. Study Area

The research was conducted across a network of cocoa farms that are either certified or in the process of certification under the Rainforest Alliance standard. These farms are located in the coastal provinces of Manabí and Esmeraldas, which play an active role in Ecuador's cocoa value chain and are highly representative of the country's agricultural and cocoa production. In Manabí, the study focused on the parishes of Wilfrido Loor Moreira and San Gregorio, both part of the canton of El Carmen. In Esmeraldas, the selected parishes were Atahualpa and Chibunga, located in the canton of Rio Verde (Figure 1).

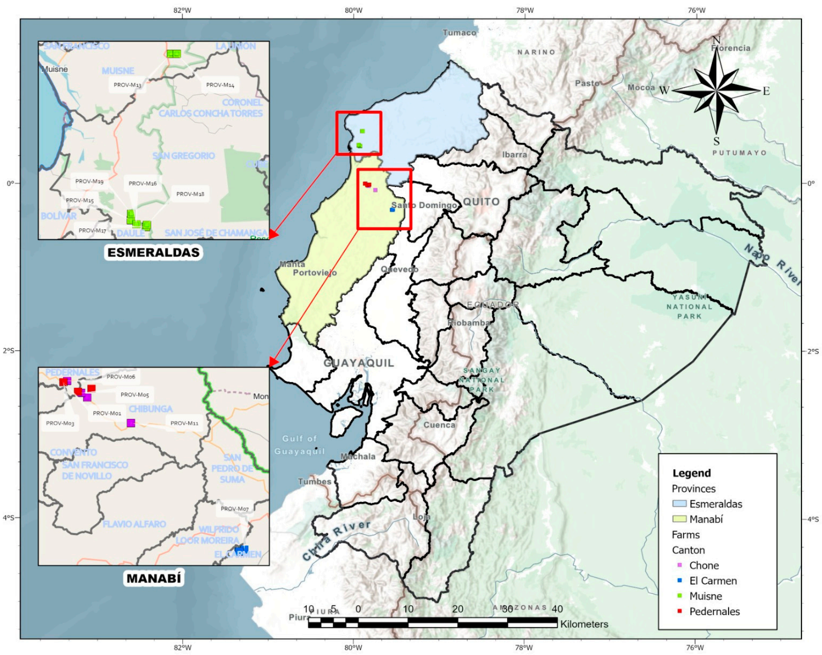

Figure 1. Study area location.

These regions present potential for cocoa cultivation, given their humid tropical climate, relatively fertile soils, and an average elevation between 100 and 300 m above sea level. However, according to agroecological suitability assessments, these areas are currently classified as moderately or marginally suitable, reflecting certain edaphic and climatic limitations under natural conditions. Despite this, such conditions can still support cocoa production when combined with adaptive agricultural practices and appropriate crop management strategies [18]. Additionally, the participating farms adopt practices that promote environmental sustainability, production traceability, and responsible use of natural resources, in line with the principles of Rainforest Alliance certification.

Our proposed methodology began with the selection of cocoa farms that were either certified or in the process of certification under the Rainforest Alliance standard. Surveys were then conducted to gather data on production and residue generation. For the collection of primary data, a structured survey was designed and administered to cocoa producers in the provinces of Manabí and Esmeraldas to characterize agricultural practices and estimate the amount of waste generated from pruning and harvesting the crop. The instrument used was constructed with the objectives of the study in mind and grouped closed questions into four areas: general characteristics of the farm (location, cultivated area and planting density), agronomic practices (pruning frequency, harvesting frequency and average yield in kg/ha), waste generation (estimate of waste per annual pruning and quintal of harvested cocoa), and current management and willingness to participate in energy utilization programs. The questions were designed to facilitate the quantification of waste. The surveys were conducted in person through direct interviews during technical field visits between October and December 2024. The values reported by the producers were compared, as far as possible, with on-site observations and standardized calculations to estimate the total biomass available per production unit.

Based on this information, the volume of residual biomass was estimated and spatially analyzed using R software. The next step involved calculating the gross and usable energy potential, taking into account the types of residues and the efficiency of conversion processes. Finally, the methodology concluded with an evaluation of sustainability indicators related to energy, environmental, and social dimensions within the cocoa supply chain (Figure 2).

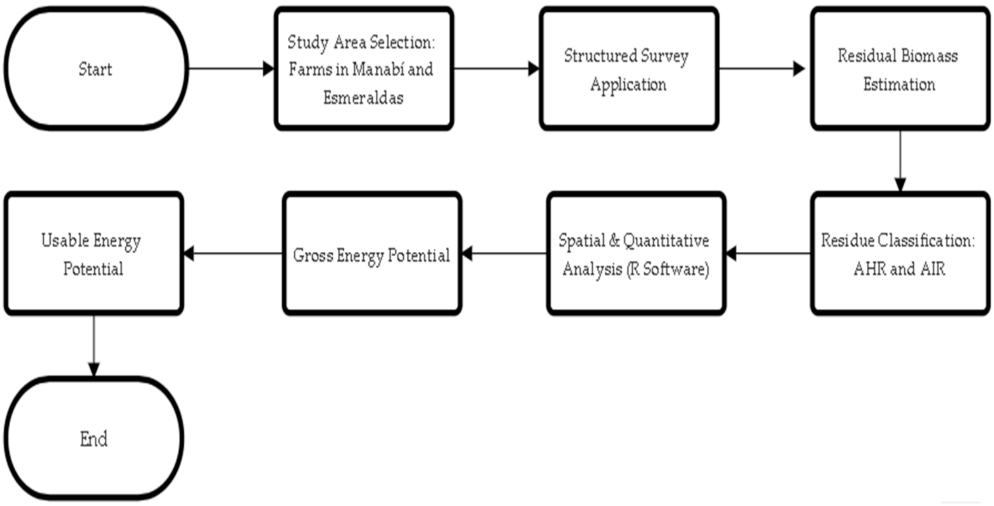

Figure 2. Research methodology flowchart.

