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The Energy Potential of Agricultural Biomass Residues for Household Use in Rural Areas in the Department La Guajira (Colombia)

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Abstract: Cooking with firewood in inefficient stoves primarily affects the rural population in poor and developing countries, usually lacking access to clean and modern energy sources. La Guajira, Colombia, is especially affected, with 40% to 60% of the departmental households relying on firewood, which increases to 80% in rural areas. In the department, only 40.4% of the population have access to natural gas, which drops to 6% in the indigenous reservations, while 68.4% have access to electricity, which reduces to 22% in indigenous reservations. Rural areas with agricultural production in the department can benefit from biomass wastes to address firewood consumption. This study quantified the agricultural biomass waste inventory in La Guajira to assess their availability for energy valorization as cooking fuel or, when possible, for electricity generation. The geolocalization of biomass wastes and rural communities was developed to overlap biomass production with the demand for firewood. Moreover, briquetting, anaerobic digestion, and direct combustion were considered small- and medium-scale options for the energy valorization of biomass wastes. Results highlighted the department's yearly production of 292,760 to 522,696 t of agricultural biomass wastes between 2010 and 2023. These wastes could yield an estimated 381 to 521 TJ/year of electricity using direct combustion, coinciding with some 21% to 28% of the electricity demand in 2022 in La Guajira. Furthermore, this electricity potential could replace 57% to 78% of the demand for firewood in the department using electric stoves. Moreover, anaerobic digestion could produce from 8.6 to 10 million m^3/year, enough to replace between 16% and 18% of the demand for firewood using biogas stoves. Finally, briquettes could replace between 28% and 49% of the firewood demand, considering the adoption of improved biomass stoves. Considering that direct combustion and anaerobic digestion technologies would be efficient on the medium scale, briquettes surfaced as the most viable approach at the small scale to take advantage of agricultural wastes to replace firewood in households in rural areas.

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1. Introduction

Poverty is characterized by insufficient resources for basic needs like food, housing, education, and health, affecting millions globally [1]. According to the World Bank and the United Nations, about half of the world's population lives under the poverty line of less than USD 2 per day [1,2], of which some 800 million people, mostly in rural areas, live with less than USD 1.25 a day, defined as extreme poverty [3]. Poverty is a complex and multidimensional phenomenon that goes beyond low income and is affected by limited access to essential goods and services [4].

Energy poverty, defined as the lack of access to electricity and modern and clean energy sources, combined with the reliance on traditional biomass sources, is one primary dimension affecting poverty [5,6]. Worldwide, about 11% of the population (i.e., about 675 million people) lack access to electricity, and nearly 2.3 billion people rely on traditional biomass fuels for cooking [7]. Energy poverty affects adequate household lighting, limiting economic and educational activities [8]. In developing countries, the use of firewood for cooking is widespread in many rural areas [9], which is estimated to cause about 4 million deaths per year because of indoor air pollution [10]. Additionally, firewood collection contributes to deforestation, the emission of greenhouse gasses, and soil degradation [11]. Particularly, in Colombia, the demand for firewood is a leading cause of biodiversity loss and increased soil erosion [12,13], mainly affecting rural areas [14], where some 20% of households lack access to electricity [15]. In the La Guajira department, 59% of the rural population has no access to electricity [15].

La Guajira has a deficit of energy infrastructure to guarantee sufficient energy access for the population [16,17]. In total, 40.4% of the departmental population lives in extreme poverty [18], and about 80% of rural area households rely on firewood for cooking, with serious health implications, disproportionally affecting women and children [13]. Addressing energy poverty in the department requires a combination of effective policies, investments in infrastructure and sustainable technologies, and community education [14]. Increasing access to fuels like LPG and natural gas could help to address this issue, although there are several barriers to this approach [9]. At the same time, electrification in rural areas is difficult at best [19]. Moreover, renewable energy sources available in La Guajira surface as a more reasonable solution to promote small-scale renewable energy projects to improve energy access and reduce firewood consumption [20–22].

In Colombia, agricultural biomass wastes could contribute to replacing firewood and supplying electricity in rural and non-interconnected areas [23,24]. The availability of agricultural biomass residues in the vicinity of low-income rural communities requires a deeper discussion to assess the reduction in traditional biomass use in rural communities [25,26].

This research will assess the potential of agricultural biomass waste as a sustainable alternative to firewood for domestic use. The study will focus on the viability of this alternative from economic, environmental, and health perspectives. It will analyze the emissions avoided by replacing firewood, including those associated with its transportation, and the health impacts on people relying on firewood for their domestic needs.

2. Materials and Methods

The methodology used in this study is depicted in Figure 1. Initially, the agricultural biomass waste is estimated using data on the production of major crops obtained from local associations and producers combined with the geolocation of waste generation during harvesting. Biomass waste is calculated using agricultural production and the waste factors reported in the literature. Based on literature data, biomass waste's physicochemical characteristics are used to assess its energy potential considering briquetting, anaerobic digestion, and direct combustion. The feasibility of a sustainable alternative to firewood and the energy potential identified for each technology are assessed by comparing the geolocation of firewood demand with biomass availability. Geolocation is assessed using ArcGIS Pro 3.1.0, which permits the assessment of the potential for grouping agricultural waste into energy clusters and optimizing biomass collection and transportation. This assessment allows the identification of suitable scenarios for implementing the technologies discussed based on technical, economic, environmental, and social considerations.

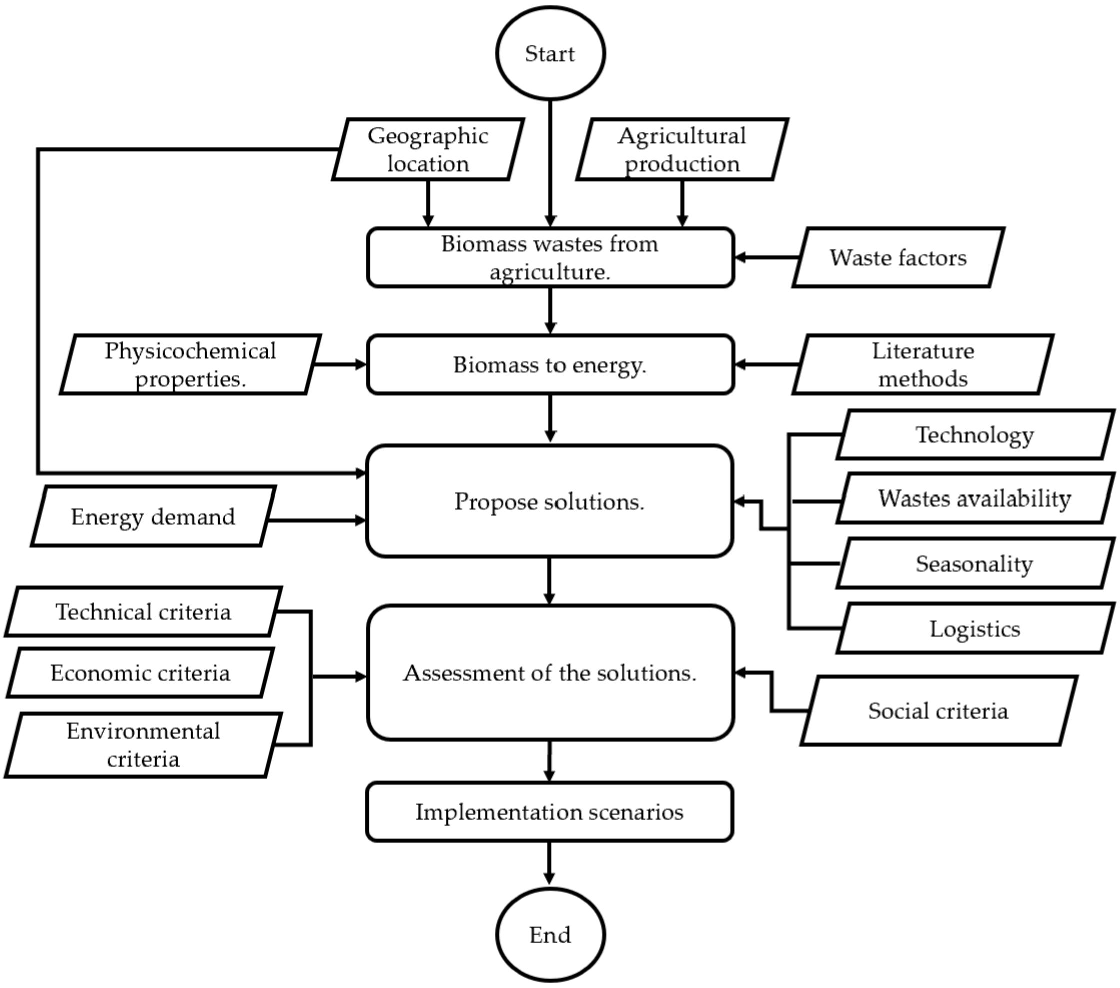

Figure 1. Methodology used in the study.

2.1. La Guajira Department

La Guajira has 20,848 km^2 distributed in 15 municipalities with about 1 million inhabitants, of which 49% live in urban areas [27]. In total, the indigenous population, mostly Wayuu, accounts for 52% [28], with 26 indigenous reservations, 84% of which are in rural areas, mainly in Media Guajira and Alta Guajira in the municipalities of Uribia (41%), Manaure (18%), Maicao (17%), and Riohacha (11%) [29]. These municipalities share the reservation "Alta y Media Guajira" which hosts 91% of the Wayuu population, of which only 22% have access to electricity, and 6% have access to natural gas [29].

Moreover, there is a high incidence of multidimensional poverty at 51% (i.e., 1.5 times higher than the national average of 34%), which increases to 73% in rural areas [30]. In addition, 71% of households in the department are affected by energy poverty, rising to 99% in remote rural areas [15,31].

2.2. Energy Mix and Access to Modern Energy

The department's residential sector consumes 1183 TJ/month, including firewood (80%), electricity (13%), natural gas (5%), liquefied petroleum gas (LPG) (1%), and charcoal (1%) [32]. The municipalities of Uribia Maicao, Riohacha, and Manaure account for 80% of the energy consumed (Figure 2).

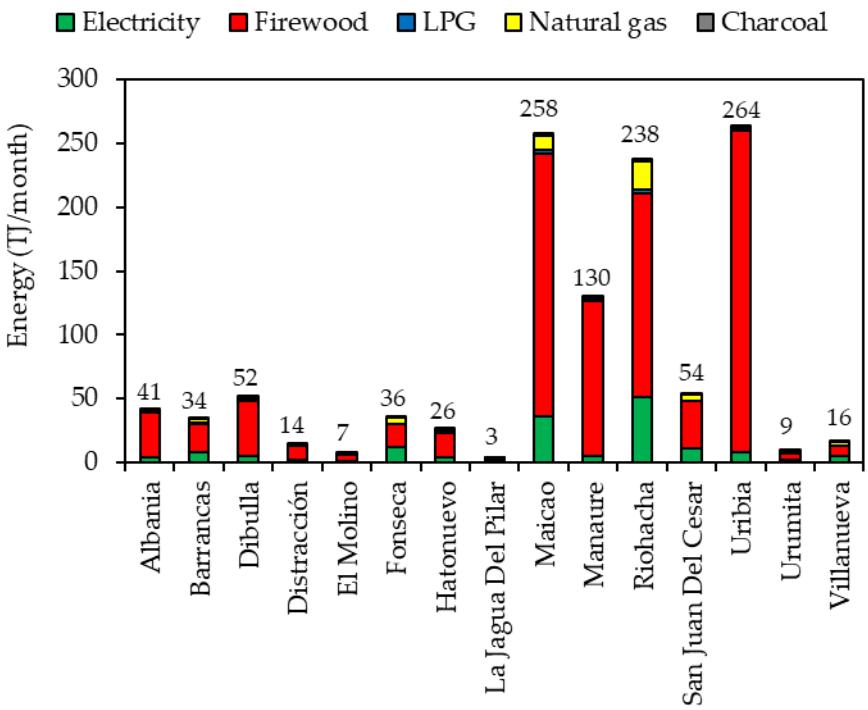

Figure 2. Energy consumption in the residential sector in La Guajira in 2022 [32].

