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Spatial Multi-Criteria Assessment for Optimal Biomass Power Plant Siting in Ecuador Using GIS

Evaluación espacial multicriterio para la localización óptima de plantas de bioenergía en Ecuador usando SIG

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Abstract— This study examines the energy and spatial potential of agricultural residues in Ecuador for biomass-based distributed electricity generation. Based on national crop production data, residues from sugarcane, rice, oil palm, and hard corn were quantified, yielding an estimated effective electrical potential of 2407.68 GWh/year. A spatial multi-criteria analysis was conducted using Geographic Information System (GIS) software, integrating road and substation proximity, terrain slope, flood risk, and distance to populated areas. Exclusion layers considered volcanic hazard zones, primary road corridors, and hydrographic basins. The resulting suitability map classified the territory into five levels. Guayas, Los Ríos, and Esmeraldas were identified as provinces combining both resource availability and logistical accessibility. Additionally, a levelized cost of electricity (LCOE) of USD 0.097/kWh was estimated for a 25 MW biomass plant. The methodology is applicable to geographic prospecting and energy potential assessment of other non-conventional renewable energy sources.

Keywords—Bioenergy, Multi-criteria analysis, Agricultural biomass, SIG, Ecuador.

Resumen— Este estudio evalúa el potencial energético y territorial de los residuos agrícolas en Ecuador para la generación eléctrica descentralizada a partir de biomasa. A partir de datos de producción nacional, se cuantificaron los residuos disponibles de caña de azúcar, arroz, palma aceitera y maíz duro seco, estimando un potencial eléctrico efectivo de 2407.68 GWh/año. Se aplicó un análisis espacial multicriterio en un sistema de información geográfica (SIG), integrando variables como proximidad a carreteras y subestaciones, pendiente del terreno, riesgo de inundaciones y distancia a zonas pobladas. Se excluyeron áreas con restricciones como zonas de amenaza volcánica, vías principales y cuencas hidrográficas. El análisis produjo un mapa nacional de idoneidad, clasificando el territorio en cinco niveles. Las provincias de Guayas, Los Ríos y Esmeraldas concentran condiciones favorables tanto en disponibilidad de biomasa como en accesibilidad logística. Además, se estimó un costo nivelado de electricidad (LCOE) de 0.097 USD/kWh para una planta de 25 MW. La metodología propuesta es aplicable a estudios orientados a la prospección territorial y a la evaluación del potencial energético de otras fuentes renovables no convencionales.

Palabras clave—Bioenergía, Análisis multicriterio, Biomasa agrícola, GIS, Ecuador.

INTRODUCTION

Biomass energy has been explored globally as a way to diversify electricity generation sources, particularly in contexts where agricultural residues are abundant. Unlike other renewable sources that depend on intermittent natural phenomena, biomass allows for dispatchable generation through thermochemical conversion of organic matter. In countries with strong agricultural economies, this approach presents a technically viable method to utilize residual matter that would otherwise be discarded or inefficiently managed (Demirbas, 2001; Zafar, 2022).

In Latin America, Brazil and Colombia have integrated biomass into their energy planning, benefiting from sugarcane bagasse and palm residues, respectively (International Renewable Energy Agency (IRENA), 2016; Marín-Apolo y cols., 2025). However, Ecuador has yet to exploit this pathway, despite possessing a similar agricultural structure and residue availability. According to national energy statistics, the country generated 63.45 % of its electricity from hydropower in 2024, while biomass contributed approximately 1.29 % to the overall mix (Agencia de Regulación y Control de Energía y Recursos Naturales no Renovables (ARCONEL), 2024). This reliance on hydroelectric generation introduces seasonal vulnerabilities, particularly during prolonged dry periods associated with climate variability, as evidenced by energy shortages in 2022 and 2023.

Given this context, agricultural biomass—especially from high-yield crops such as oil palm (*Elaeis guineensis*), rice, sugarcane, and hard corn—represents a strategic opportunity for decentralized electricity generation. These crops produce residues with acceptable moisture and energy content for direct combustion, with annual production distributed across various provinces. Prior studies in Ecuador have confirmed the physicochemical potential of these materials, but have not addressed their spatial distribution or siting feasibility (Peláez-Samaniego y Espinoza Abad, 2015; Chamba Quezada y Gómez Live, 2020).