2.2. Ethical Considerations and Informed Consent

During the collection of information from local producers and stakeholders, the confidentiality and anonymity of the data collected were guaranteed. Before conducting the surveys and interviews, the purpose of the study, its exclusive use for scientific purposes, and the voluntary nature of participation were explained to each participant. In all cases, informed consent was obtained, either verbally or in writing, by the ethical principles of research involving human subjects and current institutional standards.

Two fundamental criteria were considered for selecting the farms participating in the study: continuous involvement in cocoa production throughout the year and familiarity with the certification process under the Rainforest Alliance (RA) standard. These criteria ensured the representativeness and relevance of the production units within Ecuador's cocoa value chain, particularly in sustainable and traceable supply chains.

In order to adequately characterize the cocoa-producing farms and collect information on the residual biomass generated, a structured survey was applied to those responsible for each selected farm. The instrument consisted of nine questions addressing both qualitative and quantitative production and waste management variables. The topics addressed included cultivated area and plantation density, pruning practices, quantity and type of waste generated, annual production volume, waste derived from the harvesting process, current management of such waste, harvesting frequency, willingness to implement energy recovery systems, and the geographical location of each production unit.

The instrument was applied with support from technical personnel involved in Rainforest Alliance certification processes in the field. Surveys were conducted between October and December 2024 [19]. The producers requested that the participants be kept private at all times, and in compliance with the ethical principles of this research, the participants' privacy was guaranteed.

2.3. Estimation of Residual Cocoa Biomass

For quantifying biomass, the mathematical model established by Serato and Lesmes [20] was used. The total area (in hectares) of the farms dedicated to cocoa cultivation (A), the crop yield or cocoa production (Rc), the crop residue factor (Fr), and finally, the dry residue fraction (Yrs) were considered. Equation (1) shows the estimation of residual biomass (Mrs).

$$Mrs = A * Rc * Fr * Yrs \tag{1}$$

The residues generated in cocoa cultivation were classified into two main categories: agricultural harvest residues (AHR), comprising leaves, stems, and pods; and agro-industrial residues (AIR), mainly represented by cocoa bean shells obtained during post-harvest processing. For each type of residue, specific values for the residue generation factor (Fr) and dry residue fraction (Yrs) were applied based on the characteristics and energy potential of each fraction. The values used are detailed in Table 1.

Table 1. Residue factor (Fr) and dry residue fraction (Yrs) according to the cocoa crop [20].

Residue Type	Waste Source	Fr	Yrs
Leaves	AHR	2,66	1007
Stems	AHR	2,83	1007
Cob	AHR	5,90	1007
Agro-industrial residues	AIR	15,25	1007

Once the total mass of dry residue generated by the farms analysed was quantified, the R statistical environment (version 4.4.1) was used to process and visualize the spatial and quantitative distribution of cocoa waste biomass (in tonnes per year) in Manabí and Esmeraldas. This visualization made it possible to identify waste generation patterns at the territorial level, facilitating comparative analysis between zones and the recognition of areas with greater energy potential.

2.4. Gross Energy Potential Assessment

The gross energy potential was estimated from the direct relationship between the mass of dry residue (Mrs), expressed in tonnes per year (t/year), and the lower calorific value (LCV) of each type of residue, expressed in terajoules per tonne (TJ/t). This ratio provided an estimate of the total energy content available in the waste biomass before considering the losses associated with the conversion processes. The equation used was as follows:

$$Q = Mrs * LCV, \tag{2}$$

2.5. Assessment of the Usable Energy Potential from the Biodegradable Fraction of Cocoa Residues

The energy potential determines the capacity to generate energy [21], in this case, from cocoa waste. For this, it was necessary to apply equation 3, where PE represents the effective energy potential (kW/year); K is a conversion factor equivalent to 277,778 (kWh/TJ) [21]; Q is the gross energy potential (TJ/year); and η is the equivalent electrical efficiency for thermochemical conversion processes (Table 2).

$$PE = K * Q * \eta, \tag{3}$$

Table 2. Equivalent electrical efficiency for thermochemical conversion processes [22].

Process	η (%)
Direct Combustion (CD)	19.9
Gasification and Gas Turbine (GTG)	25–28
Gasification and Combined Cycle (GCC)	35–40
Pyrolysis and Combined Cycle (PCC)	31

The potential energy generation (PE) in MWh/year was estimated using the product of the biomass quantity, its calorific value, and the conversion efficiency, expressed directly in MWh.

2.6. Sustainability in the Supply Chain of Certified Cacao Farms in Coastal Ecuador

To assess cocoa farms' progress toward clean and sustainable energy production, the energy efficiency indicators established in the Rainforest Alliance Energy Efficiency Guide, version 1.0, were used as a reference.

This guide provides technical criteria to support compliance with requirements related to fossil fuels, electricity, renewable energy, gas, and biomass across various agricultural operations, including cocoa farms. These indicators provide a framework for evaluating current practices, identifying opportunities to integrate renewable energy, and enhancing overall energy management in certified supply chains.