Firewood is the primary cooking fuel used, accounting for 944 TJ of residential energy compared to 59 TJ of natural gas, 15 TJ of LPG, and 11 TJ of charcoal. The low efficiency of traditional firewood cooking in three-stone stoves, ranging from 3% to 4.4%, explains the high use of firewood [33].

Firewood demand in municipalities ranges from 37% to 95% of the residential energy mix. In Manaure and Uribia, with large indigenous reservations, firewood accounts for 93% to 95% of household energy, compared to 69% in other municipalities.

In 2022, per capita residential energy consumption increased to 1002 MJ/month (See Figure A1 in Appendix A), with firewood accounting for 75%, followed by electricity with 15%, natural gas with 7%, LPG with 2%, and charcoal with 1%. Notably, the natural gas and electricity per capita in municipalities like Uribia, Manaure, Maicao, Dibula, and Albania are lower than the departmental average, thus highlighting a lack of access to modern energy sources. These municipalities are characterized by dispersed rural populations, a significant barrier to accessing electricity, natural gas, and LPG [18]. In these municipalities, the multidimensional poverty index ranges from 5% to 92% [34].

Firewood Demand

In the department, some 127,364 households rely on firewood for cooking (Figure 3) (i.e., 40% to 60% of the households), of which 94% are in rural areas, particularly in areas with a higher share of indigenous people. Over 80% of the households cooking with firewood are in the municipalities of Uribia, Manaure, Maicao, Riohacha, and Dibulla in the region of Alta Guajira, with mostly Wayuu indigenous population, who traditionally rely on firewood. Household firewood consumption averages 13 to 16 kg/day [35,36]. In contrast, the demand for firewood is lower in Media Guajira and Baja Guajira, with a lower presence of the indigenous population, although the demand in rural areas remains high. The communities relying on firewood are scattered throughout the department, making it more challenging to address this issue.

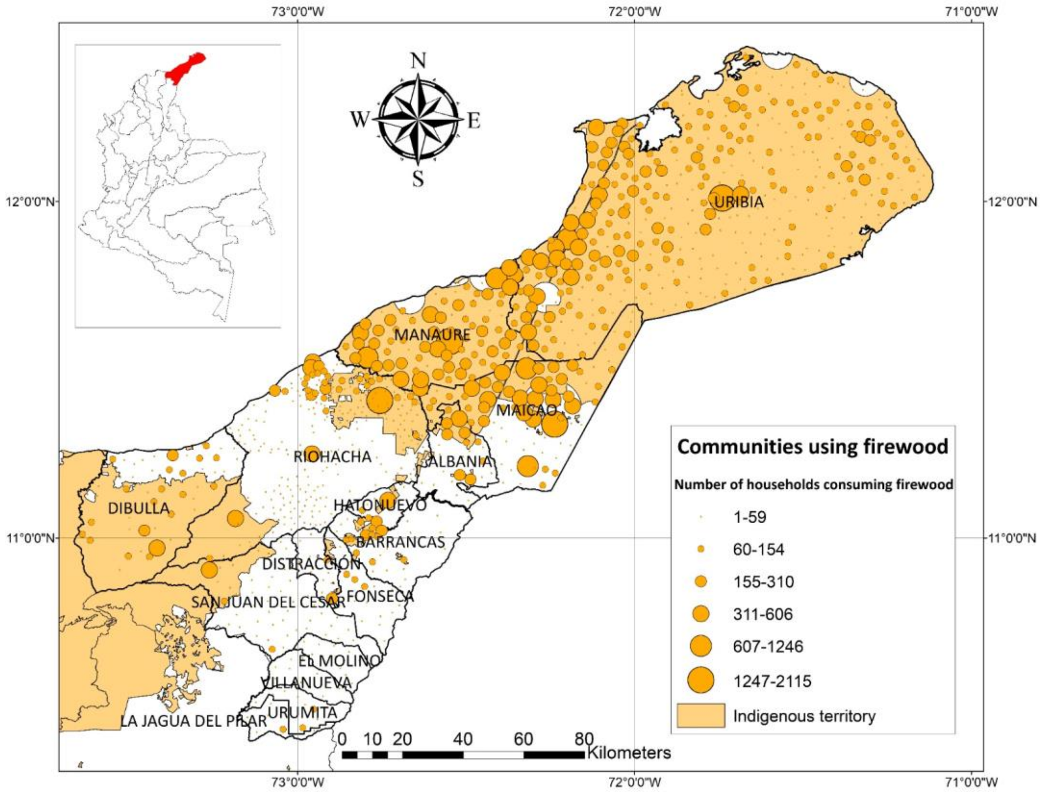

Figure 3. Communities using firewood (Source: own elaboration with ArcGIS software with data provided by [37]).

Considering a firewood consumption of 13 kg/day per household in rural Alta Guajira, 16 kg/day per household in Media Guajira, and 14 kg/day per household in Baja Guajira [38], firewood demand in the department is estimated at 640 kt/year, which coincides with the yearly deforestation of about 4242 hectares (i.e., for a biomass yield of 151 t/ha in the tropical dry forests of La Guajira) [39–41]. In addition, firewood use in La Guajira (with an emission factor of 1.52 $kg_{CO2eq.}/kg_{firewood}$ [42]) contributes to 13% of the departmental GHG emissions [43].

The department's yearly GHG emissions from firewood are estimated at 1 million t_{CO2eq} (Figure 4).

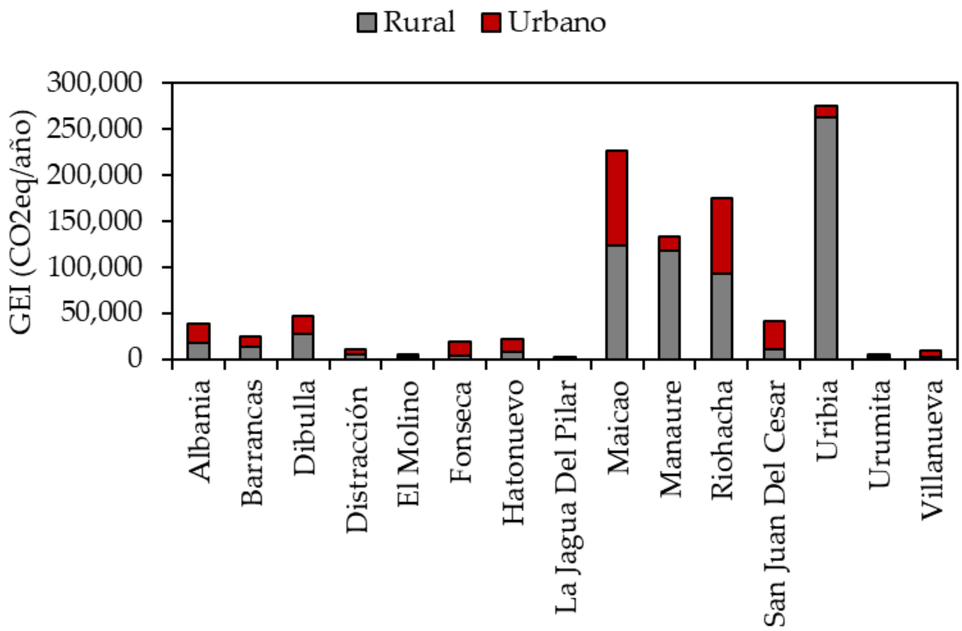

Figure 4. GHG emissions per municipality (Source: own elaboration with data from [15,18,38,42,44]).

The northern municipalities (i.e., Uribia, Manaure, and Maicao), with the most indigenous population, account for 60% of the emissions. Overall, GHG emissions are higher than estimated here because deforestation to obtain firewood drives additional emissions from Agriculture, Forestry, and Other Land Use (AFOLU).

Moreover, firewood is a costly energy source for low-income communities. Based on collection costs and health impacts, firewood is these communities' most expensive energy source [13]. Table 1 shows the cost associated with household firewood use. Firewood costs were calculated considering no collecting costs (i.e., COP 0) within a 2 km radius that rises to 160,000 COP/month for larger distances [13,45]. Health costs of 184,976 COP/month related to respiratory affections and other health issues related to firewood use have been reported [13]. Furthermore, a carbon tax estimated at 17,211 COP/t_{CO_2} is considered [13]. In terms of ecosystem services, reducing deforestation could account for 3.4 million COP/ha [13]. Replacing firewood with modern energy sources in households will free 14 h per month for productive activities, which is estimated to increase the monthly income by COP 70,000 [13]. Therefore, the annual cost of firewood is estimated at COP 667,065 million (USD 164.81 million).

Table 1. Costs associated with the use of firewood for cooking.

Costs Element	Estimated Value (Millions COP/Year)
Health	282,711.00
Firewood collection and cutting	106,986.00
Transport	244,539.00
$CO_{2eq.}$ emissions	17,819.00
Ecosystem services (reduced deforestation)	15,010.00
Total	667,065.00

2.3. Agricultural Production

With 34 crops, agriculture is one of the main economic activities in La Guajira, where 15 crops account for most of the production (Figure 5).

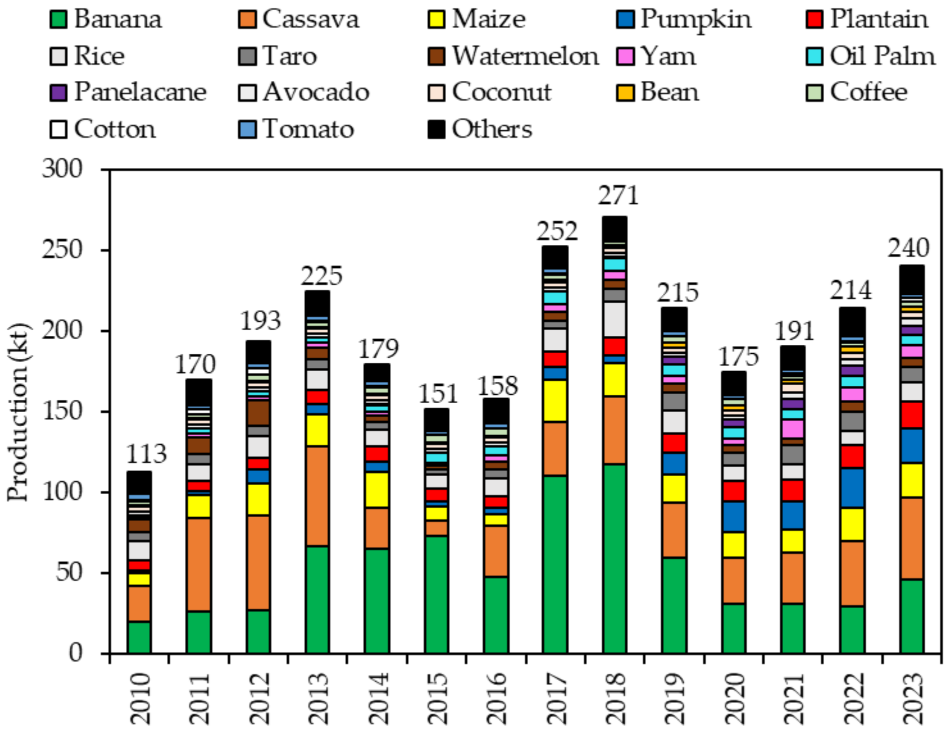

Figure 5. Agricultural production in La Guajira (Source: own elaboration with data from [46,47] and local producer associations).