The effectiveness of biomass-based generation systems depends on the availability of feedstock and on the siting of processing facilities. Factors such as proximity to road infrastructure, slope, access to substations, and exposure to flood-prone areas affect both construction costs and operational logistics (Kumar y cols., 2006; Morato y cols., 2019). Spatially explicit planning tools, particularly geographic information systems (GIS), allow for the integration of multiple georeferenced variables to support decisions regarding plant location.

In this context, spatial multi-criteria analysis (MCA) provides a systematic framework to incorporate diverse spatial factors into a composite suitability index. MCA has been successfully applied in various studies for energy resource allocation, including wind, solar, and small hydro siting (Malczewski, 1999; Aydin y cols., 2013). Its flexibility lies in the capacity to assign weights to criteria based on technical priorities and local conditions. In previous research conducted in Ecuador, the authors have demonstrated the applicability of this methodology in evaluating locations for submerged hydrokinetic generation, with results consistent with field measurements and hydrodynamic behavior (Salinas-León y Ochoa-Correa, 2025). These precedents support the relevance of MCA as a decision-support tool for territorial planning in renewable energy projects.

This study applies an MCA approach using GIS to identify the most suitable areas for the installation of biomass power plants in Ecuador. The methodology combines residue availability data with logistical, environmental, and infrastructural parameters to build a suitability model through weighted overlay analysis. The approach supports regional planning efforts by generating evidence-based maps that distinguish areas with higher feasibility for biomass energy development. It also provides a technical foundation for future public and private investment initiatives seeking to expand the country's distributed renewable energy capacity.

MATERIALS AND METHODS

General Approach

The methodological design combined quantitative energy assessment with geospatial modeling in order to determine technically and geographically feasible locations for biomass power generation in Ecuador. The procedure consisted of three stages. First, agricultural residues were classified and quantified based on crop-specific generation factors. Second, the lower heating value (LHV) of each biomass type was used to estimate the gross energy yield and the effective electrical output. Lastly, spatial suitability was analyzed using GIS, incorporating infrastructure, environmental, and topographical variables through a MCA.

Residue Identification and Quantification

The assessment focused on four crops: sugarcane, oil palm, hard corn, and rice. These crops were selected based on three criteria: availability of national production data, volume of residual biomass generated, and compatibility with direct combustion without prior conversion processes.

Residue generation was estimated using residue-to-product ratios (RPR) derived from regional literature and field studies. For sugarcane bagasse, the adopted RPR was 0.3, meaning that 300 kg of dry residue are generated per tonne of harvested cane. For oil palm residues—particularly empty fruit bunches and fibers—the RPR used was 0.26. Hard corn and rice had RPR values of 1.0 and 0.2, respectively, considering stalks and husks as primary combustible fractions (Serrano y cols., 2017; Peláez-Samaniego y Espinoza Abad, 2015).

Since not all the biomass is recoverable for energy use, a 40 % availability factor was applied to each theoretical value to account for soil nutrient recycling needs and technical losses during collection and handling (Chamba Quezada y Gómez Live, 2020). The final recoverable mass m (in tonnes/year) was computed as:

$$m = P \times \text{RPR} \times \alpha$$

where P is the annual crop production (tonnes/year), RPR is the residue-to-product ratio, and $\alpha = 0{,}40$ is the assumed availability coefficient.

Energy Yield Estimation

The energy content of each residue was estimated using the LHV adjusted for moisture content. The values used were based on national laboratory results and consistent with international references. For instance, oil palm fiber (20 % moisture) was assumed to have an LHV of 15.4 MJ/kg, while hard corn stalks (15 %) were assigned 14.8 MJ/kg. Sugarcane bagasse (50 % moisture) and rice husk (10 %) yielded 7.94 MJ/kg and 12.01 MJ/kg, respectively (Instituto Nacional de Preinversión, 2014).

The gross calorific energy Q (in MJ/year) was then obtained as:

$$Q = m \times \text{LHV}$$

To estimate the energy potentially available as electricity, a conversion efficiency of 25 % was used, consistent with typical biomass combustion systems of medium scale (15–30 MW) (Kumar y cols., 2006). The effective electrical potential (EEP), expressed in kilowatt-hours per year, was calculated as:

$$EEP = Q \times \eta \times 277{,}778$$

where: - $\eta = 0{,}25$ is the conversion efficiency, - 277.778 is the MJ-to-kWh factor (1 kWh = 3.6 MJ).

Spatial Suitability Analysis Using GIS

The third phase involved the identification of optimal locations for biomass plant installation based on spatial criteria.

