Article

Biomass Energy Potential of Agricultural Residues in the Dominican Republic

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Abstract: The Dominican Republic has significant potential for energy generation from residual biomass, with sugarcane, rice, and coconut waste having the highest energy potential. The Eastern, Northeastern, and Southern regions were identified as the areas with the most significant potential for energy generation. This potential can be harnessed to complement intermittent or unmanageable renewable energies in distributed generation networks. Biomass generation plants can be hybridized with other sources, such as wind and solar, to provide a more stable and reliable electricity supply. The methodology developed to evaluate the energy potential of residual biomass in the Dominican Republic integrates a rigorous review of the literature and agricultural databases, incorporating criteria such as annual production, residue-to-product ratio, higher calorific value, and dry matter content, culminating in a formula that synthesizes normalized data to optimize the selection and projection of biomass sources based on their potential energy contribution. The study found that the Dominican Republic has significant potential for energy generation from residual biomass, which can be leveraged to provide a more stable and reliable electricity supply.

Keywords: residual biomass; energy potential; agricultural production

1. Introduction

Agricultural residual biomass is increasingly recognized for its potential as a renewable energy source [1–3], and this trend spurs growing interest in analyzing and quantifying biomass and its energy potential in various regions [4]. However, despite its importance, there needs to be more knowledge regarding the energy potential of the residual biomass from Dominican crops [5].

The Dominican Republic must provide solutions towards a diversified matrix of renewable energy sources, allowing for a 25% renewable participation by 2025. The country is committed to the United Nations Development Program goals of reducing global greenhouse gas emissions by 25% by 2030 [6]. The National Energy Commission (CNE) reported that the country has a significant biomass potential, which could be used to achieve 300 MW of installed energy capacity by 2030 [7].

The Dominican government has been making strides towards a diversified and renewable energy matrix following the approval of Law 57-07 in 2007 on "Incentives for the Development of Renewable Energy Sources and Special Regimes". This law incentivizes developing energy generation projects using wind, solar, and biomass energy. Currently, large-scale renewable energy projects have been developed at a national level, taking advantage of the benefits provided by this legislation [8].

Existing literature proposes several methods to calculate the energy potential of residual biomass [9–13]. However, these models do not accurately predict the potential in the

Dominican Republic, as they do not optimally reflect the conditions and specific characteristics of local crops and the dynamics of agricultural production in the country [14].

Existing models for estimating the energy potential of agricultural residual biomass have several limitations when considered for application in the Dominican Republic. Firstly, many of these models are overly general and lack adaptability to local crop types and specific growth conditions, as evidenced in studies from countries like Thailand, Zimbabwe, and Malaysia [9–13]. Secondly, they usually focus on cost optimization, specific crops, or environmental aspects, failing to provide a comprehensive view of socio-economic conditions and local agricultural practices. Thirdly, many of these models do not account for seasonal variability, a significant oversight given its importance in the Dominican Republic's agricultural context.

Moreover, a significant hindrance in the existing literature is the limited accessibility of relevant information. These models are often nested within more extensive studies or proprietary systems, making it difficult for local researchers and policymakers in the Dominican Republic to access, interpret, and apply them readily.

Lastly, the existing models are generally calculation based rather than offering a more holistic methodological route. The abovementioned limits their application in contexts with unique agricultural practices, socio-economic factors, and seasonal variations. In response to these limitations, this paper provides a methodological route that accounts for local specificities, including crop types, growth conditions, seasonal variations, socio-economic conditions, and information accessibility, making it more suitable for application in the Dominican Republic.

The Method for Estimating Biomass Energy Potential (BEP) has been developed for this study in response to these limitations. This model considers both the specific characteristics of each crop type and the agricultural and climatic conditions of the Dominican Republic and incorporates the seasonal variability in the generation of agricultural residual biomass. The BEP allows for a more accurate estimate of the energy potential of residual biomass in the Dominican Republic.

The main contributions of this work are the following:

- A meticulous examination of the existing methodologies for estimating the energy potential from agricultural residual biomass, particularly in the Dominican Republic;
- Introduction and elucidation of the Method for Estimation of the Biomass Energy Potential (BEP), a novel approach meticulously designed to address the unique dynamics and characteristics of the Dominican agricultural landscape;
- Comprehensive analysis encompassing both spatial and temporal aspects of residual biomass, providing insights that are particularly relevant for both localized and broader applications;
- In-depth exploration of how biomass complements the broader energy matrix of the Dominican Republic, reinforcing the integral role of renewable energy sources;
- Investigation into residual biomass's critical routes and logistical aspects, offering tangible recommendations for optimizing resource use and enhancing the feasibility of biomass-to-energy conversion processes.

The main objective of this study is to evaluate and quantify agricultural residual biomass and its energy potential in the Dominican Republic. This approach identifies renewable resources from the country's farming activity to diversify its energy matrix. This research is particularly relevant as the government is actively seeking renewable energy sources, and the findings of this study could provide a valuable contribution towards achieving this goal.

The results indicate that residual biomass from crops could represent a significant energy source in the Dominican Republic. Given the potential relevance of this energy source in the country's energy matrix, the need to continue researching and developing strategies for its exploitation is emphasized.

This paper is structured as follows: Section 2 describes the methodology used to estimate the energy potential of biomass. Section 3 analyzes the results related to the

spatial and temporal energy potential, the critical and logistic routes of agricultural residual biomass, and its integration with other unmanageable renewable energy sources. Finally, Section 5 examines the discussion and challenges.

2. Materials and Methods

2.1. Estimation of the Biomass Energy Potential (BEP)

The Biomass Energy Potential Estimation Method (BEP) was developed in this study to characterize and evaluate the energy potential of different sources of residual biomass in the Dominican Republic. The BEP integrates various factors into a framework of systematic analysis, which allows for a comprehensive assessment of biomass sources [14].

The criteria incorporated in this method include the annual agricultural production, the residue-to-product ratio, the Higher Heating (HHV), and the residue's dry matter content (CMS) [5,15–18].

The BEP method also identifies the main characteristics that influence energy potential. It facilitates a more detailed understanding of the properties and yields of different biomass sources, providing a valuable tool for planning and optimizing the use of biomass for energy production and evaluating scenarios and projections [4].

The formulation of the Estimation of Biomass Energy Potential (BEP) model is founded on a rigorous analytical framework focused on capturing the most critical factors influencing the energy potential of residual biomass sources. The following elucidates the choice and justification of the variables constituting the equation, underscoring why these variables were selected to the exclusion of others:

Annual Production (M): This metric is a foundational estimator for quantifying available biomass. It was chosen over other potential variables, such as seasonal or per capita production, due to its ability to provide a comprehensive and direct estimate of biomass availability.