Since 2010, agricultural production in the department has more than doubled from 113 kt to 250 kt. The department's main crops (banana, cassava, and maize) account for 41% to 70% of the departmental production, while other crops like rice, pumpkin, plantain, and malanga account for 13% to 29%.

Figure 6 depicts the distribution of agricultural production in the municipalities.

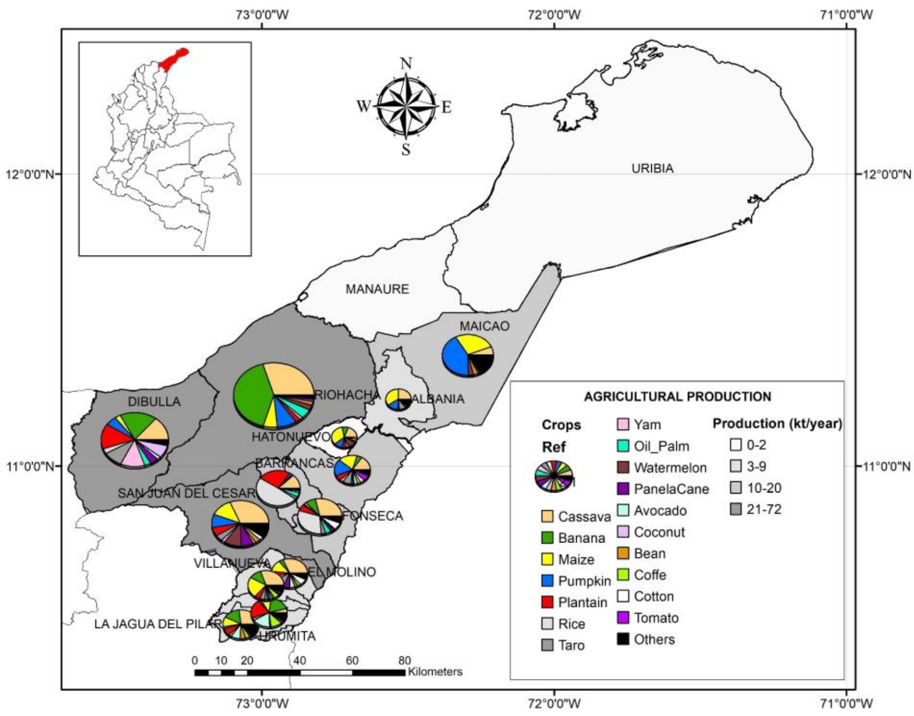

Figure 6. Municipal production (Source: own elaboration with data from [46,47] and local producer associations).

Results show the highest agricultural production in the south and central municipalities, mainly in Riohacha and Dibulla (i.e., the municipalities with lower Wayuu populations). The areas with indigenous reservations have no agricultural production. Remarkably, the reservation "Alta y Media Guajira", the biggest in the department, located in Uribia, Manaure, and partially in Maicao, Riohacha, and Albania, has no agricultural activity. Likewise, some areas of Dibulla, Rioacha, and San Juan del Cesar in "Baja Guajira" are indigenous reservations with no agricultural activity.

Biomass Wastes from Agriculture

The availability of agricultural wastes for energy applications depends on collection procedures and competing uses. Sometimes, agricultural residues are used as a source of moisture and nutrients for the soil to prevent erosion, etc. Agricultural wastes of malanga, yam, pumpkin, tomato, and watermelon are mainly used to provide moisture and nutrients to the soil. Therefore, this study does not discuss these wastes as potential biomass sources. Furthermore, rejected fruits that fail the exporting quality standards are marketed for local consumption.

On the other hand, oil palm wastes are not available for energy valorization. No agro-industries are processing the oil palm fruit in La Guajira, which means that the fruit is transported to companies located in neighboring departments, leaving the residues available elsewhere, which is why they will not be considered in this assessment.

Biomass wastes from agriculture are calculated as a function of crop production, type of crop, and waste factors (Figure 7).

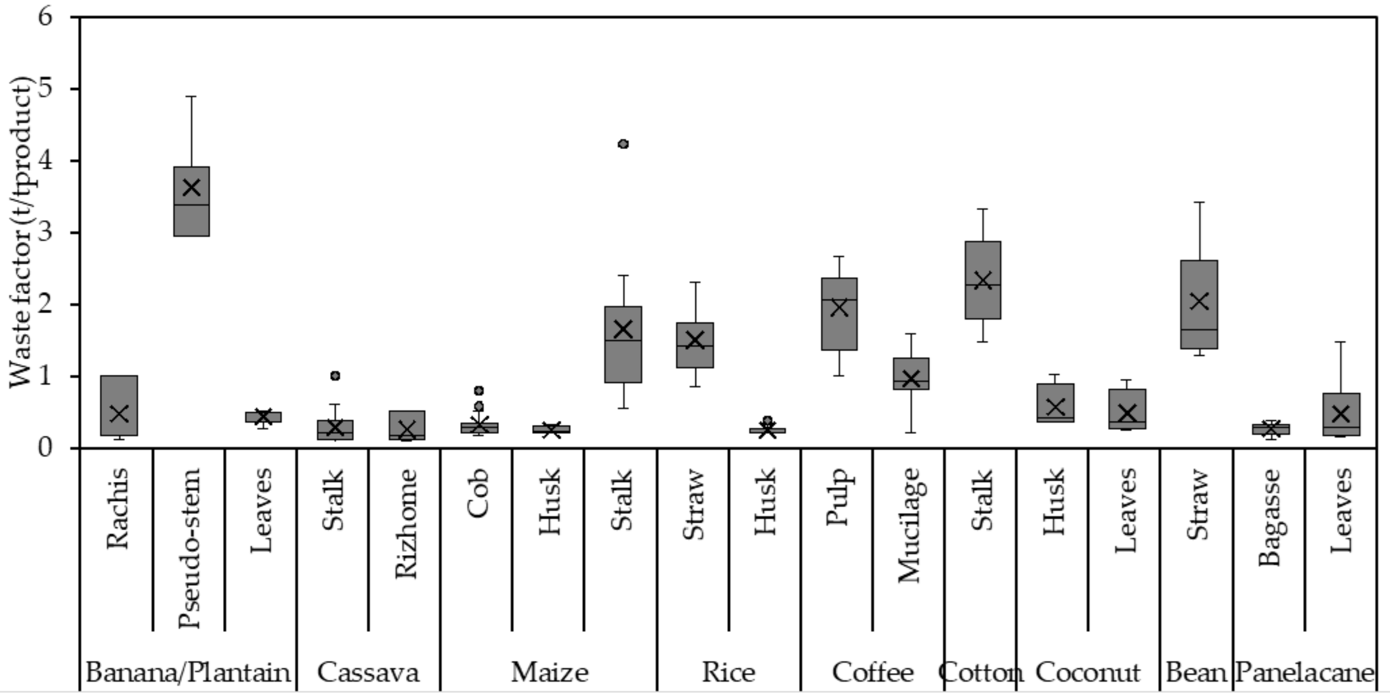

Figure 7. Wastes factors (Source: own elaboration with data from [24,48–96]).

Bananas, plantains, coffee, cotton, and beans yield the highest mass of biomass waste.

Although crops produce some biomass waste, only a fraction is available for energy applications in La Guajira (Figure 8).

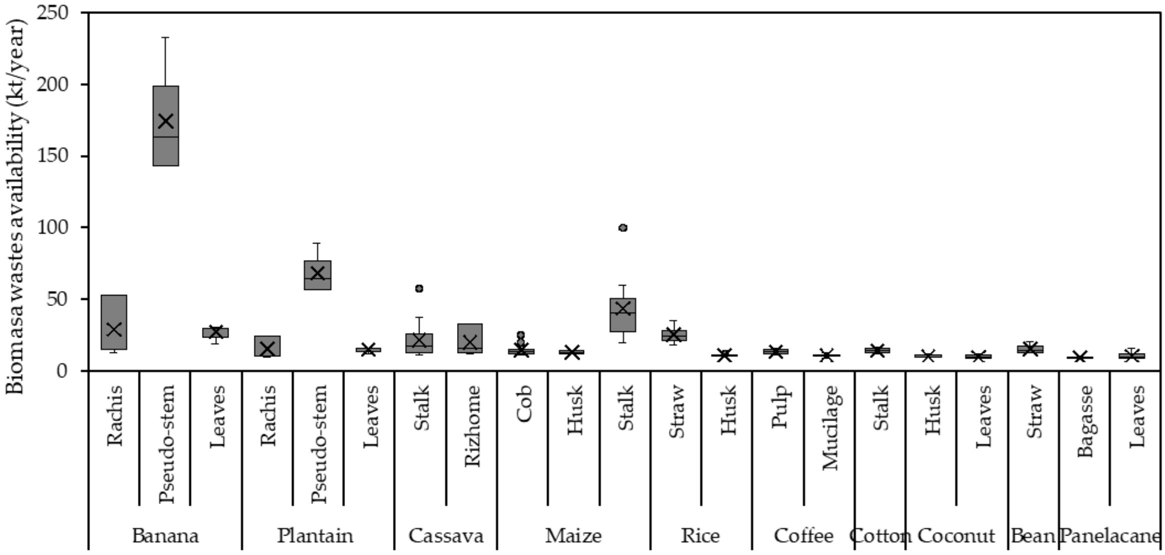

Figure 8. Agricultural wastes availability (Source: own elaboration with data from [46,47], and local producer associations).

From 292 kt to 523 kt of agricultural wastes are available in rural areas for energy applications. Bananas and plantain pseudo-stems account for 49% of agricultural wastes; considering leaves and rachis, it increases to 60%. Moreover, maize accounts for 12%, cassava stalks represent 8%, while rice straw and beans crops account for 7%. Other crop wastes add up to 13%.

Biomass wastes are available according to crop harvesting periods (Figure 9).

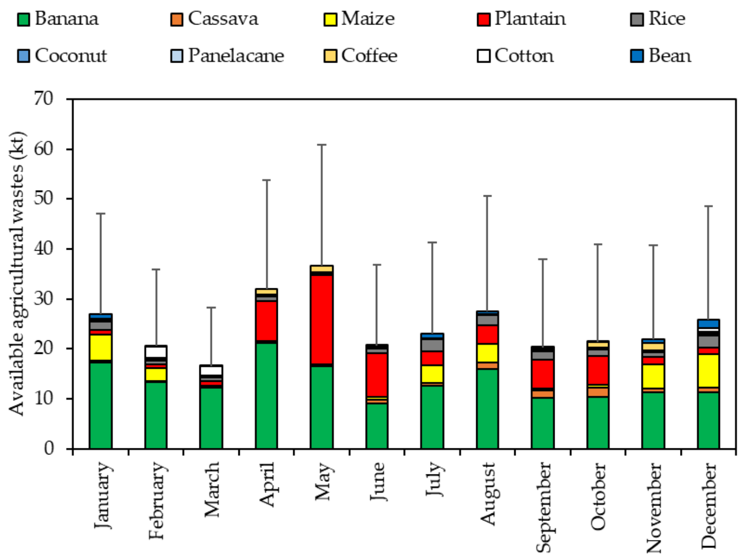

Figure 9. Seasonality of available agricultural wastes in La Guajira (Source: own elaboration with data from [46,47] and local producer associations).