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A multi-criteria evaluation was conducted using ArcGIS, employing both exclusion and preference factors. Exclusion zones included protected areas, rivers, national roads, and volcanic hazard regions. These areas were masked out of the analysis based on binary raster layers.

Six preference criteria were selected to reflect geographic, logistic, and environmental conditions: (i) effective electrical potential (from the energy model), (ii) distance to primary roadways, (iii) proximity to electrical substations, (iv) slope (percent grade), (v) flood exposure index, and (vi) distance from urban settlements. Each criterion was rasterized and standardized on a scale from 1 (least suitable) to 5 (most suitable).

Weights were assigned to each criterion through expert judgment and reference to prior MCA studies (Morato y cols., 2019; Kumar y cols., 2006). The final suitability index was calculated using weighted linear combination:

$$S = \sum_{i=1}^{n} w_i \cdot r_i$$

where: - S is the overall suitability score, - r_i is the normalized raster value for criterion i, - w_i is the assigned weight (Table 1), - $\sum w_i = 1$.

Table 1 summarizes the weights used in the MCA.

Table 1: Weights assigned to spatial preference criteria

Criterion	Weight
Effective electrical potential	0.40
Distance to primary roads	0.25
Proximity to substations	0.15
Slope	0.08
Flood exposure	0.07
Distance from urban settlements	0.05

The resulting suitability raster was classified into five categories using natural breaks (Jenks), producing a final map used to identify the most appropriate locations for biomass plant development.

Results

Effective Electrical Potential of Agricultural Residues

The calculated EEP for each crop was derived from the recoverable mass and the LHV, as detailed in the methodology. The crop yielding the highest annual EEP was oil palm, with 1273.55 GWh/year, followed by rice (733.81 GWh/year), sugarcane (220.68 GWh/year), and hard corn (179.64 GWh/year). These estimates were based on an assumed conversion efficiency of 25 % and reflect the moisture-adjusted calorific value of each residue.

The predominance of oil palm is due to the high calorific value of its fibers and to the year-round availability of its residues in the coastal regions of Ecuador. Rice husks also exhibit considerable potential due to their moderate LHV and substantial production volumes in lowland provinces. Table 2 summarizes the annual EEP estimates by crop.

Table 2: Effective Electrical Potential by Residue Type

Crop	EEP (GWh/year)
Oil palm	1273.55
Rice	733.81
Sugarcane	220.68
Hard corn	179.64

Geographic Distribution of Biomass Potential

To assess the spatial distribution of biomass resources across Ecuador, residue generation was first estimated at the crop level. Figure 1 illustrates the distribution of the four selected crops—sugarcane, rice, oil palm, and hard corn—expressed in tonnes per year per province. These maps were developed using georeferenced agricultural production data, which served as the basis for calculating the recoverable biomass by crop.

Using the crop-specific residue-to-product ratios and the assumed availability coefficient, the estimated biomass values were aggregated to construct a composite raster layer representing the total annual biomass availability per province. This aggregation resulted in the total recoverable biomass map shown in Figure 2.

The combined biomass layer was then used to estimate the provincial EEP, which reflects the energy content of the residues potentially convertible into electricity. The EEP map (Figure 3) classifies provinces into five categories using natural breaks (Jenks), allowing the differentiation of provinces based on their energy generation potential. Provinces with extensive oil palm and rice cultivation—particularly Guayas and Los Ríos—stood out due to their concentration of high-yield residues and favorable logistics.

The classification was derived from the natural breaks (Jenks) algorithm, which partitions the data into groups that maximize intra-class similarity and inter-class contrast. Class 1 includes provinces with minimal generation potential, while Class 5 corresponds to territories with the highest concentration of energy-relevant residues. These include Guayas and Los Ríos, where oil palm and rice dominate production patterns and logistical infrastructure is already in place.

The five provinces with the highest EEP concentrate more than 80 % of the national recoverable biomass. Table 3 presents these provinces along with their estimated annual biomass availability.