Residue-to-Product Ratio (RRP): This variable is integrated to pinpoint what fraction of the total agricultural product is, in fact, utilizable residue. This variable was selected over more general measures of conversion efficiency or utilization ratios, as it offers a more direct and specific index of the amount of biomass that can be converted into energy [16].

Higher Heating Value (HHV): The integration of this variable stems from the need to weigh the intrinsic quality of the biomass in question. It was preferred over other metrics like Lower Heating Value or energy density because the HHV is more representative of total energy potential [17].

Dry Matter Content (DMC): This variable was incorporated to adjust estimates according to moisture content, directly impacting combustion efficiency. This metric was chosen over other related possible variables like ash content or chemical composition due to its direct impact on extractable energy from biomass [15].

The process of selecting and validating these variables involved a rigorous review of scientific literature [14], scrutiny of pre-existing theoretical and empirical models, as well as consultations with experts in the field of bioenergy. This model, therefore, not only represents a synthesis of current knowledge in the field, but also introduces a robust, coherent, and adaptable methodological framework. Its design allows for applicability and precision across diverse agricultural and energy contexts, positioning it as an essential tool for strategic planning and decision making in global bioenergy projects.

The following equation estimates the Biomass Energy Potential (BEP) of residual biomass:

$$BEP = \sum_{i=1}^{n} (M_i \times RRP_i \times HHV_i \times DMC_i) \tag{1}$$

where:

- BEP is the Biomass Energy Potential, typically expressed in energy units like Mega-Joules or GigaJoules;
- n is the total number of agricultural products concerned;

- M is the annual production of the farm product i;
- RRP is the residue ratio for the farm product i;
- HHV is the value of Higher Calorific Value;
- DMC is the dry matter content of the farm residue (%).

This equation determines the theoretical energy potential of residual biomass for each agricultural product. Experimental data validate the accuracy of the proposed model.

2.2. Factors

Specific factors were used to ensure that the selected agricultural products were representative and suitable for the study. These factors include:

- Production Volume: Agricultural products with substantial production volumes were given precedence. The abovementioned is due to the direct correlation between production scale and the resultant volume of residual biomass, which subsequently influences energy potential.
- Geographical Distribution: Products cultivated across diverse geographical locales were deemed preferable. This broad cultivation base optimizes the spatial utility of the model by offering a comprehensive substrate for biomass generation.
- Physicochemical Characteristics of Residual Waste: Residues possessing traits conducive to energy conversion took priority. These include higher calorific values and lower moisture content, which are vital parameters for efficient bioenergy generation.
- Economic Relevance: The selection also considered the economic significance of the agricultural products within the Dominican Republic, ensuring that the derived energy potential aligns with the country's overarching economic and sustainability goals.

Data about these factors were methodically gathered from multiple authoritative sources, including national agricultural databases, scientific literature, regional agricultural studies, and consultations with local agricultural experts and stakeholders [19]. Through rigorous cross-referencing and validation processes, the most pertinent and representative agricultural products were delineated, offering an emblematic snapshot of the agrarian landscape of the Dominican Republic. This approach bolsters the credibility of the BEP model and ensures it is an adaptable tool for strategic bioenergy planning.

2.3. Data Collection

Data acquisition for this study was an intricate process that followed a methodological framework to ensure reliability and comprehensiveness. The factors driving the selection of agricultural products for Biomass Energy Potential (BEP) estimation were supported by data from various authoritative sources. These sources included:

National Databases: Official databases provided a wealth of quantifiable metrics, particularly concerning production volumes and geographical distribution of specific agricultural products within the Dominican Republic.

Agricultural Records: These offered detailed, often longitudinal, datasets allowing for scrutinizing temporal fluctuations and trends in agricultural product residues and their physicochemical properties.

Websites of Entities Related to Agricultural Production: Digital platforms from governmental and non-governmental organizations furnished additional data layers, including the economic relevance of specific agricultural products and nuances of regional distribution.

Governmental and Non-Governmental Reports: These documents serve to augment the core data, enriching the methodological framework and supporting the selection criteria. The methodology explicitly recognizes the intrinsic biases and discrepancies that may arise from these supplementary data sources. It underscores the imperative of cross-referencing information with additional databases to enhance validation processes. The approach is meticulously designed to ensure a balanced analysis, with an emphasis on the transparent disclosure of data validation scopes and the interpretive subtleties, thereby maintaining the scientific integrity of the findings.

Estimations Based on Average Values of the Relevant Agricultural Category (AC) highlight that, in scenarios where specific information on certain products was unavailable, average values derived from broader agricultural categories were relied upon. This approach, rooted in expansive databases with a wider scope, proved essential for facilitating informed extrapolations. As a result, the integrity and reliability of the findings were ensured, even in situations characterized by limited or fragmented data.

2.4. Data Curation

The process starts with gathering raw data from various sources, including peer-reviewed journals, governmental databases, and industry reports. These raw data then undergo rigorous vetting to authenticate their relevance and applicability to this study's regional and thematic scope.

Following this, data normalization was performed, converting various metrics and units into a standardized scale for direct comparison and aggregation. This step proves crucial given the diverse nature of data metrics such as calorific values and waste generation statistics.

In the data validation phase, the process includes external consultations with experts in the field and cross referencing with pre-existing datasets to ensure the integrity of the curated data. Anomalies, outliers, and any data points that could compromise the reliability of findings are identified and either corrected or excluded.

Finally, the consolidation phase organizes the data into a structured, easily navigable format, ready for subsequent analytical steps like Pareto analysis and BEP estimations. Now refined and free from discrepancies, the consolidated dataset forms the empirical backbone of subsequent analyses.

2.5. Biomass Selection

The delineation of viable biomass sources in this study is informed by an intricate methodological schema, incorporating quantitative analytics and statistical rigor. Although the methodological landscape for biomass energy potential evaluation is rich, the approach presented here represents a finely tuned calibration of critical variables that demonstrate quantifiable impact on biomass viability. This section briefly elucidates the nuanced incorporation of Pareto analysis, a mathematical technique adapted to fulfill the stringent requirements of this research.

Three principal criteria were scrutinized for their direct relevance to the energy potential of agricultural residues: Higher Calorific Value (HHV), Waste Generation, and Dry Matter Content (DMC). Empirical data for these variables were rigorously curated from peer-reviewed journals, governmental databases, and industry reports, subsequently undergoing standardization to ensure metric consistency across diversified biomass sources.

After data curation, a weighted composite score was calculated for each biomass source by amalgamating the standardized metrics, each scaled by its respective weight, to produce a singular value indicative of its overall energy potential. This composite scoring system operates under constraints to satisfy both the scientific and economic dimensions of biomass energy production, maintaining equilibrium between maximal energy output and sustainability metrics.