The availability of agricultural wastes for energy valorization varies from 24,398 to 43,559 t/month. Agricultural production peaks between April and May, coinciding with the rainy season [97,98].

About 62% of crop waste is generated in Riohacha and Dibulla, while San Juan, Fonseca, and Distracción account for 6% each. These five municipalities generate 80% of the agricultural waste in the department (Figure 10). The geolocalization highlights the lack of agricultural activities in indigenous reservations. The municipalities of Uribia, Manaure, Maicao, Albania, Barranca, and Hatonuevo are arid regions with low agricultural potential and limited water availability. Also, large areas are exploited for coal mining (e.g., in the Cerrejón mine). The per capita generation of agricultural wastes varies between 1.3 and 1.7 kg/day in Albania and Hatonuevo, increasing to 9 and 13 kg/day in Dibulla and La Jagua because of a lower population density in these municipalities [46,47].

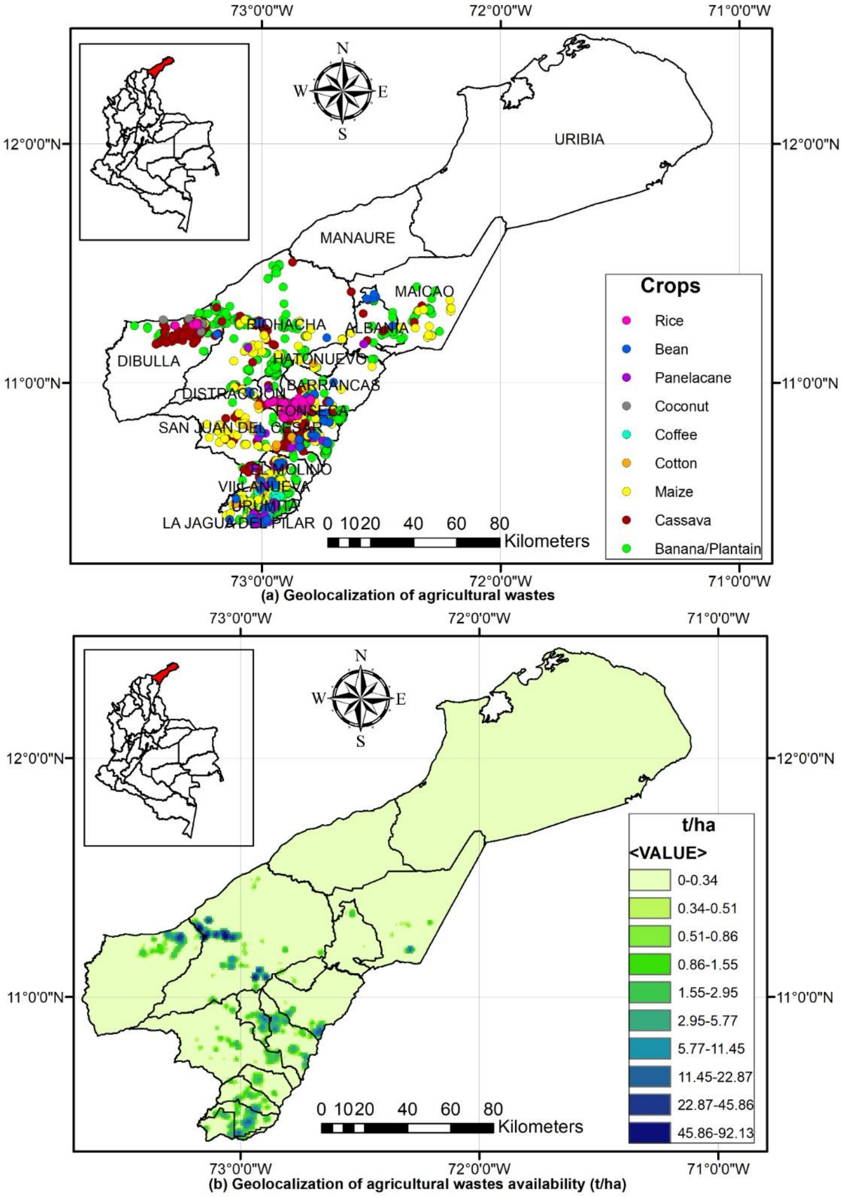

Figure 10. Municipal availability of agricultural biomass wastes (Source: own elaboration with data from [46,47] and local producer associations).

2.4. Physicochemical Properties of Agricultural Biomass Wastes

The energy potential of agricultural biomass wastes depends on their physicochemical and lignocellulosic properties, which are key to assessing the performance of waste-to-energy technologies. Table 2 presents the physicochemical properties of the agricultural wastes available in La Guajira. To ensure the representativeness of the results, the interquartile range was considered by subtracting the lower quartile from the upper quartile of the data reported in the literature (see Table A1 in Appendix B).

Table 2. Physicochemical properties of agricultural biomass wastes.

Crop	Waste	Lignocellulosic Components (%) *			Physicochemical Properties (%) *				Heating Value (MJ/Kg) *	
		X_H	X_C	X_L	MC	VM	Ash	CF	LHV	HHV
Banana/ Plantain	Pseudo-Stem	19.62–25.36	32.50–54.00	17.81–13.00	80.00–92.40	76.00–89.43	8.64–19.00	5.00–14.86	10.80–13.63	12.40–16.16
	Rachis	10.00–22.30	23.00–53.00	10.80–26.20	80.00–93.60	57.78–79.10	9.95–29.90	5.73–19.59	10.00–12.88	13.53–15.70
	Leaves	33.46–34.34	25.80–43.34	10.58–22.36	7.46–40.00	77.79–83.35	6.20–15.70	7.48–15.60	11.37–16.50	12.12–17.57
Maize	Cob	30.14–35.00	27.41–46.00	13.81–21.03	7.53–15.00	65.23–80.79	1.35–7.71	16.40–17.40	15.08–17.97	16.50–19.34
	Stalk	20.00–30.88	32.32–51.53	10.00–20.51	3.55–15.00	64.49–73.93	4.20–10.10	12.70–28.93	15.30–16.60	16.60–17.50
	Husk	19.10–35.72	32.60–43.14	15.10–23.00	5.90–12.12	75.17–82.66	2.52–9.70	7.94–20.39	15.56–17.41	17.65–19.90
Cassava	Rizhome	10.57–17.00	33.89–48.01	18.00–28.00	1.80–10.60	65.00–81.90	3.60–11.20	10.70–18.20	10.61–15.90	17.10–21.70
	Stalk	21.12–31.61	22.80–35.20	15.00–30.62	8.50–20.00	64.90–79.90	4.70–7.34	14.10–14.70	13.10–17.60	15.76–18.10
Rice	Husk	21.30–29.70	28.60–38.57	19.20–24.40	3.31–12.40	52.30–76.56	9.48–20.00	14.02–23.40	12.77–16.41	14.09–17.44
	Straw	19.70–31.82	32.00–39.17	13.10–25.00	5.60–10.29	54.68–76.84	8.69–19.19	9.08–18.20	13.06–15.76	13.89–19.01
Coffee	Pulp	11.00–19.03	20.33–43.98	12.46–21.04	80.00–83.60	34.73–82.50	2.50–8.53	7.19–33.08	12.60–15.90	14.79–16.28
	Mucilage	-	-	-	97.56	-	-	-	2.00	-
Bean	Straw	19.60–16.00	21.40–38.00	10.20–16.00	4.50–15.00	69.10–75.30	5.93–6.80	18.77–24.10	14.65–16.41	17.20–17.60
Cotton	Stalk	11.90–20.00	32.00–48.80	18.20–25.50	4.55–12.00	61.21–78.61	1.34–6.66	15.80–25.12	15.21–17.10	17.23–18.32
Coconut	Husk	15.20–25.50	21.26–37.60	25.02–41.30	7.25–11.28	61.50–85.30	2.50–5.39	5.88–17.68	18.00–19.02	19.31–20.95
	Leaves	22.49–31.58	39.05–56.71	18.15–28.44	2.55–10.49	78.03–89.96	4.67–6.97	5.37–17.01	17.67–19.71	17.77–20.83
Panela cane	Bagasse	20.00–32.00	33.00–46.00	15.00–32.00	5.92–75.00	76.00–88.40	1.94–9.00	8.00–18.00	15.40–17.90	17.20–20.00
	Leaves	30.40–33.28	39.70–44.50	22.80–12.30	6.70–50.00	68.00–86.64	3.70–7.50	8.60–16.90	15.72–17.90	17.30–18.61

* Hemicellulose fraction (X_H), cellulose fraction (X_C), lignin fraction (X_L), moisture content (MC), volatile matter (VM), ash (CZ), fixed carbon (CF), low heating value (LHV), and high heating value (HHV).

Hemicellulose (X_H) and cellulose (X_C) benefit anaerobic digestion, while lignin (X_L) provides strength to briquettes but hinders biodegradation [99]. Moreover, moisture affects combustion. Thus, anaerobic digestion is selected for biomass wastes with over 50% moisture, yet pretreatment is needed to address high lignin content, like that in coffee stalks and rice husks. Furthermore, low moisture content (MC), like in the case of rice husks or cotton stalks, favors briquetting, whereas high moisture is optimal for anaerobic digestion [100]. Volatile matter (VM) enhances thermal energy release and low ash content (Ash) while reducing solid wastes [101], which is ideal for direct combustion. The calorific value (LHV, HHV) determines the energy efficiency of direct combustion and briquetting technologies [102]. Coconut shells and sugarcane bagasse are suitable for briquetting, while banana pseudo-stem and coffee mucilage are more indicated for anaerobic digestion, optimizing available resources [103,104].

2.5. Biomass to Energy

Thermochemical technologies (e.g., packed bed, fluidized bed, pulverized fuel systems) are suitable for biomass sources under 50% moisture, while bioconversion technologies are more indicated for biomass sources over 50% moisture [56]. Therefore, this study considers direct combustion and anaerobic digestion for the energy valorization of agricultural wastes.

Moreover, mechanical treatments like briquetting (e.g., using either screw extruder, roller, piston, or manual presses [104–106]) increase the energy density of biomass, facilitating the transport, storage, and production of alternatives to firewood. Briquettes burn with a small flame, producing less smoke, and are more durable than firewood [55,107].

2.5.1. Briquettes

Briquetting, defined as the compaction of biomass to increase its bulk density, has some advantages, making it an attractive alternative as a cooking fuel in rural households [108]. The main briquetting modes include the screw extruder press, the roller press, the piston press (mechanical or hydraulic), and the manual press [55,104–106,108–111]. Table 3 compares briquettes and firewood as cooking fuels.

Table 3. Comparison of briquettes with firewood (Source: own elaboration with data from [55,108,112]).