In the framework of this research, the proportion of energy from renewable versus non-renewable sources was established as the leading indicator. This indicator was prioritized in the preliminary participatory mapping process of the value chain for sustainable cocoa production to strengthen energy traceability and improve the decision-making process.

For the collection of primary data, a structured, georeferenced survey was designed and administered to cocoa producers in the provinces of Manabí and Esmeraldas. The survey aimed to gather detailed information on energy consumption patterns, sources of energy used, production outputs, and the generation of agricultural residues. This approach enabled a comprehensive understanding of current energy practices and opportunities for adopting cleaner and more efficient energy alternatives. To provide spatial context, the Inverse Distance Weighting (IDW) interpolation method was applied to estimate values in the areas surrounding the surveyed locations [23]. This allowed for the spatial representation of residual cocoa biomass by year and the gross energy potential of the farms, offering a clearer view of spatial variability and dynamics. Additionally, the survey incorporated social and environmental dimensions. The social component included a child labor indicator, aligned with international sustainability standards, while the environmental component used biomass-derived energy as a metric to assess the impact of agricultural waste utilization on local ecosystems.

3. Results

3.1. Characterization of Cocoa Production from Farms

From the survey applied to the owners of cocoa farms, it was possible to identify the main characteristics of the production units, which are detailed in Table 3.

Table 3. Characteristics and agricultural practices of the farms.

Questions	Results
1. Crop surface	Less than 3 ha: 30% (6 farms) 3–5 ha: 35% (7 farms) 6–10 ha: 25% (4 farms) More than 10 ha: 25% (3 farms)
2. Crop density	Less than 700 plants/ha: 5% (1 farm) 700–900 plants/ha: 55% (11 farms) More than 900 plants/ha: 40% (8 farms)
3. Pruning frequency	2 times per year: 50% (10 farms) 1 time per year: 40% (8 farms) 3 times per year: 5% (1 farm) Once every 3 years: 5% (1 farm)
4. Pruning Waste	100% leave it on the soil as compost
5. Current Rentability	More than 800 kg/ha: 75% (15 farms) 400–600 kg/ha: 15% (3 farms) 601–800 kg/ha: 10% (2 farms)
6. Harvest Waste	76–100 kg/QQ: 70% (14 farms) Less than 50 kg/QQ: 20% (4 farms) 50–75 kg/QQ: 10% (2 farms)
7. Current disposition of residues	100% leave it on the soil as compost
8. Harvest frequency	Twice a month: 70% (14 farms) Weekly: 20% (4 farms) Monthly: 10% (2 farms)
9. Willingness to participate in workshops	Yes: 90% (18 farms) No: 10% (2 farms)

In terms of cultivated areas, most of the farms were small and medium-sized, with 65% of the producers managing areas of less than 5 hectares. This dimension corresponds to sustainable family farming systems, which are recognized as important actors in the new models of agricultural development due to their role in food security, environmental sustainability, and rural economy [24].

It should be considered that, in the framework of this research, there was homogeneity in certain agricultural practices. It was observed that 90% of the farms had a planting density of more than 700 plants per hectare, and an equivalent percentage carry out pruning at least once a year. This standardization suggests a consolidated technical level among producers, possibly due to previous training processes. However, one of the objectives of Rainforest Alliance certification is to strengthen these capacities by incorporating environmental and social approaches that allow progress toward truly sustainable production models [25].

Regarding the performance of the farms, it was evident that 75% had a productivity exceeding 800 kg/ha, which confirmed the significant influence of management practices on productive performance. It should be noted that 25% of the farms maintained cocoa crops within areas of primary forest.

This study identified that 80% of the farms cultivated the CCN-51 variety, while the remaining 20% maintained the Nacional variety; 50% of the producers pruned twice a year, while 40% did it once a year. Currently, the management of these residues was limited: according to survey data, 100% of the producers left both pruning and harvesting residues on the soil as compost, following a traditional organic fertilization practice. While this contributes to soil health, it also reflects a lack of valorization of these residues for other potential uses, such as energy generation [26]. This scenario reveals the opportunity to assess the energy potential of residual biomass, especially considering that 70% of the farms generated between 76 and 100 kg of waste per quintal of harvested cocoa. Finally, it is highlighted that 90% of the farmers expressed interest in participating in training programs.

3.2. Total Quantification of Biomass from Cocoa Farms

The analysis of the residual biomass generated by the cocoa farms allowed for the identification of relevant patterns in terms of waste volume and spatial distribution. These findings are fundamental for estimating the energy potential of the supply chain and establishing sustainable valorization strategies for agricultural by products.

The cacao production units generated residual biomass ranging from 50 to 6500 tons per year (Figure 3). This variability was closely linked to the geographical distribution and specific productive characteristics of each farm. Figure 3 illustrates the spatial distribution of the surveyed farms using a colour scale derived from Inverse Distance Weighting (IDW) interpolation. This representation shows the estimated biomass (tons/year) between farm locations in both provinces, providing a broader understanding of biomass generation patterns. Such visualization supports future planning efforts, particularly for farmers interested in quantifying biomass availability in their vicinity. Each surveyed farm is identified by a unique code (e.g., PROV-M15), which is labeled in the figure. Additionally, the results highlight that biomass production varied significantly among farms, with some exhibiting notably higher output than others.