The sorted composite scores formed the empirical bedrock for a Pareto analysis aimed at isolating the "vital few" from the "trivial many". This Pareto analysis was applied subtly but effectively prioritized biomass types based on their cumulative contribution to potential energy output. It was a pivotal step, enabling the model to focus on high-impact biomass types while systematically eliminating lower-impact options without compromising the comprehensiveness or integrity of the research.

Thus, the Pareto-optimized selection honed the study's focus and underscored its robustness and reliability. The ultimate list of selected biomass types can be regarded as an optimized subset, each of which fulfills rigorous energy potential and sustainability criteria, contributing to the high-resolution character of the Biomass Energy Potential (BEP) estimation model presented herein.

2.6. Temporal-Spatial Estimation of Biomass Potential

The approach to a robust spatio-temporal estimation of biomass energy potential is grounded in the regionally and quarterly applied Biomass Energy Potential (BEP) model, as defined by Equation (1). This methodology aims to quantify energy potential and enhance logistical fidelity in the biomass residual collection and storage phases. The discussion elucidates the multifaceted methodological framework and identifies the data sources harnessed.

Regional Disaggregation: Access to an amalgam of national databases and agricultural registries was secured to particularize agricultural waste production. The aforementioned information allowed for the delineation of specific regions exhibiting a high yield of the designated agricultural residuals.

Temporal Disaggregation: Agricultural production data were seasonally segmented into quarterly intervals, thereby acknowledging the variances in growth cycles and harvest practices within a calendar year.

BEP Model Application: The BEP model (Equation (1)) was judiciously applied in each delineated region and corresponding quarterly interval. This iterative computational application facilitated a nuanced estimation of the residual biomass potential.

Spatio-Temporal Mapping: Geographic Information System (GIS) tools were employed to render a coherent spatio-temporal visualization. This cartographic representation illuminated the geographically and temporally diversified energy potential of residual biomass.

2.7. Analysis of Technologies Relevant to Residual Biomass Valorization

In the field of biomass valorization, identifying the most appropriate technology requires a comprehensive understanding of its conversion methodologies. For this study, a systematic review of the literature was conducted, coupled with a market research analysis, to encompass the vast array of biomass conversion technologies [20].

Technologies such as combustion, gasification, pyrolysis, fermentation, anaerobic digestion, and oil extraction for biodiesel production were critically examined in [21]. The criteria for evaluation were multifaceted. Firstly, the efficiency of biomass-to-energy conversion was appraised, as this metric determines the overall performance and potential energy output [22]. Economic feasibility was then evaluated, taking into account both the capital and operational expenses associated with each technology [23]. Additionally, the potential for scaling, robustness, and flexibility in handling varied biomass types was evaluated, given the inherent heterogeneity of biomass sources. Furthermore, considerations about workforce and technical requirements were factored in, reflecting the human and technical resources needed for each technology [24].

The culmination of this methodological assessment led to a cost-benefit analysis. While many studies in the literature offer a cost-benefit perspective, it is imperative to acknowledge the variability in the functional units employed across different studies [25]. In this study, efforts were made to ensure data consistency, and where necessary, normalization techniques were employed to facilitate a direct comparison.

3. Results

3.1. Energy Potential of Residual Biomass in the Dominican Republic

The energy potential of residual biomass in the Dominican Republic was estimated using the Biomass Energy Potential Estimation Method (BEP) developed in this study. According to the findings, the total energy potential of residual biomass in the country is approximately 117,360,196.60 GJ/year. For context, the total energy consumption of the Dominican Republic reached 20,135.68 GWh during the year 2022 [26].

Figure 1 shows the distribution of the energy potential of residual biomass by category. The categories with the highest energy potential are residues of traditional products, reaching 35%, cereal residues at 29%, and oilseed residues at 24%.
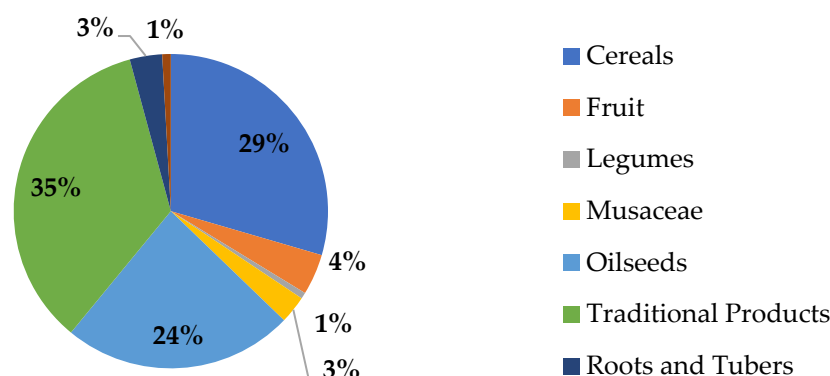
Figure 1. Distribution of the energy potential of residual biomass by category in the Dominican Republic.

3.2. Analysis of Results by Category and Type of Agricultural Residue

When analyzing the results according to the type of agricultural waste in the Dominican Republic, it is observed that sugarcane residues have the highest energy potential, reaching approximately 40,180,801.15 GJ/year. Next are rice residues with 30,685,922.26 GJ/year, followed by coconut residues with 27,379,007.31 GJ/year. These findings are relevant to identifying investment opportunities in biomass conversion technologies and implementing training and support programs for farmers to manage and utilize agricultural residue. Compared to other countries in the region, the Dominican Republic shows similar estimates. Ecuador reports an energy potential in rice residues of 28,356,980 GJ/year, followed by sugarcane with 15,746,260 GJ/year [5].

Table 1 presents a comprehensive analysis of the energy potential of residual biomass, segmented according to different agricultural categories [19]. For certain products, where specific data related to variables such as Higher Heating Value (HHV), Residual Ratio (RR), and Dry Matter Content (DMC) were not available in existing literature, an alternative approach was employed. Specifically, the study calculated the average values of these variables for the Relevant Agricultural Category (AC) as a substitute for missing data on individual products. This method is designed to provide a more robust estimation when product-specific data are unavailable by utilizing averaged values from the broader agricultural category to which the product belongs.

Table 1. Energy potential estimate 2021 (GJ/year).