Table 3: Top Five Provinces by Effective Electrical Potential

Province	EEP (GWh/year)	Available biomass (t/year)
Guayas	891.09	1,263,517
Los Ríos	702.83	1,066,434
Esmeraldas	438.58	720,426
Sucumbíos	133.98	220,417
Manabí	124.81	174,583

Spatial Suitability Analysis

To determine locations that meet the spatial requirements for biomass plant deployment, a MCA was conducted using GIS-based raster overlay. This process integrated six prefe-

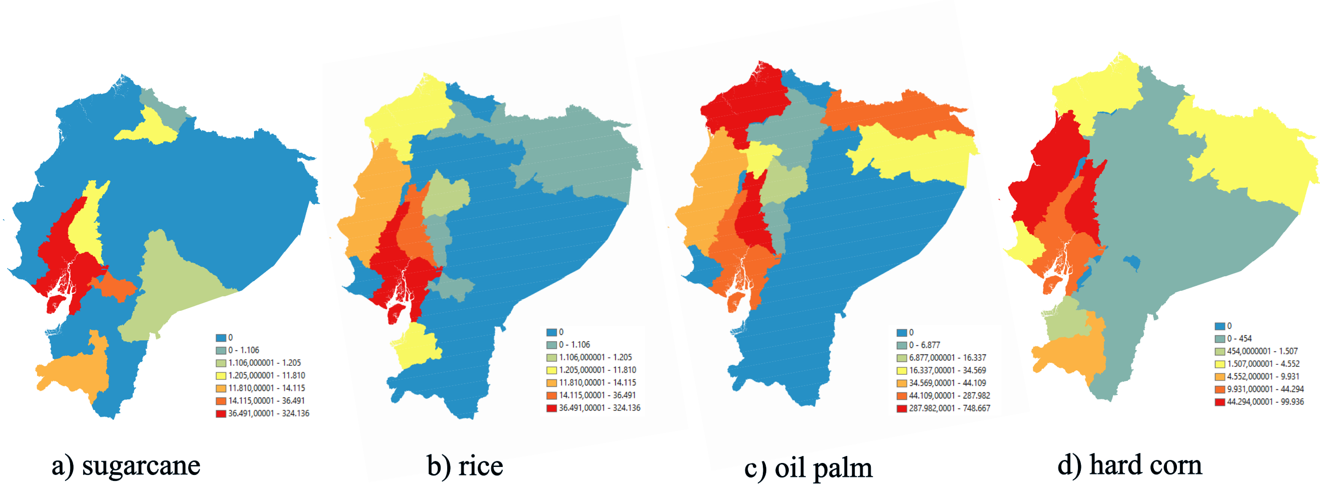

Fig. 1: Geographic distribution of main crops in Ecuador by production volume (t/year): a) sugarcane, b) rice, c) oil palm, d) hard corn.

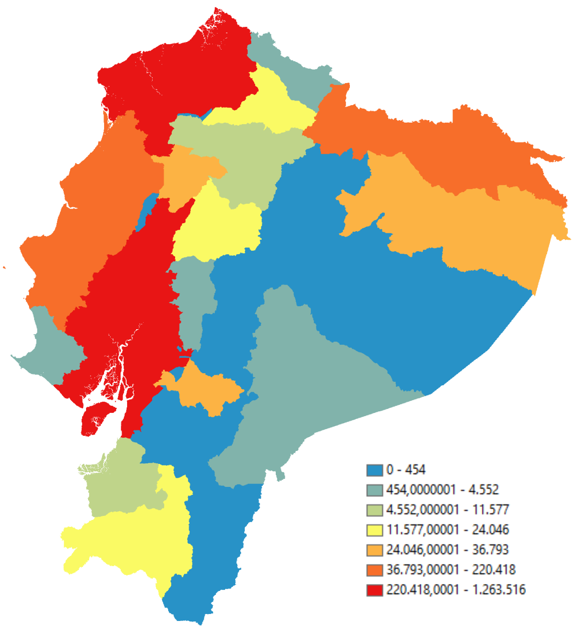

Fig. 2: Total estimated recoverable agricultural residues by province (t/year).

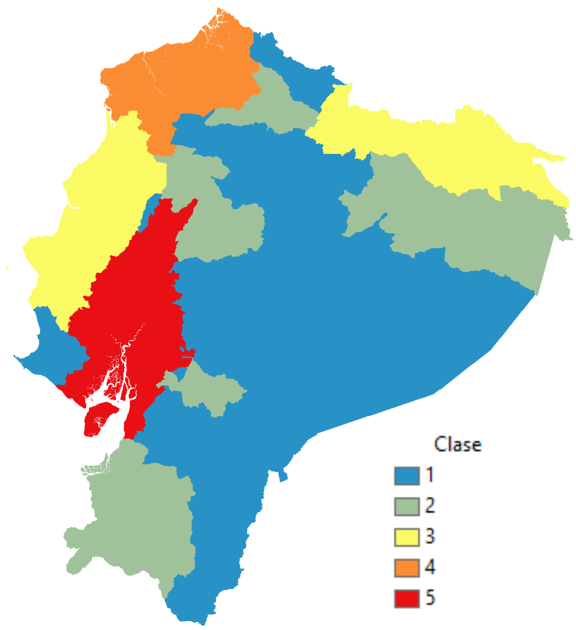

Fig. 3: Provincial classification of effective electrical potential (EEP). The scale includes five classes based on annual generation potential: Class 1 (0–4.42 GWh), Class 2 (4.42–21.02 GWh), Class 3 (21.02–133.98 GWh), Class 4 (133.98–438.57 GWh), and Class 5 (438.57–891.09 GWh).