Biomass Source	**Calorific Value (MJ/kg)**	**Stove Efficiency (%)**	**Useful Energy (MJ/kg)**
Briquettes	18.0–22.0	35%	9.0–11.0
Firewood	15.0–21.0	<20%	3.0–4.2

Firewood and briquettes have similar calorific values, although briquettes achieve higher stove efficiencies. Thus, you require two to three times more firewood than briquettes to meet the same cooking demand [55,108,110,112].

The annual gross energy potential is estimated using the waste/product ratio method proposed by [49], and the following equations are used:

$$\mathrm{M_i} = F_r \cdot P_\mathrm{i} \tag{1}$$

$$\mathrm{WB_i} = \mathrm{M_i} \cdot \mathrm{LHV}_i \cdot \mathrm{MR}_i \tag{2}$$

$$\mathrm{WB}_T = \sum \mathrm{WB}_i \tag{3}$$

where

$\mathrm{M_i}$— residual biomass i (kt);

F_r—waste/product ratio;
P_i—crop production (kt);
LHV_i—low heat value of biomass briquettes (MJ/kt);
MR_i—mass ratio of briquettes produced to briquetting residues;
WB_i—biomass briquette energy potential from each residue;
WB_T—total energy potential.

A mean value of 1/6 was considered for the mass ratio of briquettes produced to briquetting residues (MR_i) [112].

2.5.2. Anaerobic Digestion (AD)

Anaerobic digestion is used chiefly on biomass sources with over 50% moisture. This process is developed in fermenting tanks in the absence of oxygen in four stages:

1. Hydrolysis;
2. Acidogenesis;
3. Acetogenesis;
4. Methanogenesis.

Substrates are frequently pretreated to improve methane yields. Biogas can be used for electricity generation, cooking fuel, transport fuel, etc. [113].

The biomethane potential (BMP) of lignocellulosic biomass is calculated as follows [114]:

$$BMP_i = 378.X_{C_i} + 354.X_{H_i} - 194.X_{L_i} + 313.X_{R_i} \quad (4)$$

where
BMP_i—biochemical methane potential of biomass source i $\left(\frac{L}{Kg_{VS}}\right)$;
X_{C_i}—cellulose fraction of biomass I;
X_{H_i}—hemicellulose fraction of biomass i;
X_{L_i}—lignin fraction of biomass i;
X_{R_i}—fraction of the remaining biomass constituents.

The technical methane potential was calculated considering the required energy to preheat the reactor and preheating heat losses of 10% [115]:

$$TMP_i = BMP_i - \frac{\sum_1^j 1.1.M_i.c_P.(T_R - T_0)}{LHV_{CH_4}} \quad (5)$$

where
TMP_i—technical methane potential of biomass source i $\left(\frac{m^3}{t_{biomass}}\right)$;
c_P—specific heat of the raw material (taken as $4.2\ KJ/Kg.°C$);
T_R—operational temperature of the digester (°C);
T_0—average atmospheric temperature (°C);
LHV_{CH_4}—lower heating value of methane $\left({}^{kJ}/_{m^3}\right)$.

The energy potential of biomass anaerobic digestion is calculated as follows [56]:

$$W_{E.DA_i} = M_i.TMP_i.LHV_{CH_4} \quad (6)$$

where
$W_{E.DA_i}$—bioenergy potential of the i-est biomass source available for anaerobic digestion (GWh).

The total bioenergy potential for anaerobic digestion can be calculated as follows [56]:

$$W_{E.DA} = \sum_1^j W_{E.DA_i} \quad (7)$$

2.5.3. Direct Combustion

The energy potential of biomass in combustion technologies was calculated as follows [56]:

$$W_{E.D.C_i} = M_i \cdot LHW_{w.b_i} \quad (8)$$

where
$W_{E.D.C_i}$—energy potential of direct combustion for biomass i (GWh);
M_i—residual biomass mass i (kt);
$LHW_{w.b_i}$—lower heating value on a wet basis for biomass i (GWh/kt).

Moreover, the lower heating value (LHV) was determined based on the moisture content (MC) and higher heating value (HHV) [116]:

$$LHV_{w.b} = HHV_{d.b}.(1 - MC) - 2.447.MC \quad (9)$$

where $w.b$ stands for wet basis, and $d.b$ stands for dry basis.

The total energy potential $W_{E.D.C}$ of biomass sources suitable for direct combustion is calculated as follows [56]:

$$W_{E.D.C} = \sum_1^j W_{E.D.C_i} \quad (10)$$

2.5.4. Energy Clusters

Considering the proximity of agricultural wastes to populations demanding firewood, energy clusters can be considered to replace firewood in these communities. Different studies discussed the efficiency of biomass collection and transportation, indicating that transporting biomass is feasible within a 15.6 km radius of biomass plants with costs of around 0.76 USD/t-km [117]. Within a 15 km radius, biomass transport has adequate economic and environmental performance [118]. Without biomass sources, a supply distance of 31 km can be considered [119]. However, in rural areas, farmers frequently transport biomass within a 10 km radius of the biomass plant with costs of around 0.14 USD /t-km [120,121]. Moreover, when discussing the domestic use of firewood, results point to a radius of 2 to 5 km of households and communities [122,123], which coincides with observations in communities in La Guajira [45].

2.6. Emissions of Particulate Matter (PM)

Frequently, cooking is developed in enclosed and poorly ventilated rooms, where firewood combustion generates considerable amounts of PM, particularly PM10 (coarse particles, i.e., with an aerodynamic diameter ≤ 10 μm), PM2.5 (fine particles, i.e., with an aerodynamic diameter ≤ 2.5 μm) [124], and TSPs (total suspended particles), which include all airborne particles including PM2.5, PM10, and larger particles [45]. Particles with diameters greater than 10 μm are referred to as settling particles (SPs); due to their larger size and weight, these particles do not remain suspended in the atmosphere for long and tend to settle quickly [45].

The biggest threat in firewood kitchens comes from PM2.5 particles, which have the highest airborne concentrations and can affect the eyes and respiratory system [125]. High concentrations of these particles are associated with various respiratory diseases, including mucosal irritation, conjunctivitis, tearing, laryngitis, bronchitis, ischemic heart disease, stroke, chronic obstructive pulmonary disease, and lung cancer [126].

Table 4 shows the PM emission factor for the different cooking fuels considered in this study.

Table 4. PM emission factor for different cooking fuels.

Cooking Fuels	PM2.5	PM10	TSP	Sources
Firewood (g/kg)	14.38	15.70	16.23	[127]
	14.80	15.01	17.94	[45]
	14.67	14.98	15.77	[128]
	16.40	17.00	17.30	[129]
Briquettes (g/kg)	0.35–1.11	-	-	[130]
	2.52	2.52	2.69	[127]
			0.4–2.91	[131]
			2.7–6.4	[132]
	1.51–1.67 0.10–0.11 *			[133]
	4.12–2.22			[134]
	1.22–11.28			[135]
Biogas (mg/MJ)	7.4	7.4	7.4	[136]
	12.54	12.54	12.54	[137]
Electricity (g/kwh)	-	-	-	-
Charcoal (g/kg)	2.4	2.4	2.4	[127]
	8.9–11.2	8.9–11.2	8.9–11.2	[130]
LPG (mg/MJ)	6.7	6.7	6.7	[138]
	9.5	9.5	9.5	[136]
Natural Gas (g/m^3)	0.16	0.16	0.16	[136]

* g/MJ.

Solid fuels like firewood, charcoal, and agricultural biomass briquettes generate significant amounts of PM, with PM2.5 accounting for 70% to 90% of the total. The concentration of PM2.5 exceeded the 168 mg/MJ threshold established for clean cooking fuels when using firewood [139]. However, it is noteworthy that briquettes produce less PM than firewood, making them a healthier alternative. On the other hand, biogas and electricity production generate marginal PM emissions, making them cleaner options for cooking in enclosed spaces. Therefore, replacing firewood with these alternatives can reduce PM emissions to levels that preclude health-associated consequences.

3. Results

The energy potential of the biomass sources considered in this study is discussed in this section.

3.1. Briquetting Potential

All available agricultural wastes were considered for briquette technologies, except for coffee processing wastes, mainly wastewater containing coffee mucilage (Figure 11).

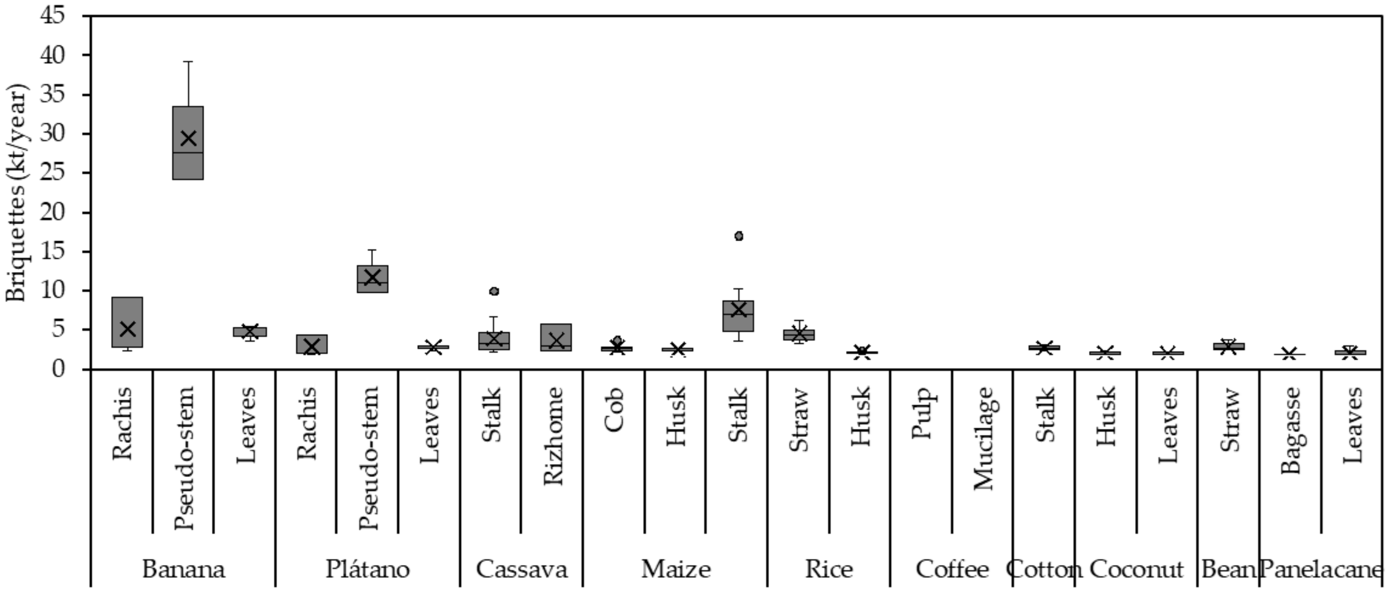

Figure 11. Briquettes production.

From 48 to 85 kt of briquettes could be produced yearly. Banana and plantain agricultural wastes account for 49% of the briquette potential. However, a closer discussion is needed since these crop wastes have high moisture and might require a drying process that will increase energy costs [140]. Maize, rice, coconut, sugarcane, cotton, and bean wastes are more suitable for briquette production due to their higher calorific value and combustion efficiency [104].