Category	Agricultural Product	Agricultural Production 2021 (Tonnes)	RRP	Source	DMC (%)	Source	HHV (MJ/ton)	Source	Energy Potential Estimate 2021 (GJ/year)
Cereals	Rice	1,341,839.50	1.33	[15]	0.88	[15]	18,180.00	[27]	30,685,922.26
	Corn	114,820.60	2.24	[15]	0.88	[15]	16,500.00	[28]	3,924,019.55
	Sorghum	465.50	3.01	[15]	0.88	[15]	15,100.00	[29]	28,381.79
Fruit	Avocado	1,319,939.12	0.20	[15]	0.20	[15]	19,100.00	[30]	1,068,475.40
	Cherry	13,401.94	0.20	[15]	0.20	[15]	21,950.00	[31]	10,471.29
	Granadille	1413.41	0.20	AC	0.20	AC	20,000.00	AC	35,047.60
	Soursop	33,874.81	0.20	[15]	0.20	[15]	20,000.00	[32]	22,308.80
	Guava	24,526.56	0.20	AC	0.20	AC	17,000.00	AC	2774.81
	Papaya	2,316,871.41	0.20	[15]	0.20	[15]	17,810.00	[33]	1,816,611.52
	Sour Lemon	110,354.13	0.20	[15]	0.20	[15]	15,860.00	[34]	65,662.12
	Tangerine	22,930.85	0.20	AC	0.20	AC	17,000.00	AC	18,384.03
	Mango	160,627.64	0.20	[15]	0.20	[15]	16,140.00	[34]	74,830.20
	Melon	56,835.45	0.20	[15]	0.20	[15]	16,200.00	[29]	39,889.58

Table 1. *Cont.*

Category	Agricultural Product	Agricultural Production 2021 (Tonnes)	RRP	Source	DMC (%)	Source	HHV (MJ/ton)	Source	Energy Potential Estimate 2021 (GJ/year)
	Orange D.	184,853.43	0.20	[15]	0.20	[15]	16,310.00	[29]	141,385.52
	Pineapple	963,502.09	0.20	[15]	0.20	[15]	18,900.00	[35]	738,715.28
	Pitaya	2477.57	0.20	AC	0.20	AC	18,002.80	AC	534.68
	Watermelon	1,253,218.58	0.20	[15]	0.20	[15]	19,280.00	[36]	750,925.15
	Grapefruit	2743.20	0.20	[15]	0.20	[15]	16,330.00	[37]	3589.46
	Sapote	193,213.50	0.20	[15]	0.20	[15]	18,342.00	[38]	147,499.79
Legumes	Pigeon Pea	42,711.58	0.20	[15]	0.90	[15]	11,200.00	[39]	98,884.03
	Guard Beans	37,441.74	0.20	AC	0.90	AC	16,732.00	AC	375,799.76
	White bean	10,683.48	0.20	[15]	0.90	[15]	18,800.00	[31]	5374.47
	Black bean	3455.39	0.20	[15]	0.90	[15]	18,800.00	[31]	127,759.87
	Red bean	2,607,413.15	0.20	[15]	0.90	[15]	16,860.00	[31]	137,087.68
	Chinise bean	5037.85	0.20	AC	0.10	AC	18,000.00	AC	2028.53
Musaceae	Banana	40,532.51	0.20	[15]	0.20	[15]	16,150.00	[40]	1,798,492.60
	Plantain	2,249,880.14	0.20	[15]	0.20	[15]	16,270.00	[41]	1,543,115.65
Oilseeds	Coconut	871,417.72	1.70	[15]	0.84	[15]	20,000.00	[42]	27,379,007.31
	Peanut	12,121.23	1.38	[15]	0.94	[15]	27,770.00	[43]	500,283.61
Traditional Products	Cocoa (Grain)	155,712.80	0.20	[15]	0.90	[15]	16,670.00	[44]	467,231.83
	Coffee	35,684.00	0.20	[15]	0.90	[15]	24,230.00	[45]	155,632.20
	Sugarcane	12,137,491.40	0.67	[15]	0.27	[15]	18,300.00	[46]	40,180,801.15
	Tobacco	21,685.30	0.20	[15]	0.90	[15]	18,000.00	[47]	70,260.37
Roots and Tubers	Sweet potato	114,056.61	1.00	[15]	0.29	[15]	18,710.00	[48]	705,868.60
	Mapuey	3056.35	0.20	AC	0.30	AC	18,631.00	AC	1956.48
	Yam	69,127.30	0.94	AC	0.29	AC	19,000.00	AC	355,161.82
	Potato	170,680.20	1.00	[15]	0.21	[15]	14,120.00	[43]	602,058.08
	Taro	87,850.90	0.94	[15]	0.29	[15]	19,694.00	[49]	422,170.60
	Manioc	325,666.77	0.82	[15]	0.35	[15]	17,120.00	[50]	1,819,146.67
Vegetables	Peppers	95,248.76	0.20	[15]	0.10	[15]	15,264.44	[51]	31,284.78
	Garlic	6664.69	0.20	[15]	0.10	[15]	15,830.00	[43]	1049.31
	Celery	21,826.00	0.25	AC	0.19	AC	16,000.00	AC	14,824.83
	Auyama	98,005.04	0.20	[15]	0.10	[15]	10,210.00	[34]	34,507.07
	Bangana	10,790.66	1.88	AC	0.88	AC	19,000.00	AC	540,004.10
	Eggplant	48,795.21	0.20	AC	0.10	AC	17,680.00	AC	19,174.59
	Broccoli	6761.09	0.20	AC	0.10	AC	16,000.00	AC	2398.02
	Zucchini	424.80	0.20	[15]	0.10	[15]	19,000.00	[34]	98.99
	Onion	149,121.67	0.20	[15]	0.10	[15]	16,380.00	[34]	51,723.14
	Cauliflower	2930.51	0.20	[15]	0.10	[15]	16,100.00	[34]	1012.66
	Cundeamor	8361.12	0.25	AC	0.19	AC	17,966.40	AC	8980.79
	Lettuce	12,570.14	0.20	AC	0.10	AC	16,000.00	AC	4321.74
	Molondron	17,687.93	0.20	AC	0.10	AC	18,000.00	AC	5892.27
	Chinese Musú	3342.05	0.20	AC	0.20	AC	17,966.40	AC	2715.30
	Oregano	5487.10	0.20	AC	0.90	AC	18,160.00	AC	22,321.98
	Parvol	4118.15	0.20	AC	0.30	AC	17,966.40	AC	3994.36
	Cucumber	25,015.98	0.20	[15]	0.10	[15]	17,200.00	[52]	10,241.45
	Radish	3238.00	0.25	AC	0.19	AC	16,000.00	AC	3338.22
	Cabbage	80,034.50	0.20	AC	0.10	AC	21,260.00	[34]	39,660.53
	Chayote	1,073,549.55	0.20	AC	0.10	AC	19,000.00	AC	165,200.48
	Tindora	27,793.55	0.20	AC	0.10	AC	17,966.40	AC	12,928.48
	Tomato	57,774.52	0.20	[15]	0.10	[15]	26,000.00	[53]	30,388.33
	Carrot	99,685.35	0.20	[15]	0.10	[15]	13,880.00	[43]	30,585.02

3.3. Spatial and Temporal Analysis of Residual Biomass

The spatial and temporal analysis of residual biomass in the Dominican Republic was performed with the BEP model. This approach provided insight into the distribution and availability of residual biomass over time and across the national territory.