rence criteria and three geographic exclusions. Each layer was processed and standardized before being combined into a composite suitability index.

Figure 4 presents the preference layers used in the weighted overlay. These include:

- **Road accessibility**: Euclidean distance to primary and secondary roads.
- **Proximity to settlements**: Calculated as distance from urban areas, favoring intermediate locations for distribution efficiency.
- **Distance to substations**: Derived from geolocated electrical infrastructure datasets.
- **Slope**: Extracted from digital elevation models, with lower gradients preferred to reduce construction complexity.

In parallel, exclusion zones were defined to mask out areas incompatible with biomass infrastructure. These included:

- **Volcanic hazard zones**: Based on official risk zoning maps.
- **Hydrographic basins**: Protected areas surrounding river headwaters.
- **Transport corridors**: Buffers applied to first- and second-order roads to maintain safety distances and preserve transit zones.

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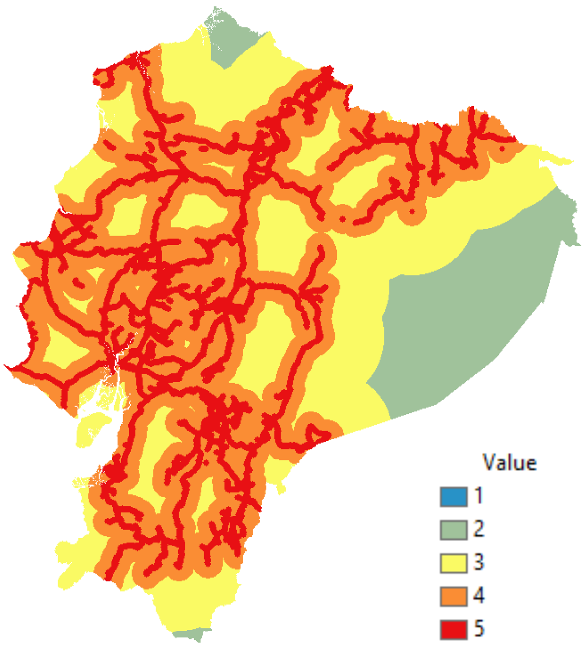
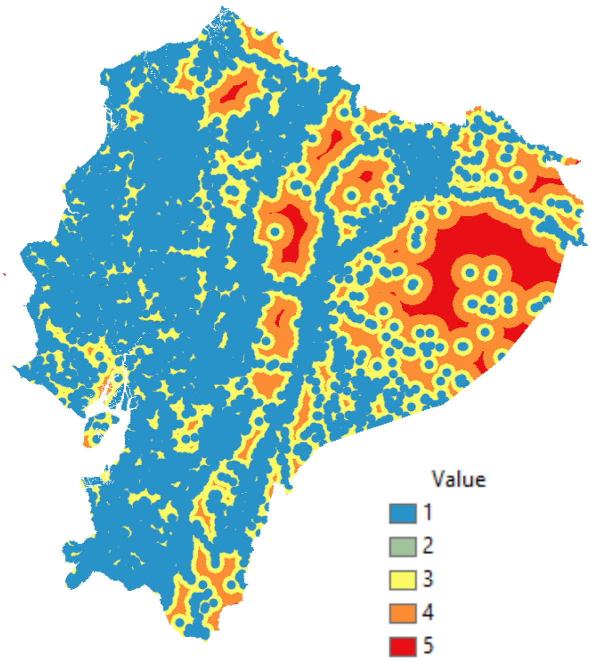
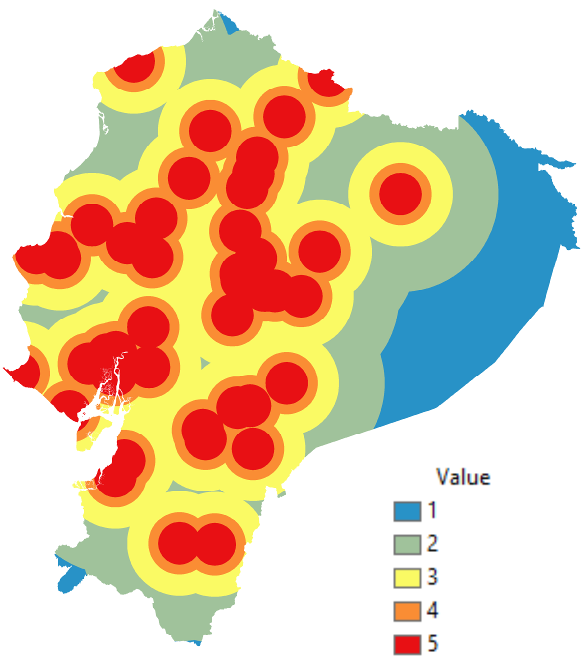