The spatial distribution of cacao residual biomass in the provinces of Manabí and Esmeraldas revealed a clear correlation with the areas of highest cacao production. In particular, the province of Esmeraldas concentrated the most significant volumes of residual biomass during the year 2024, standing out as the primary generation hub for biomass generation within the coastal region of Ecuador.

Figure 4 presents a more detailed view of the geographical distribution of residual cocoa biomass across the study area, using IDW interpolation. The province of Esmeraldas is particularly prominent, displaying the most intense tones on the color scale, which reflect a higher concentration of agricultural waste. This intensity was directly associated with the greater density of cocoa plantations in that region. Like Figure 3, this spatial representation provides insight into the gross energy potential derived from cocoa residues. It offers a valuable geographical perspective for informing future planning and sustainable management of cocoa farms.

The relationship between the cultivated area and the amount of biomass generated highlighted Esmeraldas as the region with the most significant potential for the energy utilization of agricultural waste, with values ranging between 2500 and 6000 tons per year. These results underscore the importance of prioritizing this province in future energy recovery strategies within the cocoa supply chain.

In the Manabí region, biomass distribution remained within the map's color scale, with values ranging from 50 t/year to 2500 t/year, indicating a lower potential for waste generation compared to other areas. When comparing the residual biomass values of cocoa distributed in the farms of Manabí and Esmeraldas with the results obtained by Núñez et al. [27], who reported a value of 120 t/year of biomass in cocoa production systems, it is evident that the areas evaluated in the present research had significantly higher biomass production. This finding suggests a favorable scenario for energy utilization from agricultural residues in these provinces.

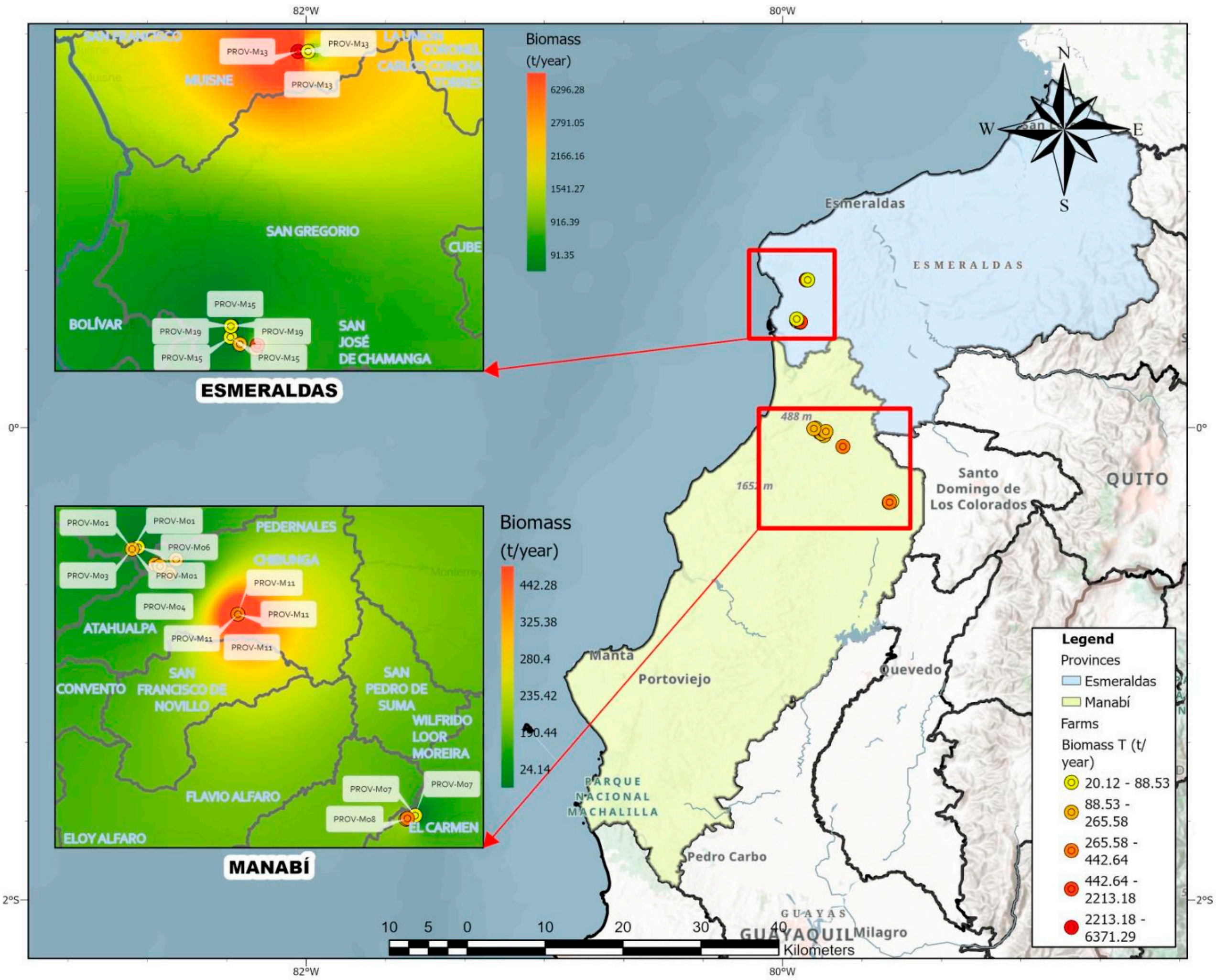

Figure 3. Spatial distribution of residual cocoa biomass (t/year) in surveyed farms across Esmeraldas and Manabí, with enlarged insets of high-density areas. Farm codes and biomass values are shown using a color scale based on IDW interpolation.