Briquettes from agricultural wastes might potentially replace 28% to 49% of the departmental firewood demand, estimated at 640 kt/year.

3.2. Potential of Anaerobic Digestion

The agricultural wastes considered have a technical methane potential between 21 and 60 $m^3/t_{biomass}$, which results from considering banana and coffee wastes (Figure 12).

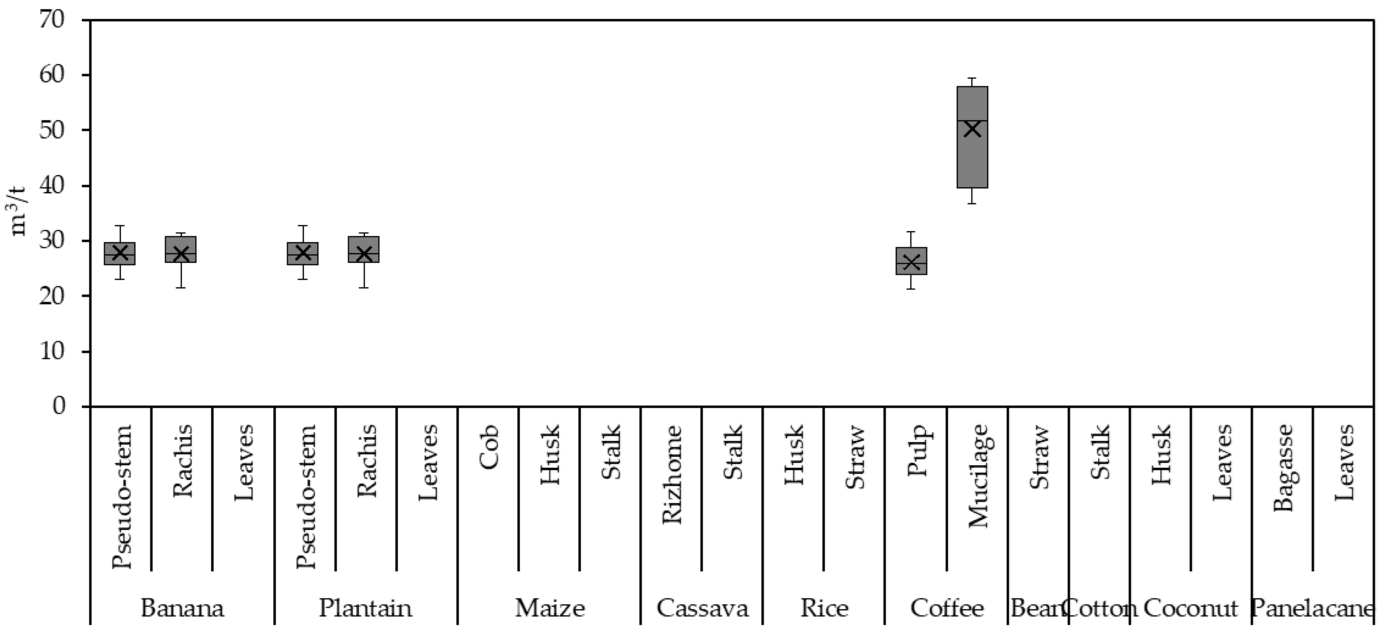

Figure 12. Technical methane potential of biomass wastes for anaerobic digestion.

Agricultural wastes with over 50% moisture show a departmental biochemical methane potential of 8.6 to 10 million m³/year, of which banana and plantain waste account for 90% (Figure 13).

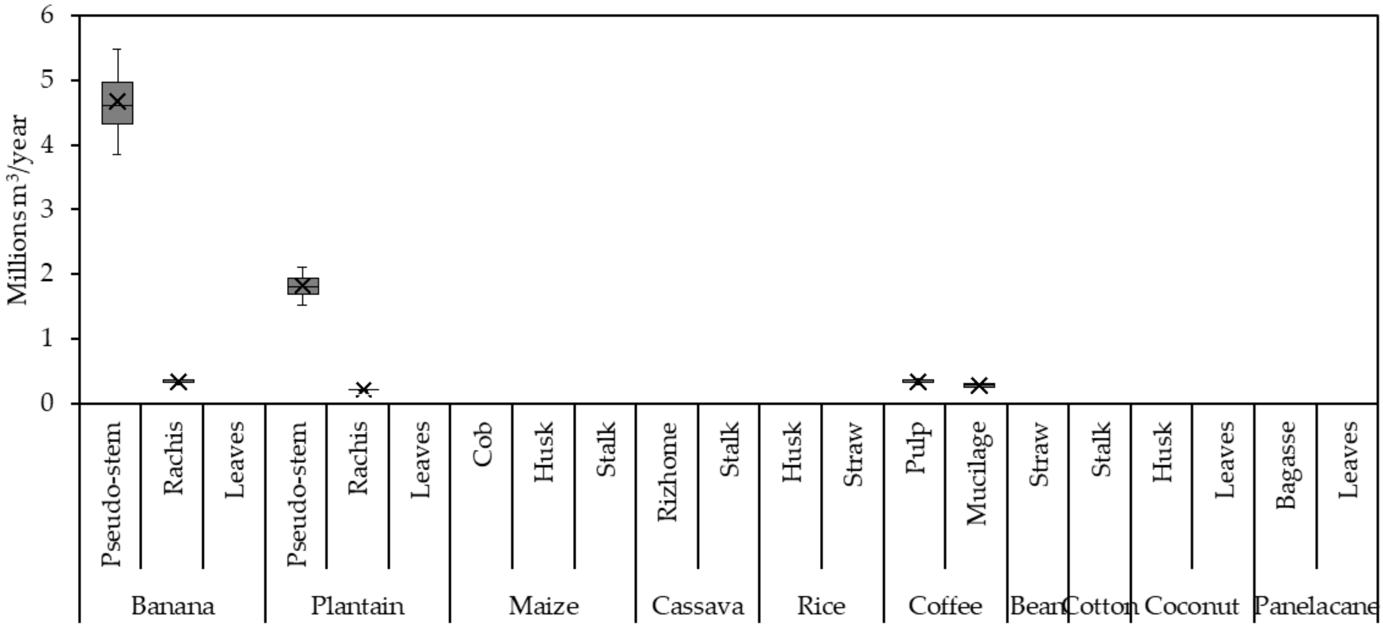

Figure 13. Biochemical methane potential of agricultural wastes.

Discussing the potential applications of biogas to replace firewood as a cooking fuel in rural areas is essential, the extended use of three-stone stoves with firewood with efficiencies of around 4.4% annually demands 334 TJ of useful heat [33], which, using biogas stoves with thermal efficiencies of some 37.2% [33], could be reduced to some 40 TJ/year. All in all, the biogas potential identified could support 16% to 18% of the energy demand for cooking.

Although small-scale digesters with a biogas yield from 0.8 to 1.7 m³/day (i.e., with 50 to 75% of CH_4) demanding a daily supply of 50 kg of biomass have been exploited in Colombia [22,141], several challenges remain before household digesters can be a feasible alternative [142]. Therefore, medium-scale digesters with higher automation and yields are more indicated.

3.3. Direct Combustion Results

The heat potential from the direct combustion of the different agricultural wastes was estimated at 3728 to 4749 kWh/t (Figure 14).

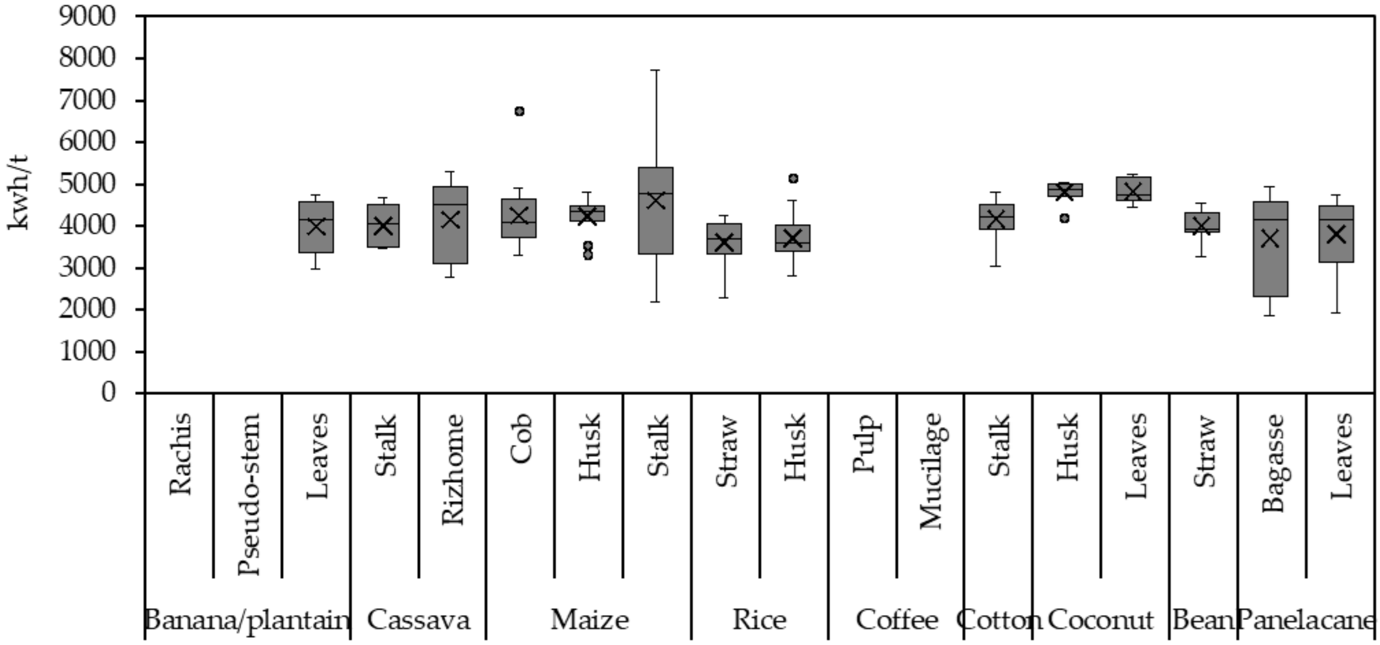

Figure 14. Energy potential of biomass available for direct combustion.

For the electricity potential of agricultural wastes, an electrical efficiency of 28% [143] and a self-consumption rate of 20% by the generation technology [144] were considered (Figure 15).