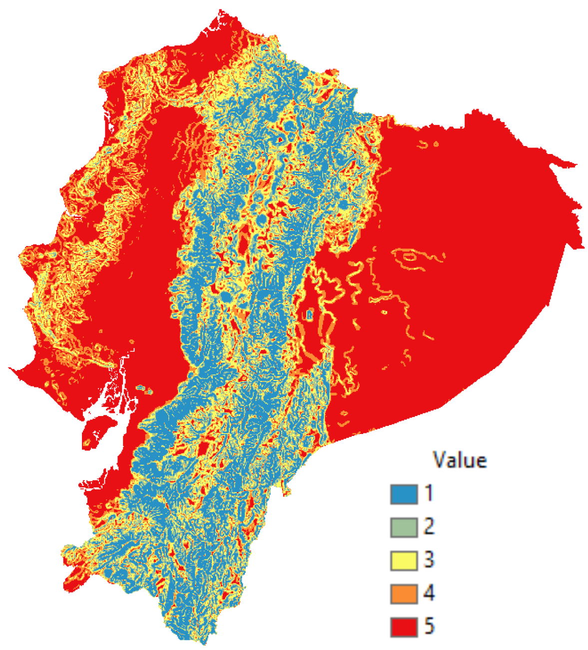
(a) Road accessibility



(b) Proximity to settlements



(c) Distance to substations



(d) Terrain slope

Fig. 4: Spatial preference criteria used in the multi-criteria analysis.

Figure 5 shows the geospatial representation of these exclusion factors.

Once standardized and reclassified, the preference layers were weighted according to the scheme in Table 1. The raster overlay was computed through weighted linear combination, and the output classified into five levels using the Jenks natural breaks method.

Figure 6 shows the final suitability map. Areas in Class

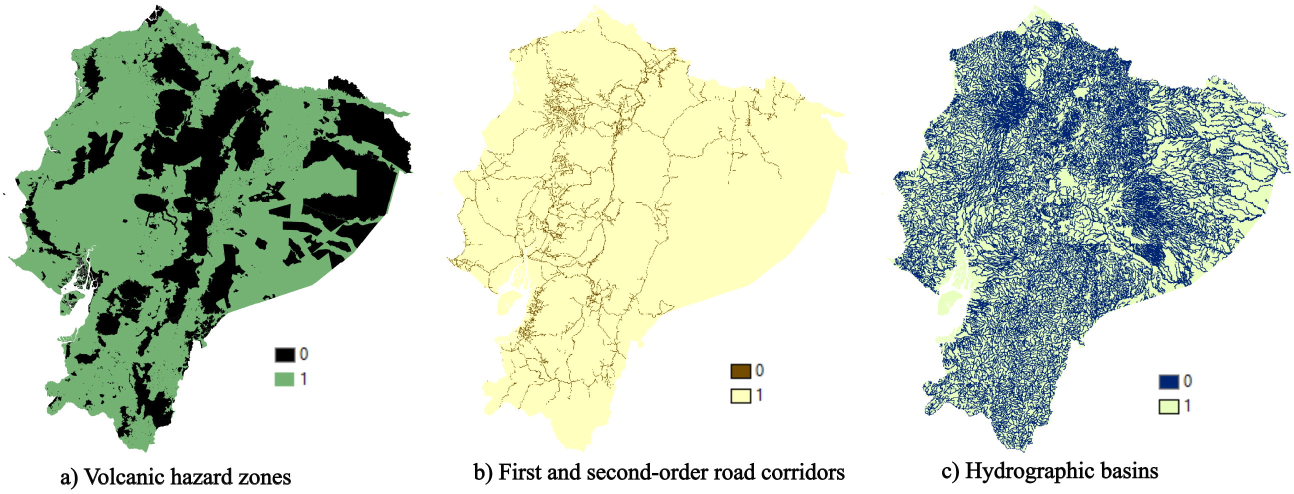


Fig. 5: Geographic exclusion layers. a) Volcanic hazard zones, b) First and second-order road corridors, c) Hydrographic basins.