This calculation integrated the primary sources of residual biomass generated during the cocoa harvest, including leaves, stems, fruits, and pods.

The energy potential distribution showed that most farms generated values below 7 TJ/year. Additionally, two notable cases were observed: farm 13 and farm 18, which presented a gross energy potential of 89.07 TJ/year and 30.94 TJ/year, respectively. These values were directly related to the number of hectares cultivated in these farms.

The variability in energy potential between farms indicates the importance of considering multiple factors when evaluating the bioenergetic potential of each productive unit. It should be pointed out that the present research incorporates a comprehensive approach by including all agricultural cacao residues in the energy analysis [28]. Previous authors emphasized that the gross energy potential should consider the entirety of agricultural biomass resources and thus their contributions to sustainability.

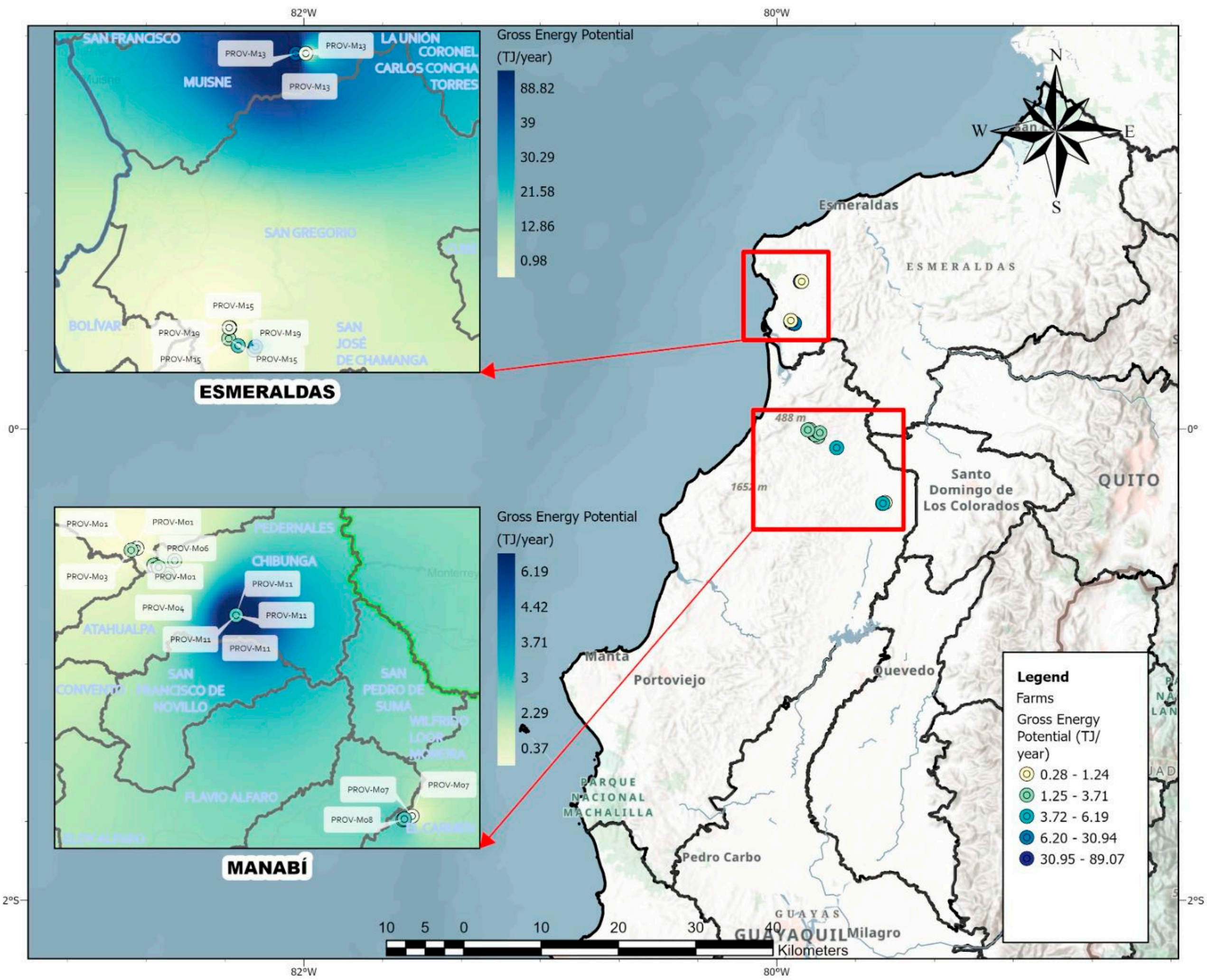

Figure 4. Spatial representation of gross energy potential (GJ/year) from residual cocoa biomass in the study area, with emphasis on high-density production zones in Esmeraldas and Manabí, based on IDW interpolation.

3.3. Effective Energy Potential

Biomass requires specific transformation processes due to its geographical dispersion [29]. However, it should be noted that only farms 13 and 18 reached the high potential threshold set at 1000 MWh/year, identifying them as the farms with the most significant strategic contribution to implementing bioenergy production technologies.