The results obtained in 2021 highlight several regions for their significant potential for energy generation from residual biomass, representing 72% of the potential estimate. The Eastern region leads with an estimated energy potential of 43,051,322.71 GJ/year. It is followed by the Northeast region, with a possibility of 30,345,180.18 GJ/year. Additionally, the Southern region is in third place, with a potential of 8,136,159.54 GJ/year.

Figure 2 is a georeferenced map illustrating the geographical distribution of the energy potential of residual biomass in the Dominican Republic. This map highlights the areas with the highest concentration of resources, offering an adequate visualization of the regions with the most significant potential for using residual biomass.
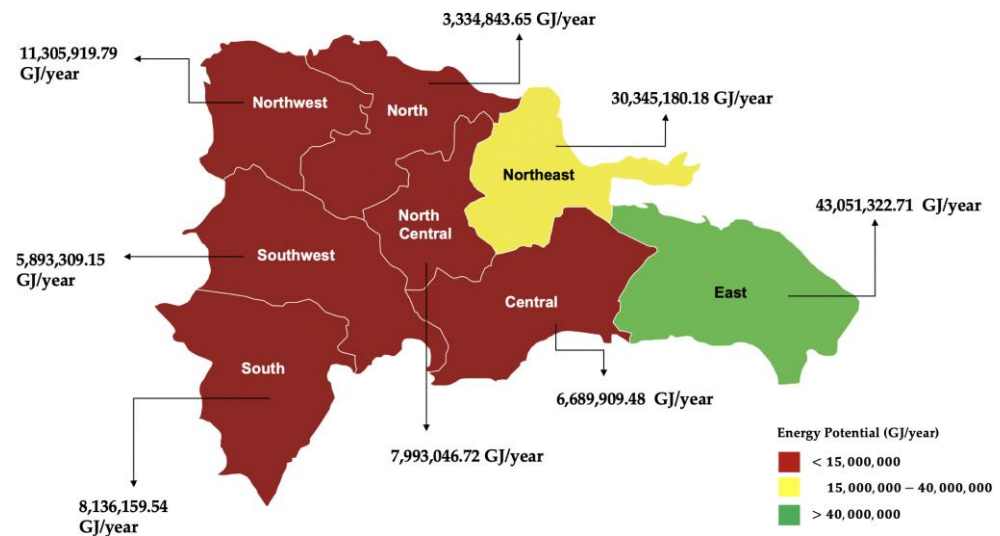

Figure 2. Geographical distribution of the energy potential of residual biomass in the Dominican Republic.

In this study, particular emphasis is placed on the temporal analysis, examining how the production of residual biomass varies throughout the year. This aspect is vital for understanding the fluctuations in availability and its subsequent impact on the potential energy generation.

During the first quarter (Q1), the production of residual biomass was recorded at 4,086,136.88 tons. This figure rose in the second quarter (Q2) to 4,790,723.65 tons. By the third quarter (Q3), the production observed a slight reduction, amounting to 4,592,181.09 tons. The last quarter, Q4, witnessed a more significant decline in production, totaling 3,347,662.23 tons.

These quarterly variances in biomass production are closely associated with the average temperatures of each quarter [54]. In Q1, with an average temperature of 25.7 °C, the energy potential reached 33,947,060.98 GJ. As temperatures rose to an average of 27.2 °C in Q2, the energy potential concurrently increased, reaching 45,383,746.37 GJ. However, the subsequent quarters observed a dip in energy potential, correlating with the declining temperatures. In Q3, with a temperature of 26.4 °C, the possibility was 20,718,585.40 GJ. Finally, Q4, which had an average temperature of 24.9 °C, observed the lowest energy potential of 16,974,540.85 GJ.

The prominence of the Eastern, Northeastern, and Southern regions in terms of energy generation potential from biomass is rooted in their robust agricultural development. These regions, endowed with fertile soils and advanced irrigation systems, are the heart of the country's agricultural production, with crops ranging from sugarcane to cereals and tubers. The constant agricultural production in the Dominican Republic is underpinned by its tropical climate, allowing for multiple planting and harvesting cycles throughout the year. This climatic advantage, characterized by stable temperatures and well-distributed rainfall periods, ensures a steady flow of agricultural residues that can be converted into

energy biomass. Moreover, the existing infrastructure in these regions for the collection, processing, and distribution of agriculture can be readily adapted for biomass management, minimizing initial investment costs, and optimizing the value chain. It is for these technical and geographical reasons that the Eastern, Northeastern, and Southern regions emerge as areas with the highest potential in converting agricultural residues into sustainable energy sources.

This temporal analysis underscores the integral relationship between biomass production, ambient temperatures, and energy potential. It is imperative to consider these variations in production throughout the year, as they significantly affect the overall assessment of energy potential from residual biomass in the Dominican Republic.

3.4. Evaluating the Complementary Role of Biomass in the Dominican Republic's Energy Matrix

Installed capacity and power generation in the national interconnected electricity system of the Dominican Republic reached 5004.4 MW and 21,455.4 GWh, respectively, according to the publication made by the System Operator in the annual operation and market report of the year 2021 [26]. Figure 3 shows that the largest installed capacity corresponds to coal and the lowest to biomass's primary energy source. Regarding production, natural gas outperforms coal, and biomass outperforms Fuel Oil #2. In this comparison, biomass represents 30 MW of installed capacity and 224 GWh of energy injected into the transmission grid.
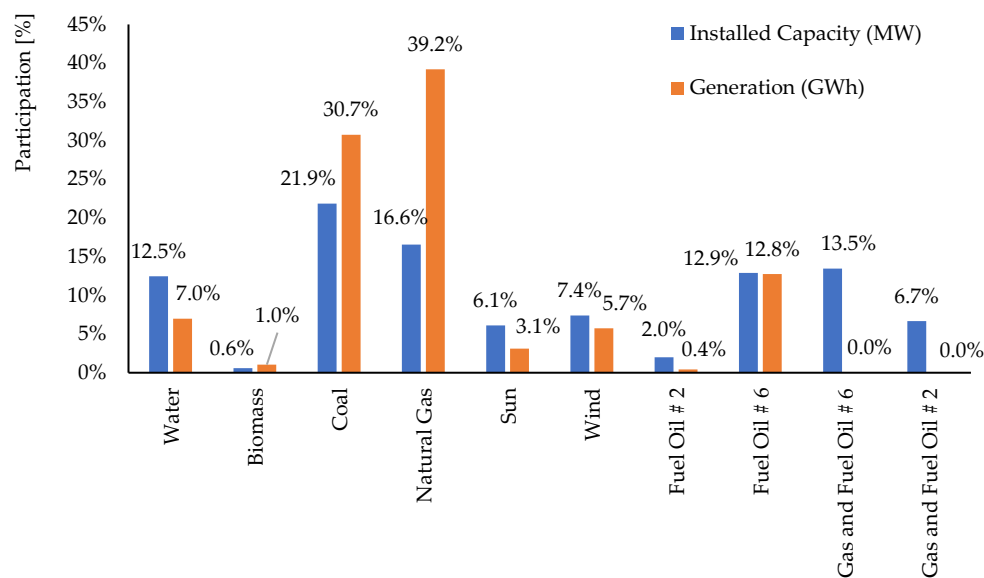

Figure 3. Percentage of installed capacity and production by primary energy source in 2021.