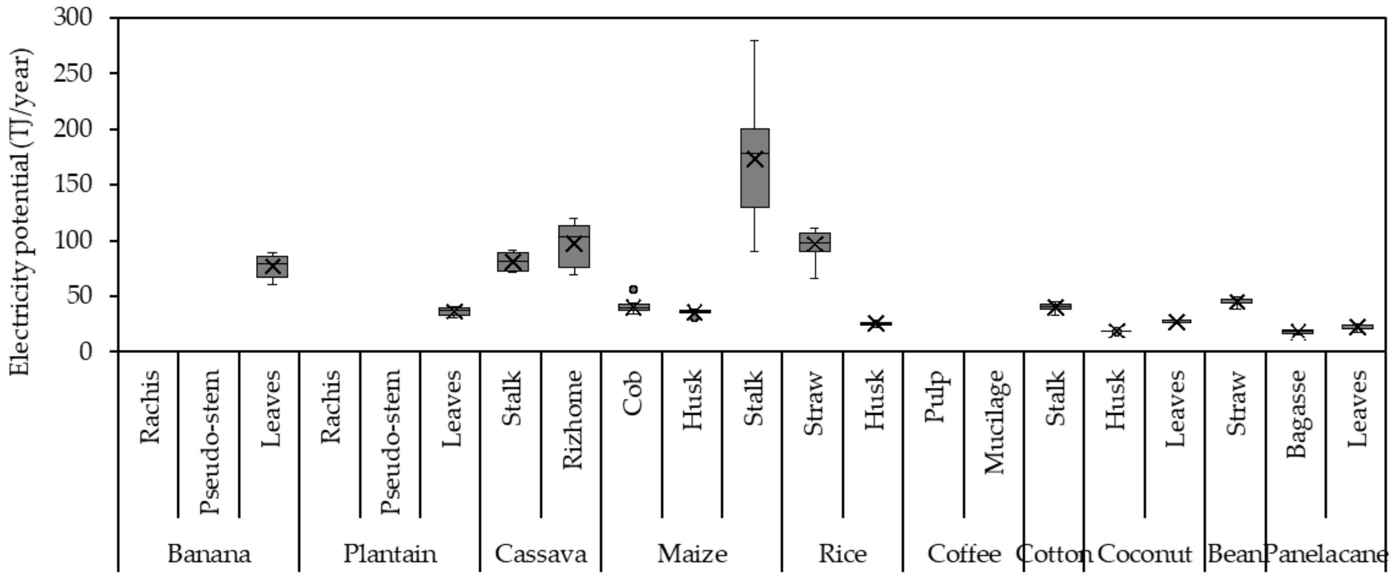

Figure 15. Electricity potential of the available agricultural wastes.

The energy potential from direct combustion is estimated at 1700 to 2325 TJ/year, which could generate from 381 to 521 TJ/year of electricity. This electricity could power electric cooking systems to replace firewood and provide lighting and other services to improve rural areas' quality of life. Electric stoves with 50% efficiency [33] can support 57% to 78% of the firewood demand. However, the geographical dispersity and the seasonality of wastes are significant barriers to electricity generation in this case.

3.4. Potential Energy Clusters

A 5 km radius is considered for clustering different biomass sources (Figure 16) to identify areas with potential for biomass-based energy production.

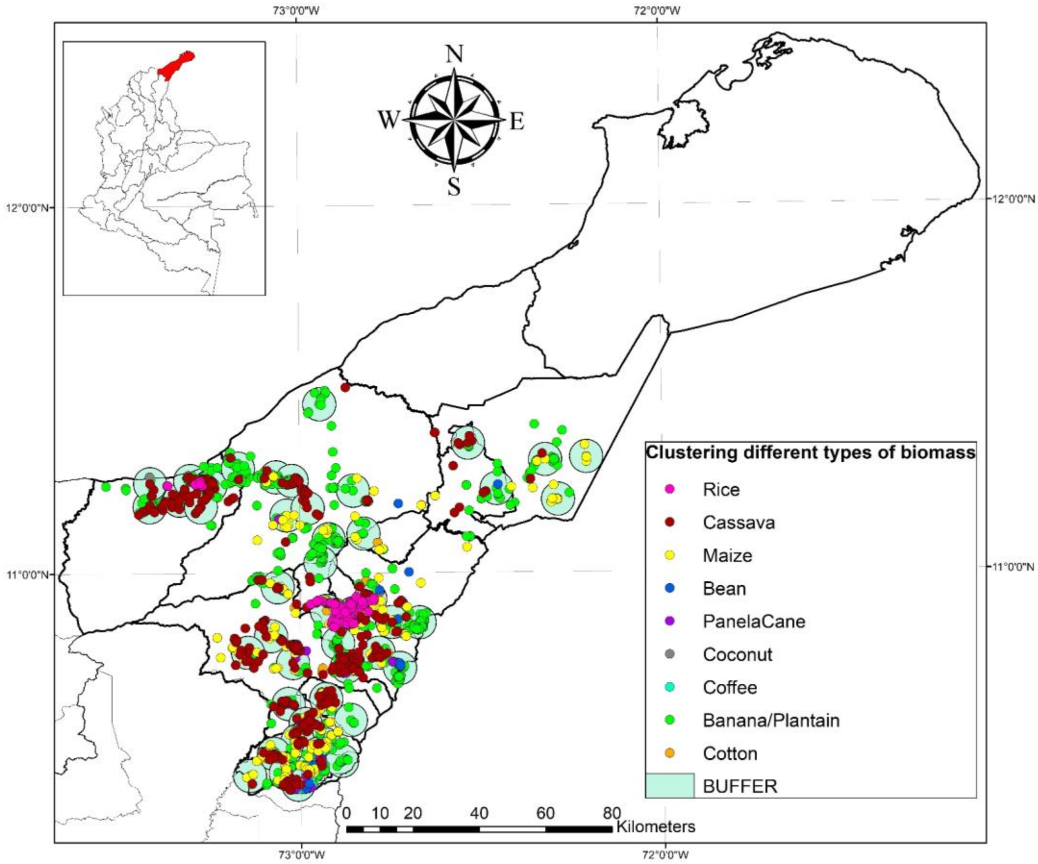

Figure 16. Clustering different types of available agricultural wastes (Source: own elaboration with data from [46,47], and local producer associations).

Forty-seven places with potential for energy clustering have been identified, rising as potential scenarios for implementing biomass-to-energy technologies (Figure 17). Although biomass sources are concentrated near these potential clusters, assessing the feasibility of energy projects in these areas is necessary.

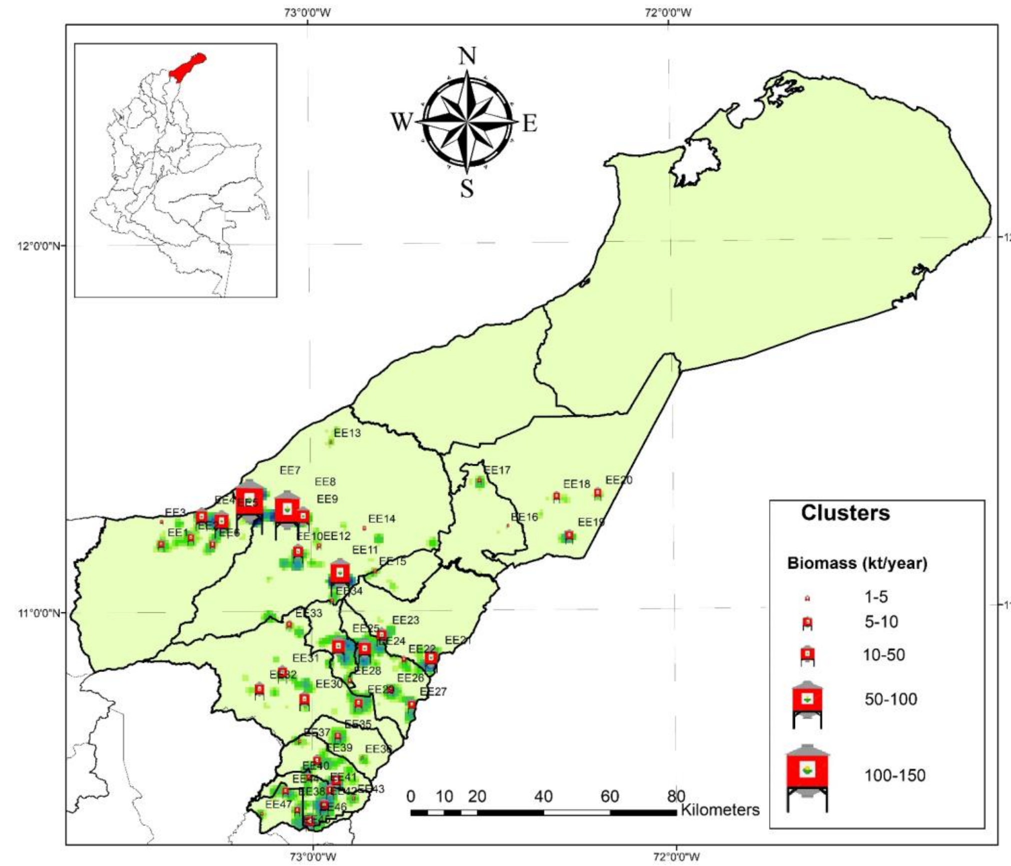

Figure 17. Implementation scenarios.

The results highlight the higher potential for clustering in the south and central municipalities, mainly in Riohacha and Dibulla. Figure 18 shows the available agricultural wastes per scenario.

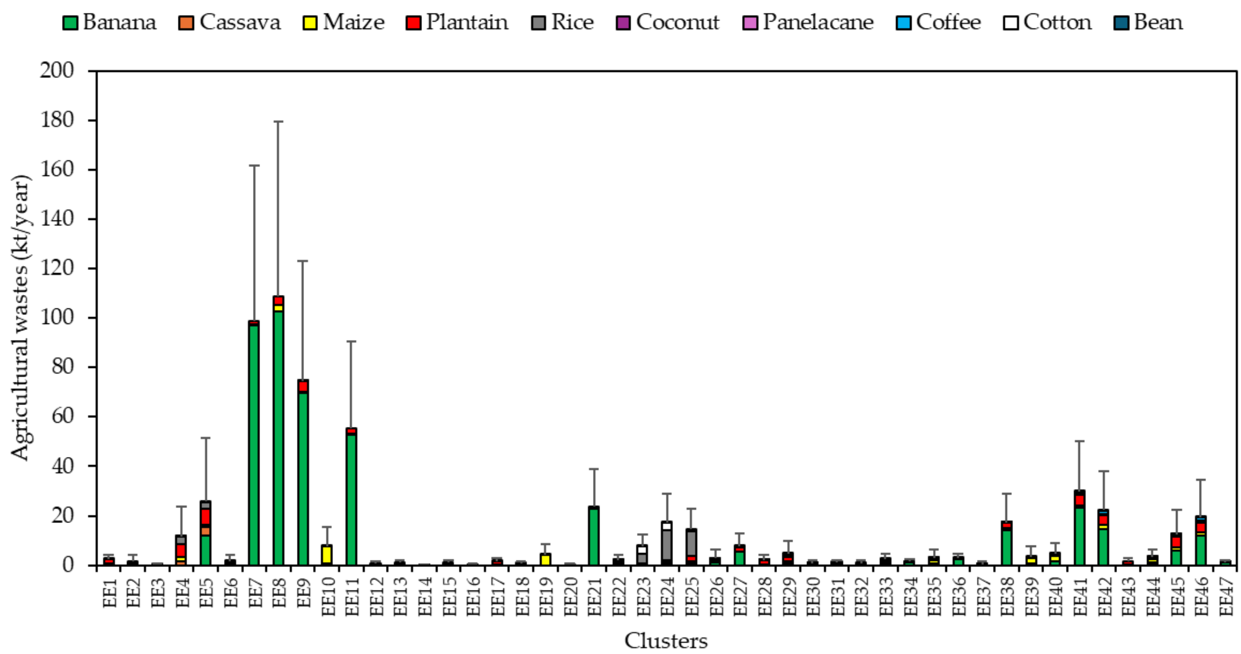

Figure 18. Availability of agricultural wastes by scenario.