Figure 5 shows that 75% of the 20 evaluated farms exceeded the minimum viability threshold of 100 MWh/year in terms of effective energy potential. This threshold was adopted based on international case studies (e.g., [30]) as a benchmark for the minimum energy output needed for decentralized biomass energy systems to be considered viable. These results suggest that a large majority of the farms had favorable conditions for bioenergy utilization. However, none of the farms reached the 1000 MWh/year level, underscoring the importance of exploring cooperative strategies to aggregate biomass resources and enhance collective energy production.

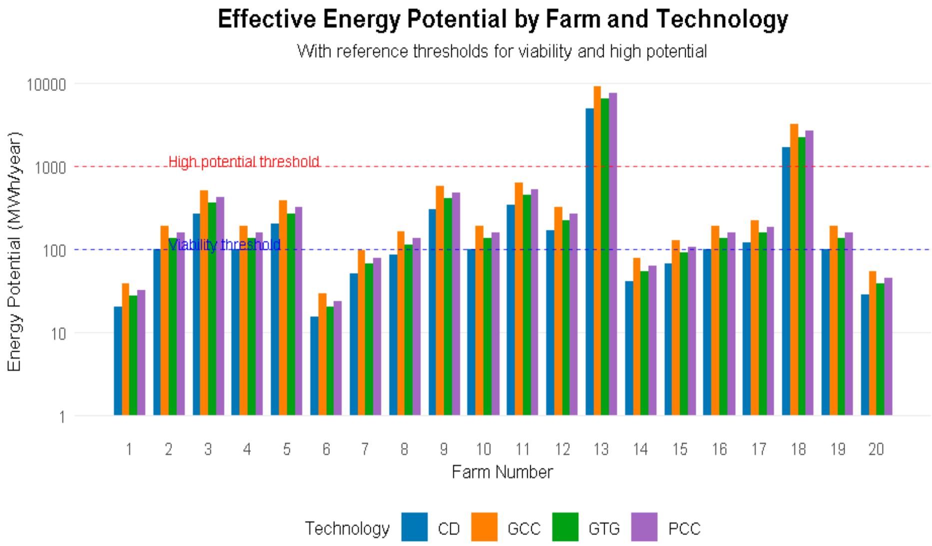

Figure 5. Effective energy potential by farm and technology.

3.4. Agroecological Zoning of Cocoa in Esmeraldas and Manabí

To assess the true potential of the study area, this study analyzed the agroecological suitability for cocoa cultivation in the provinces of Manabí and Esmeraldas, using data provided by the Ministry of Agriculture and Livestock of Ecuador [31]. This analysis was based on official zoning criteria, which classify land according to natural soil conditions, topography, and climate. The resulting map (Figure 6) showed the spatial distribution of areas categorized as optimal (green), moderate (yellow), marginal (orange), and unsuitable (grey) for cocoa production.

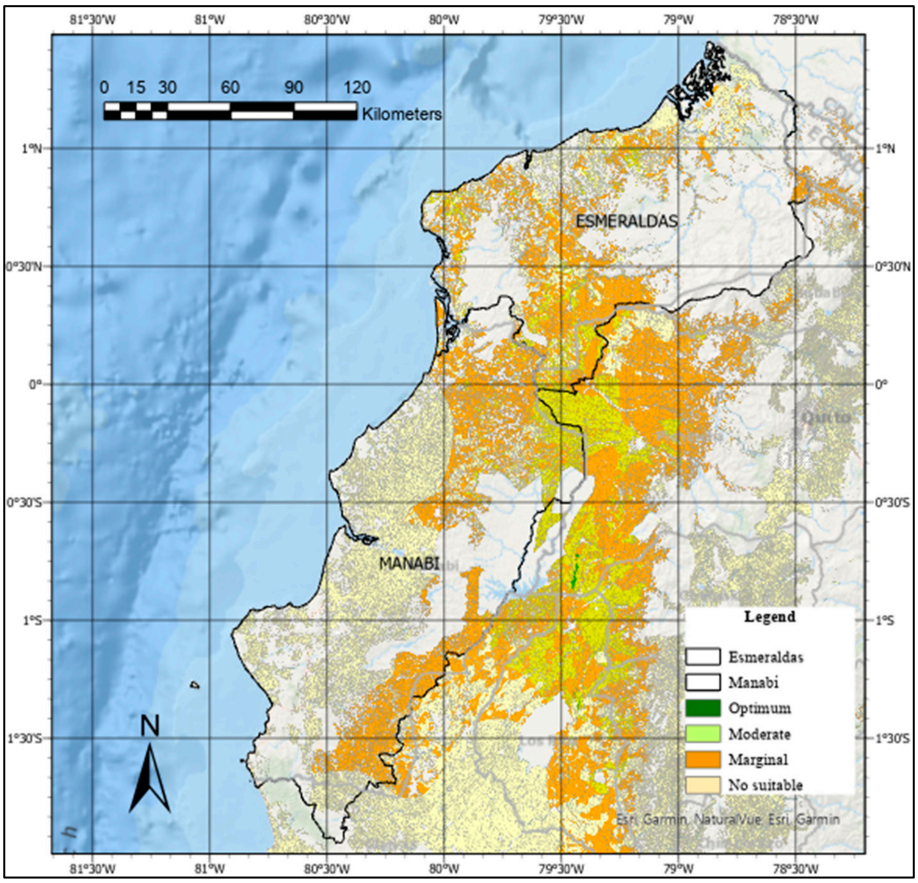

Figure 6. Agroecological zoning of cocoa in Esmeraldas and Manabí.