5 combine high biomass availability with favorable topography, short distances to key infrastructure, and low exposure to environmental constraints. These locations are predominantly found in coastal provinces, particularly in Guayas and Los Ríos, but also appear in portions of Esmeraldas and Manabí. In contrast, high-residue regions with severe slopes or restricted access ranked lower in the composite index.

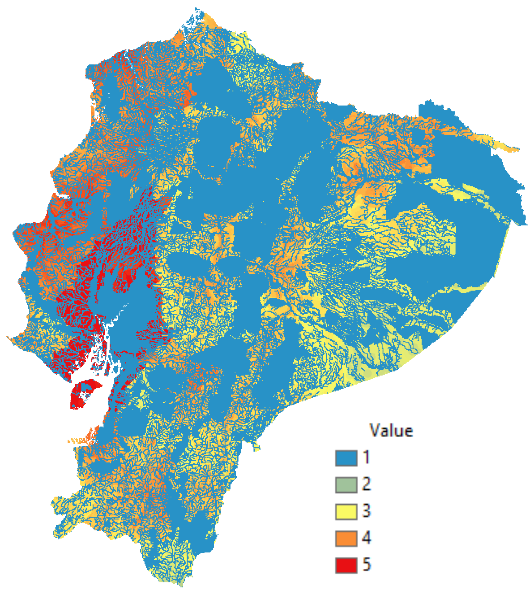


Fig. 6: Final suitability map for biomass plant siting in Ecuador. Classified into five levels: Class 1 (least suitable) to Class 5 (most suitable).

Economic Evaluation: LCOE Estimation

To assess the economic feasibility of biomass power generation, the levelized cost of electricity (LCOE) was estimated for a hypothetical 25 MW combustion-based facility. The LCOE represents the average cost per unit of electricity generated over the plant's lifetime and was calculated using the following equation (International Energy Agency (IEA) y OECD Nuclear Energy Agency (NEA), 2020; Short y cols., 2005):

$$\text{LCOE} = \frac{\sum_{t=1}^{n} (I_t + O_t + F_t)/(1+r)^t}{\sum_{t=1}^{n} E_t/(1+r)^t}$$

where:

- I_t = investment expenditures in year t,
- O_t = operation and maintenance costs in year t,
- F_t = fuel costs in year t,
- E_t = electricity generated in year t,
- r = discount rate,
- n = project lifetime in years.

The analysis used the following assumptions:

- Installed capacity: 25 MW
- Capacity factor: 70 %
- Project lifetime: 20 years
- Discount rate: 10 %
- Capital cost: USD 2,200 per kW installed
- Annual O&M costs: 4 % of capital cost
- Fuel cost: USD 8.5 per tonne (agricultural residues)

Based on these parameters, the annual energy generation was estimated at 153.3 GWh/year, and the resulting LCOE was calculated as USD 0.097/kWh. This estimate reflects conservative assumptions adapted to Ecuadorian market conditions. All monetary values are expressed in 2024 USD.

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Discussion

The technical and spatial analysis confirms that residues from Ecuador's agricultural sector have the capacity to support distributed electricity generation through biomass combustion systems. Among the residues evaluated, oil palm fiber stands out due to its combination of thermal properties and continuous generation throughout the year. Rice husks, while seasonal, exhibit sufficient volume and energy content to sustain regional-scale applications, especially when integrated with complementary feedstocks. Although sugarcane bagasse is already used in industrial cogeneration, particularly in sugar mills, its spatial availability is more concentrated and its use for independent biomass facilities may be constrained by industrial self-consumption. Hard corn stalks present lower energy yields per hectare but could support small-scale systems in zones with limited alternative residues.

Geospatial analysis demonstrates that residue density alone is insufficient to guide infrastructure placement. The highest scoring provinces in terms of suitability—Guayas, Los Ríos, and Esmeraldas—combine favorable logistical conditions (access to highways and substations) with topographic stability and minimal environmental exclusion zones. Conversely, provinces with biomass availability but unfavorable terrain or flood exposure (e.g., certain Andean zones) may require additional infrastructure investment or adaptation in plant design.