Various primary resources are employed in the energy industry to generate electrical power. In electrical markets, renewable sources (water, sun, wind, biomass) and natural gas are the most used inputs due to their low production cost. In contrast, Fuel Oil is found at the opposite end of the spectrum [55].

Natural gas is primarily composed of methane, with varying proportions of other hydrocarbons (ethane, propane, butanes, and pentanes, among others), and various contaminants, including H_2S, CO_2, and CO. Fuel Oil is a residue from the atmospheric and vacuum distillation of crude oils. It is the heaviest of the fuels obtained from the atmospheric distillation of crude oil and is primarily composed of hydrocarbon molecules containing more than 20 carbon atoms. Regarding the typification of Fuel Oil used for power dispatch, Fuel Oil #6 is a fuel made from residual products obtained from oil refining processes. It is typically used in combustion processes for heating, whereas Fuel Oil #2 is a high-quality fuel for industrial use in furnaces, boilers, dryers, cogeneration engines, and others. It

is specially formulated to provide better combustion performance and reduce unburned product emissions [56].

According to the energy generation potential calculated with the BEP method, in the Eastern region, the electricity system could incorporate 1365.15 MW of generation from biomass, 962.24 MW in the Northeast region, and 257.99 MW in the Southern region. The topological reality of the network and the efficiency of the combustion process impose restrictions to define the amount that the system can technically assimilate without creating system overloads, which is why an evaluation of the potential of the biomass resource cannot be considered without comprehensive electrical and energy studies of the system, i.e., transmission, generation, and demand.

In 2021, the performance of the wholesale electricity market of the Dominican Republic exhibited marginal energy costs with an increasing trend as of August, as verified in Figure 4. In this period, it was necessary to frequently dispatch expensive thermoelectric plants, justifying cheaper alternatives, such as renewable energy production sources like wind, solar photovoltaic, and biomass. Figure 5 compares these production resources, showing that from July onwards there is a reduction in wind generation, and in October there is a decrease in biomass production due to maintenance work carried out at a single plant that concentrates the total biomass production in the electricity market. The SWERA program (Solar and Wind Energy Resource Assessment, sponsored by the Global Environmental Fund) has assessed the solar energy potential in the Dominican Republic. The potential for global solar radiation (average solar radiation on a horizontal surface) ranges between 5.25 and 5.50 kWh/m^2/day in the eastern half of the country and 5.50 to 5.75 and up to 6.00 kWh/m^2/day in the western half. These figures are notably high and facilitate the use of solar heaters, photovoltaic solar systems, and interconnected thermal solar power plants within the SENI grid [26]. Therefore, it is pertinent to take advantage of the thrust of biomass when the wind is extinguished, as shown from July onwards, and in the night periods, when the solar PV cannot produce, complementing this lack of energy injection.
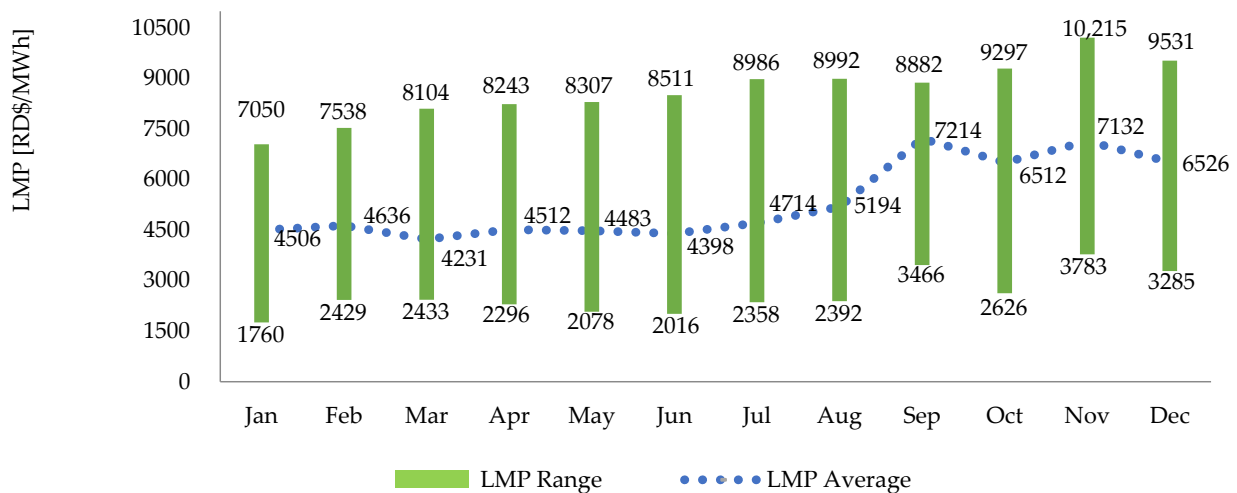

Figure 4. Average and range of marginal costs in the Dominican electricity market during 2021.