The analysis revealed that the two provinces have areas classified as moderate (yellow) and marginal (orange). This pattern shows certain edaphic and climatic limitations under natural conditions; however, it also represents an excellent opportunity to develop sustainable production systems.

Through the implementation of adaptive agroecological practices such as agroforestry systems, tolerant varieties and soil conservation techniques can be properly managed in these areas to maintain crop productivity and stability. This approach not only contributes to agricultural sustainability and climate resilience but also enables the use of cocoa waste biomass as a renewable energy source [32].

The energy recovery of agricultural byproducts such as husks, cobs, and pruning residues can complement local energy needs in rural areas, diversify the income of smallholders and reduce dependency on fossil fuels, thus contributing to equitable energy access and climate change mitigation. In this context, areas with moderate and marginal aptitude acquire a new strategic value as a basis for cocoa production and as generators of usable biomass within a territorial model of circular economy.

The spatial distribution of residual cocoa biomass showed different patterns between the provinces of Manabí and Esmeraldas, influenced by factors such as plantation density, pruning frequency, agricultural practices, and accessibility. In cantons such as El Carmen and Muisne, where intensive production systems predominate, there was a higher concentration of waste generation from both pruning and harvesting, suggesting a high potential for the development of decentralized bioenergy initiatives. This concentration enables the prioritization of strategic areas for the installation of collection centers, thereby reducing logistics costs. However, the energy use of this waste faces significant challenges, such as technological limitations and a lack of adequate conversion equipment (anaerobic digesters, dryers, gasifiers) [33], which restrict the adoption of local solutions. Furthermore, it is essential to consider that economic viability relies on adequate incentives, sustainable business models, and a legal framework that promotes the recovery of agro-industrial waste. Finally, social acceptance is also a critical factor: although a majority of producers expressed their willingness to participate in utilization programs, cultural and technical knowledge barriers persist that could affect the effective implementation of these schemes. Therefore, energy recovery strategies must combine technical, territorial, and social criteria to ensure their sustainability.

4. Discussion

Applying good agricultural practices alongside appropriate technologies can significantly improve crop yields [34]. These practices offer ecological benefits, including improved soil fertility, enhanced water retention, and biological pest control, all of which contribute to increased productivity and higher economic returns for farmers [35]. Moreover, the volume and composition of agricultural waste are directly influenced by the level of technological adoption and the specific cocoa varieties cultivated on each farm [36]. Despite these opportunities, the current handling of agricultural waste largely follows a traditional approach, often lacking valorization strategies and remaining underutilized in terms of energy and nutrient recovery [26].

However, this agricultural byproduct, particularly cocoa residues, represents a promising renewable energy source. Valorizing such waste could diversify farm income streams while reducing dependence on non-renewable energy sources. Innovations in biomass energy production not only improve the overall efficiency and sustainability of the cocoa value chain but also strengthen the energy resilience of rural communities. As noted by Thomson et al. [37], farmers' perceptions and values play a crucial role in the success of bioenergy initiatives, acting as drivers in the shift toward cleaner, self-sufficient production systems.

In the context of the ongoing climate crisis, adopting renewable energy sources has become increasingly urgent. Utilizing residual biomass from cocoa cultivation and processing presents a sustainable solution that aligns with circular economy principles and improves energy efficiency, particularly in rural agricultural regions of developing countries. These strategies can help to diversify local energy matrices, reduce reliance on fossil fuels, and mitigate the environmental impacts associated with poor organic waste management.

The use of renewable energies—such as cocoa biomass—not only reduces the volume of organic waste but also lowers emissions released during decomposition, contributing to improved air quality. For instance, recent studies examining air quality in urban and rural environments emphasize the need for cleaner energy alternatives to reduce atmospheric pollutants [38]. Cocoa shells, as a form of agro-industrial waste, offer a lower-emission alternative to fossil fuels when used for energy generation.

Variability in the quantity of residual biomass observed among farms may be influenced by factors like soil fertility and local climatic conditions [30]. Spatial patterns across Manabí and Esmeraldas become particularly significant given that for every ton of cocoa produced, an estimated 9–10 tons of residual biomass are generated [39]. These figures highlight the urgent need to implement efficient waste management and valorization strategies, especially within the framework of circular economy models. Supporting this, Montalván et al. [40] estimated that one hectare of cocoa production can yield around 0.16 metric tons of usable waste—mainly pruning material and pods—with an energy potential of approximately 23,908.75 kWh per month. This provides a strong foundation for considering on-farm energy use.

The potential energy capacity identified in this study supports broader goals of environmental sustainability, enabling more efficient use of agricultural resources and encouraging the adoption of circular economy models. On a national level, Ecuador's National Electricity Operator (CENACE) [41] has projected the need to add 1080 megawatts of power to address the country's ongoing electricity crisis (2024–2025). In this context, cocoa residual biomass emerges as a clean, viable, and decentralized energy source to help bridge this energy gap.

Cooperative strategies, such as forming energy associations among producers, are especially relevant. International experiences, such as those in China, where biomass energy supports university campuses with up to 96 MWh/year—help validate the 100 MWh/year viability threshold adopted in this study for Ecuadorian cocoa farms [42]. This threshold serves as a benchmark for the minimum energy output required to justify investment in decentralized biomass systems. In our analysis, 75% of the evaluated farms exceeded this threshold, suggesting that many are already well-positioned to adopt bioenergy solutions. However, none of the farms individually reached the 1000 MWh/year level, reinforcing the need to strengthen cooperation among producers to aggregate biomass and increase collective energy output. Such approaches can reduce reliance on centralized fossil-fuel infrastructure and improve national energy security through local, sustainable solutions.