Crop calendars also influence plant viability. Rice and sugarcane residues are bound to harvesting cycles, resulting in seasonal surpluses. These patterns introduce limitations on year-round operation for plants depending exclusively on these inputs. Oil palm cultivation, largely located in the coastal region, yields residues more steadily across the calendar year, which allows for a more predictable supply stream. Combining residues with differing seasonal profiles may reduce storage requirements and increase operational stability, as previously observed in mixed-feed biomass systems in Colombia and Southeast Asia (Morato y cols., 2019).

Economically, the estimated LCOE for a biomass facility of 25 MW capacity was USD 0.097/kWh. This value reflects the localized cost structure, including fuel collection, labor, transportation, and interconnection. While higher than LCOE benchmarks in countries with large-scale supply chains—such as Brazil (USD 0.06–0.08/kWh)—the estimated value remains competitive in Ecuador's context, where fossil-based electricity still forms part of the dispatch matrix and faces volatility in fuel supply costs (International Renewable Energy Agency (IRENA), 2023).

The development of distributed biomass energy systems in Ecuador may benefit from further regulatory adjustments. Although current legislation recognizes renewable generation under the distributed model, specific incentives for biomass—such as feed-in tariffs, tax exemptions, or concessional financing—remain limited. Encouraging cooperative models involving small producers could increase supply chain reliability and promote inclusive rural development. Moreover, integrating biomass facilities into local development plans would help align infrastructure investment with national electrification and sustainability goals.

In summary, aligning biomass availability with spatial and technical criteria leads to a more precise identification of viable plant locations. The findings provide a basis for pilot-scale implementation and suggest that regional development strategies can benefit from incorporating biomass energy, particularly in zones with abundant crop residues and logistical connectivity.

Conclusions

This study combined energy estimation with spatial modeling to evaluate the suitability of agricultural residues for electricity generation through biomass combustion in Ecuador. The analysis focused on four crop types with established energy potential: oil palm, rice, sugarcane, and hard corn. Together, these residues could yield an estimated annual output of 2407.68 GWh, based on conservative assumptions regarding recoverable biomass and thermal conversion efficiency.

Spatial analysis revealed that provinces such as Guayas, Los Ríos, and Esmeraldas not only concentrate the highest volumes of biomass but also offer geographic and infrastructural conditions compatible with biomass facility deployment. These include relatively flat terrain, access to primary roadways, and proximity to substations. The use of a weighted overlay method within ArcGIS allowed for the integration of energy potential with spatial preference and exclusion layers, resulting in a suitability map that can guide infrastructure planning at the regional scale.

In parallel, a cost analysis estimated the levelized cost of electricity for a 25 MW biomass plant at USD 0.097 per kWh. This value remains within a competitive range for Ecuador's generation mix, especially for decentralized applications where transmission costs and grid extension are limiting factors. The estimate reflects current local conditions, including transportation logistics and fuel availability, and is consistent with values reported in comparable Latin American contexts.

For biomass projects to scale, future planning efforts should focus on regions with predictable feedstock availability and suitable siting conditions. Technical design must account for crop seasonality, which can be mitigated by combining residues with complementary harvest cycles. Beyond technical considerations, institutional frameworks will play a decisive role in advancing project implementation. Supportive measures—such as local incentives, risk-sharing mechanisms, and standardized permitting processes—could encourage private participation and improve deployment timelines.

The methodological framework applied in this study may also be adapted to other regions in Ecuador or countries with similar agricultural profiles, provided that geospatial and production data are available. As part of a broader energy diversification strategy, bioenergy holds promise as a locally sourced and grid-compatible complement to intermittent renewables.

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AUTHOR CONTRIBUTIONS

Conceptualization: M.E.V.-I., Y.M.-A. and D.O.-C.; methodology: M.E.V.-I., Y.M.-A. and D.O.-C.; formal analysis: M.E.V.-I., Y.M.-A. and D.O.-C.; investigation: M.E.V.-I., Y.M.-A. and D.O.-C.; resources: D.O.-C.; data curation: Y.M.-A. and M.E.V.-I.; writing — original draft: Y.M.-A. and M.E.V.-I.; writing — review and editing: D.O.-C.; visualization: Y.M.-A. and M.E.V.-I.; supervision: D.O.-C.; project administration: D.O.-C. All authors have read and approved the final version of the manuscript.

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