3.5. Critical Routes and Logistics of Residual Biomass

This section presents the findings from analyzing critical routes and logistics of residual biomass in the Dominican Republic. Two primary technologies have been considered for biomass valorization: gasification and direct combustion. These technologies have been selected due to their ability to adapt to various types and scales of waste, enabling an effective transformation of biomass into usable energy [14].
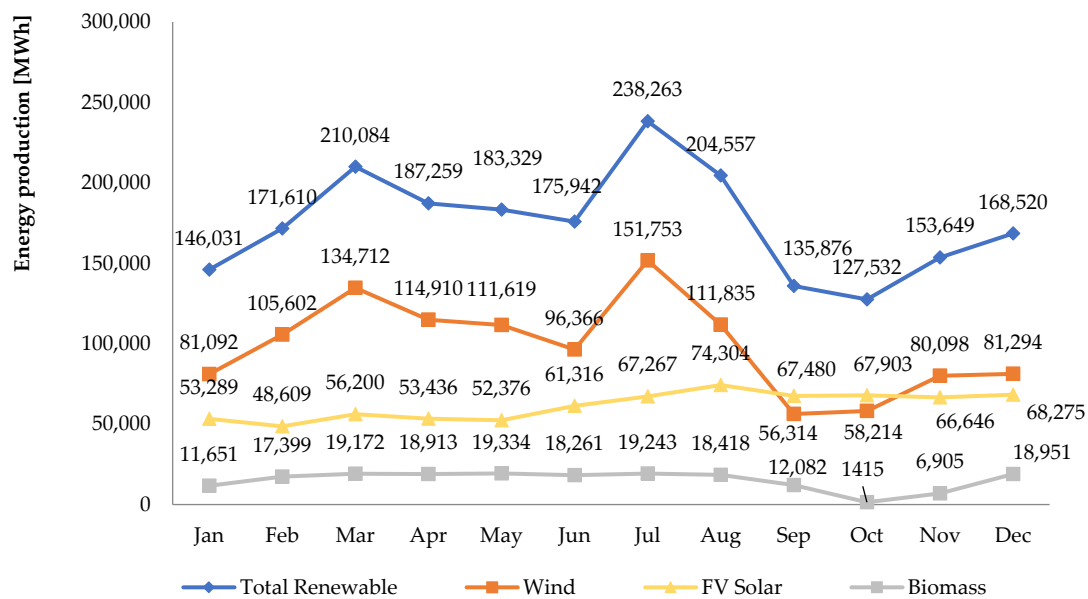
Figure 5. Wind, solar PV, and biomass energy production in the Dominican electricity system during 2021.

The analysis has focused on three essential agricultural products: coconut, rice, and sugarcane, which comprise approximately 83% of the estimated energy potential of biomass. Specific variables linked to these agricultural products have been considered, such as the dry matter content of the main product and the Higher Caloric Value (HHV) per unit weight.

According to the experimental results presented in the study, the compositional attributes and energy potentials of various agricultural residues were quantified. Rice exhibited an average dry matter content of 88%, an ash composition of 16.1% [57], and a High Heating Value (HHV) of 18,180 MJ/ton. In contrast, coconut demonstrated a moderately high dry matter content of 84%, a comparatively lower ash composition of 1.2% [57], and an HHV of 20,000 MJ/ton. Sugarcane presented an average dry matter content of 27%, an ash composition of 1.26% [57], and an HHV of 18,300 MJ/ton. These metrics offer significant insights into the evaluated agricultural residues' specific characteristics and inherent energy potential, thereby serving as a foundational basis for their effective utilization in energy conversion technologies.

It is essential to consider specific logistical challenges arising from the geography of these regions. Specifically, the Eastern region and the Northeast region, despite their high energy potential, are located at opposite ends of the Dominican geography, exceeding 300 km distance, where it is suggested that it does not exceed 70 km radius between biomass [57,58], is used optimally to produce multiple products, and tries to be self-sufficient and not harmful to the environment [59]. This factor introduces significant challenges for the joint collection, transport, and processing of waste biomass in a single power generation facility.

The geographical distance between these regions can significantly increase logistics costs and the carbon footprint associated with biomass transport, which could decrease the overall efficiency of the energy transformation process. In addition, the need for storage and processing infrastructure in both regions may represent additional investment costs.

Therefore, it is essential to evaluate these logistical aspects when planning the implementation of biomass valorization technologies. Solutions include developing decentralized infrastructures for biomass processing in each region or optimizing transport routes and collection systems to minimize costs and environmental impact. This integrated perspective will maximize the potential of residual biomass as a renewable energy source in the Dominican Republic.

In the realm of biomass valorization, several technologies have been explored worldwide, including pyrolysis, anaerobic digestion, and fermentation [60,61]. Pyrolysis, for instance, produces bio-oil, but challenges in its upgrading and the need for specialized equipment can be deterrents [62,63]. Anaerobic digestion primarily yields biogas, beneficial for regions with a consistent supply of wet biomass but might not offer the highest energy output [64]. Fermentation is central in biofuel production but is limited by feedstock type and often requires significant preprocessing [65]. When considering the Dominican Republic's unique context, with its distinct agricultural profile and logistical challenges, gasification and direct combustion stand out in [66]. Their adaptability to various waste types and scalability makes them apt for addressing the nation's energy needs using residual biomass. Their proven efficacy in biomass-to-energy conversion, coupled with their relative simplicity and the existing agricultural infrastructure, further cements their relevance for the region.

The assertion that gasification is the most convenient technology for valorizing biomass in the Dominican Republic warrants careful consideration, especially given that most mature technologies currently rely on direct combustion. While gasification offers advantages such as higher energy efficiency [14] and a synthesis gas rich in hydrogen and carbon monoxide, these benefits facilitate optimal electricity and heat generation from rice, coconut, and sugarcane waste. However, the ash limitations associated with rice husks present a significant constraint, complicating the definitive choice between gasification and direct combustion technologies [67]. In this context, direct combustion may be pivotal in the initial implementation phase, delivering immediate economic and environmental benefits and laying the groundwork for future large-scale gasification efforts. Therefore, it is imperative to weigh the specific properties of each type of biomass in deciding upon the most suitable technology for its valorization.

4. Discussion

4.1. Energy Potential and Distribution

This research has illuminated the substantial energy potential of residual biomass in the Dominican Republic, estimated at approximately 117,360,196.60 GJ/year. Notably, crop residues from traditional products like sugarcane, rice, and coconut comprise a significant portion of this potential [19], aligning well with the country's existing agricultural landscape. The focus on these agricultural byproducts represents a natural extension of existing practices and provides an impetus for more sustainable agriculture.

When scrutinized by category, the dominant contributors to this energy pool were crop residues (35%), cereal residues (29%), and oilseed residues (24%). By comparing these findings with existing data from countries like Ecuador [5], the Dominican Republic stands to benefit considerably from investing in biomass-to-energy technologies. For example, Ecuador's energy potential from rice and sugarcane residues stands at 28,356,980 GJ/year and 15,746,260 GJ/year, respectively [5]. This similarity underscores the global relevance and applicability of biomass energy technologies.

Table 2 reveals the potential for diverse energy capabilities within Latin America as reflected in its per capita residual biomass potential. Leading the potential are El Salvador and Guatemala, with substantial projections of 52.71 and 34.80 GJ per year, respectively. In sharp contrast, the potential for Argentina and Chile is notably lower, at just 0.06 GJ and 0.02 GJ per capita per year, highlighting the disparity in potential biomass resource exploitation across the region. Brazil and Cuba also show significant potential, each with projections exceeding 30 GJ per inhabitant. Meanwhile, Mexico and Honduras demonstrate noteworthy potential, with projections over 20 GJ per capita, indicative of their substantial biomass resources. The Dominican Republic, Ecuador, Paraguay, Peru, and Uruguay present intermediate energy potentials, signaling emerging opportunities for the development of their renewable energy sectors. These estimates emphasize the broad spectrum of energy capacities that Latin American countries could achieve from biomass,

contingent on the strategic management of their natural resources and the development of their energy infrastructure.