Past studies [43] have shown that most farmers discard cocoa husks in open fields, missing an opportunity to recover valuable resources. This practice can cause health issues due to the attraction of pests and the slow decomposition of biomass, which may harm crop productivity. By evaluating the energy potential of cocoa shells, this study contributes to the development of agro-industrial waste recovery strategies in Ecuador. As a solid biofuel, cocoa shells possess favorable energy properties but may require pre-treatment due to their volume and texture, which can complicate transportation and storage [44]. Nonetheless, they represent a feasible and sustainable option for decentralized energy generation in rural cocoa-producing regions.

The findings from this study also align with previous research on the energy potential of cocoa waste, particularly the widely cultivated CCN-51 variety, known for its high productivity and biomass yield. For example, Carvajal et al. [45] demonstrated that cocoa waste can be converted into both biogas and syngas through anaerobic digestion and thermochemical gasification, respectively. Notably, biogas exhibits a higher calorific value (17.24 MJ/kg) compared to syngas (15.85 MJ/kg). These results further support the feasibility of integrating cocoa waste into decentralized local energy systems, especially in provinces such as Esmeraldas and Manabí, where cocoa production is most concentrated. Implementing such systems could significantly reduce the environmental impacts of agricultural waste disposal, enhance local energy resilience, and add socio-economic value to the cocoa production chain—directly benefiting smallholder farmers through cost savings and income diversification. Future research should aim to expand the spatial and temporal scope of analysis and incorporate advanced geospatial tools, such as remote sensing and GIS [46] to map and monitor biomass availability across broader cocoa-growing regions [47]. This integrated approach would enable a more robust and dynamic assessment of energy potential, contributing to the formulation of circular economy strategies that support Ecuador's transition toward a more sustainable agricultural and energy model [48].

The energetic valorization of cocoa biomass can also play a strategic role in strengthening the post-harvest and industrial stages of the cocoa value chain. Currently, much of the biomass generated, such as shells and pruning residues, is discarded or underutilized. By transforming this waste into bioenergy, producers can close material loops within the supply chain, reduce environmental externalities, and optimize resource use [49]. Furthermore, the implementation of local energy recovery systems from agricultural residues encourages rural development, reduces logistical dependence on external energy sources, and adds economic resilience at the community level. This also contributes to compliance with sustainability certifications that increasingly require integrated waste management and circular economy practices.

The use of agro-industrial waste such as cocoa husks and pruning residues as an energy source represents an innovative alternative for diversifying renewable sources in rural areas. It is also important to recognize their ecological function within the agricultural system. Various studies have shown that leaving biomass on the soil surface has benefits such as contributing to the conservation and improvement of organic matter, regulating soil temperature, aiding weed control and reducing erosion processes [50]. These functions are important for maintaining soil fertility and ensuring the resilience of agroecosystems, especially in tropical contexts vulnerable to climate change.

Participating farmers seek to leave this residue in the field, and any energy recovery initiative must be part of a sustainable resource management approach. Specialized literature and environmental certification standards, such as those promoted by the Rainforest Alliance, warn that biomass removal can only be considered viable when it does not compromise the essential ecological functions of the soil [51]. It is therefore important to mention that using this waste provides nutrients such as carbon, nitrogen, and potassium, which serve to ensure better yields in cocoa crops. Therefore, it is necessary to establish technical criteria that define the limits of sustainable extraction according to the type of waste, the characteristics of the crop, and the local agroecological context. Including these assessments as an integral part of the design of bioenergy systems would ensure that energy generation from waste does not conflict with the conservation of agricultural ecosystem services, promoting a circular and resilient approach [10].

5. Conclusions

This study demonstrates that cocoa waste biomass from farms in Esmeraldas and Manabí has significant potential to contribute to renewable energy production, particularly when efforts are coordinated across communities. While individual farms may not generate large amounts of energy on their own, working together to share and utilize available biomass can lead to more efficient resource use and support the development of decentralized, community-based energy systems. The volume of residual biomass varied widely between farms, ranging from 50 to 6500 tons per year, and energy potential extended from less than 7 to over 89 terajoules annually. These differences are shaped by a range of factors, including plant density, agronomic practices, and environmental conditions. By accounting for all cocoa production byproducts, such as leaves, stems, pods, and fruit shells, the study offers a more complete assessment of available biomass and helps to lay the foundation for circular economy strategies in rural cocoa-growing areas. Around 75% of the farms analyzed surpassed the viability threshold of 100 megawatt-hours per year, suggesting that many are already in a strong position to adopt sustainable bioenergy systems. Beyond energy production, the valorization of cocoa waste can also support Rainforest Alliance certification goals, improve farm income stability, and reduce environmental impacts associated with organic waste. Moving forward, efforts should focus on promoting cooperative energy models, improving technical capacity, and introducing policy incentives that encourage smallholder participation in Ecuador's renewable energy transition. Strengthening the integration of energy, environmental, and social sustainability in cocoa production can not only support national energy goals but also position these farms as leaders in responsible agro-industrial practices.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The primary data supporting the findings of this study, including calculated spatial outputs such as those shown in Figures 3 and 4, are not publicly available due to privacy and confidentiality agreements with participants. However, these data can be made available by the corresponding author upon reasonable request.

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