Table 2. Comparative overview of per capita residual biomass potential in Latin American nations.

Country	Number of Inhabitants	Energy Potential per Capita (GJ/Year)	Source: Authors' Own Calculation Based on
Argentina	46,234,830	0.06	[68]
Brazil	215,313,500	33.37	[69]
Chile	19,603,730	0.02	[70]
Colombia	51,874,020	4.54	[71]
Costa Rica	5,180,830	0.07	[72]
Cuba	11,212,190	32.71	[73]
Dominican Republic	11,228,820	10.45	Authors' calculation
Ecuador	18,001,000	12.45	[5]
El Salvador	6,336,390	52.71	[74]
Guatemala	17,357,890	34.80	[75]
Mexico	127,504,130	23.37	[76]
Paraguay	6,780,740	6.25	[77]
Peru	34,049,590	8.95	[78]
Uruguay	3,422,790	6.45	[79]
Honduras	10,432,860	37.96	[80]

4.2. Temporal-Spatial Estimation and Seasonal Variability

The BEP model employed in this study also facilitated a spatial-temporal analysis that pinpointed areas within the Dominican Republic possessing the highest residual biomass potential. The Eastern region emerged as a focal point, with an estimated energy potential of 43,051,322.71 GJ/year. Additionally, seasonal variability was identified, with the energy potential peaking in the year's second quarter. These insights are critical for efficient resource allocation and planning, especially in adapting to seasonal variations in energy generation.

4.3. Complementary Role in Energy Matrix

This research has further emphasized the complementary role that biomass could play in the Dominican Republic's energy matrix. With an existing installed capacity of 30 MW, biomass already has a foothold in the country's energy sector. Given the estimated potential, notably in the Eastern and Northeast regions, the country could feasibly add up to 1365.15 MW and 962.24 MW, respectively, from biomass alone. However, these are not just numbers on paper; they require carefully examining the energy system's topological constraints to prevent overloads and inefficiencies.

In the realm of renewable energy integration, the amalgamation of biomass generation with wind and solar sources stands out as a transformative approach. Technically, biomass offers the unique advantage of consistent energy generation, counteracting the intermittency inherent in wind and solar, thus ensuring a continuous power output irrespective of varied climatic conditions [81]. The advent of sophisticated power management systems, capable of discerning the most efficient energy source in real time, further capitalizes on this synergy [82]. Infrastructurally, there is potential for shared facilities, optimizing initial investments and operational costs [83]. From a logistical perspective, the concept of agrivoltaics—combining biomass cultivation with solar installations—has gained traction, showcasing optimized land utilization that simultaneously drives energy and agricultural yields [84]. Furthermore, a unified supply chain approach can seamlessly align biomass production with the operational dynamics of wind and solar facilities, maximizing resource allocation [85]. Nonetheless, challenges loom, with land resource allocation being at the forefront, potentially leading to escalated land prices or conflicts [86]. Moreover, managing

such an intricate multi-modal energy system necessitates advanced control mechanisms to ensure efficiency and reliability [87].

4.4. Logistics and Technology Selection

Additionally, the study analyzed the logistical constraints and technology alternatives for biomass valorization, mainly focusing on gasification and direct combustion. The geographical distances between the high-potential regions exacerbate the logistical challenges. Given the recommendation that biomass should optimally be used within a 70 km radius [57], the distance exceeding 300 km between the Eastern and Northeast regions presents a considerable obstacle.

This paper serves as a starting point for future research endeavors in biomass energy within the Dominican Republic and in a broader global context. To further elaborate on the findings, economic feasibility studies are suggested to explore the associated costs of implementing biomass energy technologies across various regions of the country. Subsequent research could also focus on optimizing biomass conversion technologies, such as gasification and direct combustion, to address specific constraints like ash generation in the case of rice residues. Moreover, it would be beneficial to investigate more efficient logistical approaches for transporting residual biomass, especially considering the geographical limitations identified in this study. Finally, comparative studies with other types of renewable energy sources could be undertaken to assess the efficacy of biomass within a more diversified energy matrix.

5. Conclusions

This paper has shown the significant energy potential of residual biomass in the Dominican Republic, highlighting mainly the East, Northeast, and South regions. These findings reinforce the postulates of previous work that indicate that the valorization of residual biomass can be a viable strategy to diversify renewable energy sources and improve energy security in the country.

In alignment with international studies, the findings corroborate that specific agricultural residues, namely, rice, coconut, and sugarcane, hold promise for energy generation through gasification and direct combustion processes [5]. However, it is crucial to highlight that rice may not be the most suitable candidate for direct combustion due to its high ash content. The efficacy of these technologies is contingent upon various site-specific and chemical compositional factors, including but not limited to biomass availability and quality, as well as logistical and infrastructure conditions [14]. Therefore, it is imperative to consider these multiple parameters when evaluating the suitability of each biomass type for specific energy conversion technologies.

The estimated energy potential supports investment prospects for electricity production. Nonetheless, comprehensive electrical and energy assessments are necessary to consider grid limitations. Considering hybrid solutions incorporating alternative combustion sources could offer a viable strategy in scenarios where biomass supply may be intermittent. The abovementioned would allow for compensation of variable energy generation from wind and solar PV technologies. Moreover, the analysis of logistical pathways and distribution of residual biomass reveals that, although the East and Northeast regions boast considerable energy potential, their geographical separation presents a noteworthy challenge for unified biomass processing at a single facility. This observation highlights the need to explore decentralized processing solutions or advanced logistical optimizations to mitigate these challenges.

The model proposed in this study, which combines the assessment of the energy potential of residual biomass with the analysis of logistical and technical constraints, differs from previously published models in that it provides an integrated and practical view of the biomass value chain. This perspective facilitates the estimation of energy potential and highlights obstacles that might impede the efficient implementation of biomass valorization technologies.

This study highlights the inherent variability and complexity of residual biomass data, and while meticulous approaches have been used to estimate the energy potential, it is suggested that future research strengthens the methodology through cross-validation techniques. Furthermore, the implementation of comparative analysis with advanced predictive models is encouraged to enhance data interpretation and reduce potential biases in biomass valorization. The findings suggest that the Dominican Republic should systematically incorporate these data into policy frameworks. Harnessing residual biomass requires an integrated approach encompassing technological, infrastructural, and regulatory considerations. Engaging with industry experts and researchers can guide sustainable biomass utilization policies. It is paramount to establish best practices for biomass processes and incentivize sectoral research.

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