The identified scenarios highlight a potential for valorizing agricultural wastes using direct combustion, anaerobic digestion, and briquetting. Particularly, direct combustion is ideal in scenarios EE1, EE2, EE4, EE5, EE6, EE7, EE8, EE9, EE10, EE11, EE12, EE18, EE19, EE21, EE22, EE23, EE24, EE25, EE26, EE27, EE29, EE30, EE31, EE32, EE33, EE35, EE36, EE37, EE38, EE39, EE40, EE41, EE42, EE43, EE44, EE45, EE46, and EE47 due to the abundance of lignocellulosic wastes like maize, cassava, rice, and cotton, characterized by low moisture content and high energy density. On the other hand, anaerobic digestion is more indicated in scenarios EE4, EE5, EE7, EE8, EE9, EE11, EE18, EE21, EE22, EE25, EE26, EE27, EE29, EE33, EE36, EE38, EE40, EE41, EE42, EE43, EE44, EE45, EE46, and EE47 due to the abundance of high moisture content wastes like banana, plantain, and coffee, ideal for biogas production. Finally, briquetting is suitable for scenarios EE2, EE4, EE5, EE7, EE8, EE9, EE10, EE11, EE12, EE18, EE19, EE21, EE22, EE23, EE24, EE25, EE26, EE27, EE29, EE30, EE31, EE32, EE33, EE35, EE36, EE37, EE38, EE39, EE40, EE41, EE42, EE43, EE44, EE45, EE46, and EE47, where low moisture content wastes like maize, rice, and cotton are abundant, making them optimal for compaction and densification.

In some scenarios (e.g., EE2 and EE4), the suitability of briquetting and direct combustion coincides. Therefore, which approach is more indicated in each case must be defined on a cluster-by-cluster basis. Clustering permits the valorization of 48% to 50% of the department's agricultural biomass wastes for domestic use. Expanding the clustering radius to 10–20 km significantly increases the potential, although this option would be more feasible for biomass plants than for domestic use.

Energy Clusters to Replace Firewood in Rural Areas

Table A2 in Appendix B shows the evaluation of each scenario, considering each energy cluster as a potential location for domestic biomass plants. This assessment comprehensively analyzes each scenario's characteristics and viability for implementing biomass utilization technologies to replace firewood demand.

In the evaluated scenarios, briquetting technologies can substitute the firewood demand of 6487 to 7245 households (i.e., 5.1% to 5.7% of the households currently depending on firewood in La Guajira). In scenarios EE3, EE6, EE13, EE14, EE15, EE16, EE17, EE20, and EE28, replacing 100% of the domestic firewood demand with briquettes within the clusters is unfeasible (see Figure A2 in Appendix A).

Anaerobic digestion technologies can replace the demand for firewood in 3560 to 3721 households (i.e., in some 3% of the households relying on firewood in La Guajira). In the scenarios EE1, EE2, EE3, EE6, EE10, EE12, EE13, EE14, EE15, EE16, EE17, EE19, EE20, EE23, EE24, EE28, EE30, EE31, EE32, EE34, EE35, EE37, and EE39, it is unfeasible to replace 100% of the domestic firewood demand within the clusters with anaerobic digestion technologies (see Figure A3 in Appendix A).

Direct combustion can replace the demand for firewood in 7032 to 7365 households (i.e., between 5.5% and 5.8% of the households relying on firewood in La Guajira). In scenarios EE3, EE13, EE14, EE15, EE16, EE17, EE20, EE28, and EE34., it is unfeasible to replace 100% of the demand for domestic firewood with direct combustion technologies (see Figure A4 in Appendix A).

In indigenous reserve areas, no biomass residues are available to replace firewood. Although the department's clustering potential is low, it could reduce the externalities associated with firewood consumption with estimated annual benefits ranging from COP 8.4 to COP 9.4 million using briquetting technologies, COP 9.1 to COP 9.5 million using direct combustion, and COP 4.6 to COP 4.8 million using anaerobic digestion.

Moreover, a clustering radius of 10 to 20 km has a higher potential, yet this is only feasible for biomass plants rather than households.

3.5. Greenhouse Gas (GHG) Emissions Savings

When using biomass and other fuels such as firewood, charcoal, LPG, and natural gas as energy sources for cooking, it is essential to consider the associated environmental impact, particularly regarding GHG emissions, which play a crucial role in global climate change.

Table 5 shows the GHG emission factor for different cooking fuels used in this study [42,145].

Table 5. Emission factor of selected cooking fuels.

Emission Factor	Briquettes	Firewood	Charcoal	Biogas	LPG	Electricity
CO_2 (t_{CO2}/TJ)	65.36	89.5	88.1	84.4	67.2	55.3
CH_4 (kg_{CH4}/TJ)*	2	30	1	1	1	3
N_2O (kg_{N2O}/TJ)*	0.7	4.0	1.5	0.1	0.3	1
CO_{2eq} ($t_{CO2eq.}$/TJ)*	66.5	91.4	88.5	84.4	67.2	55.4

* Equivalent CO_2 of CH_4 (28 $kg_{CO2eq.}$) and N_2O (265 $kg_{CO2eq.}$) [146].

Given briquettes' higher energy density, combustion emissions are higher than other energy sources.

Since the department's GHG emissions from cooking with firewood are higher than the potential emissions from biogas, briquettes, or electricity, replacing firewood can reduce GHG emissions in La Guajira (Figures 19–21).

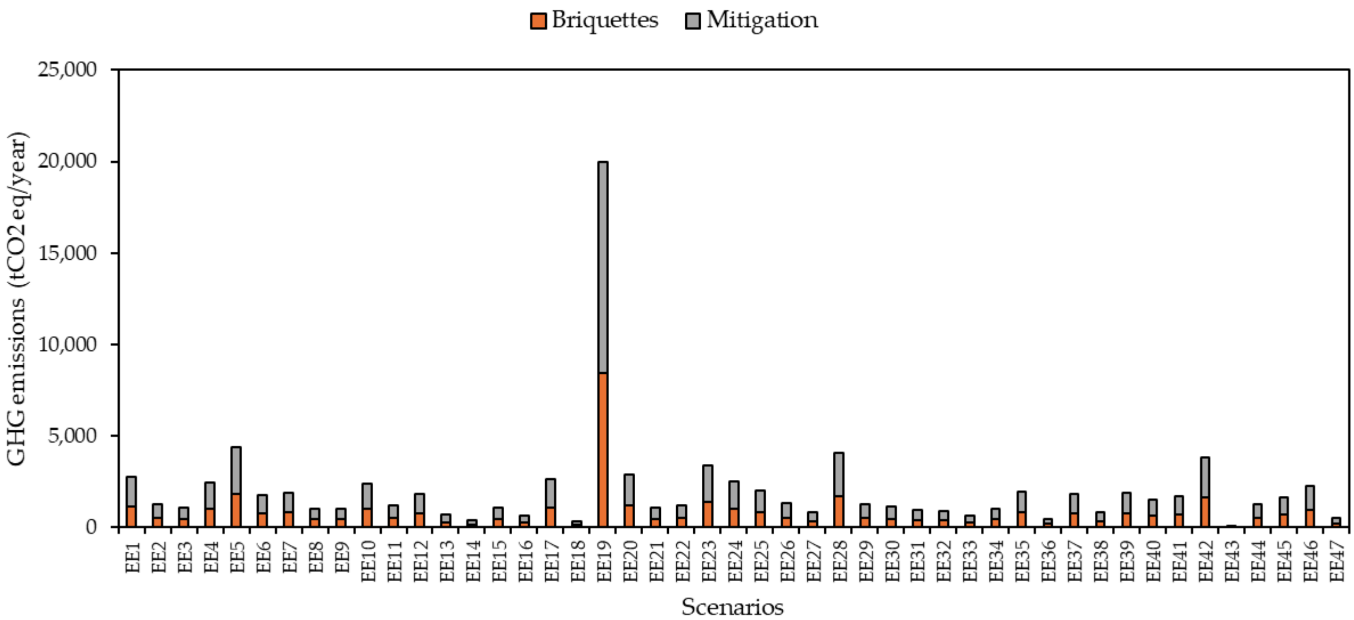

Figure 19. Estimated GHG emissions from briquettes-based cooking to replace firewood.

Using briquettes could reduce GHG emissions by 51,522 to 57,542 $t_{CO2eq.}$/year, corresponding with 59% to 66% of the current emissions estimated from firewood.

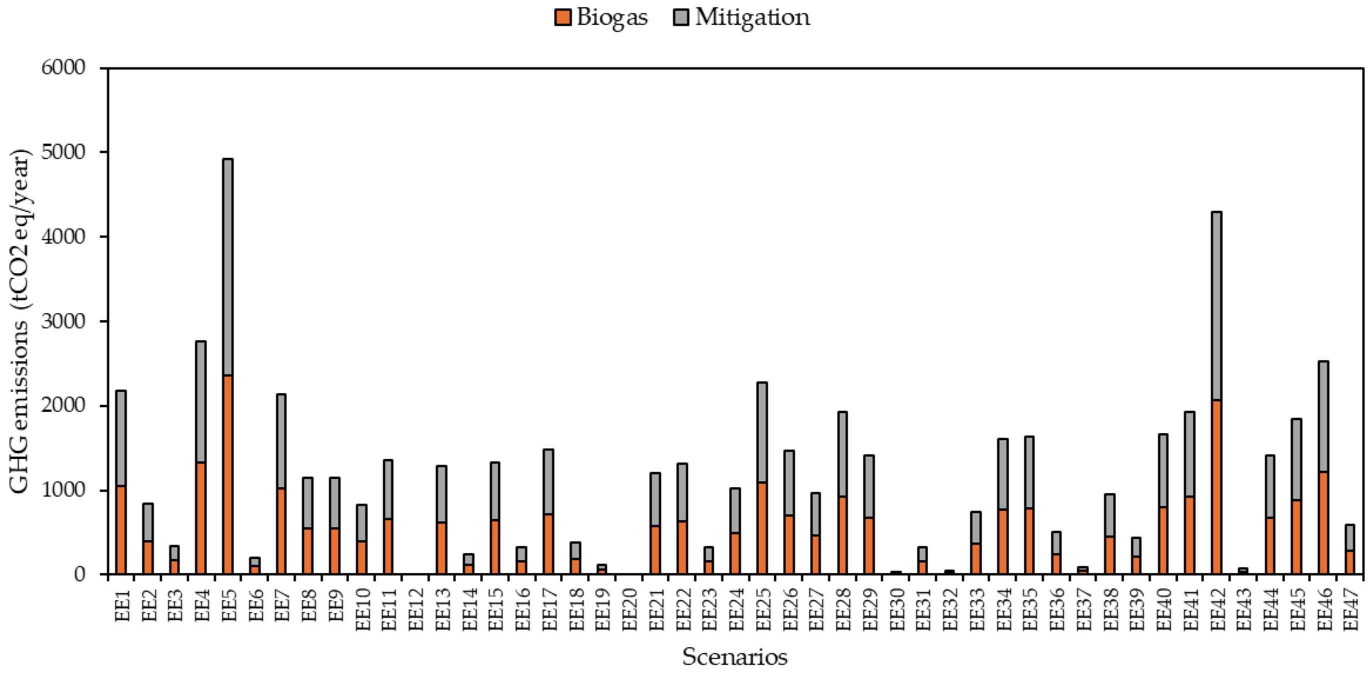

Figure 20. Estimated GHG emissions from biogas-based cooking to replace firewood.

Biogas can reduce GHG emissions by 28,277 to 29,554 $t_{CO2eq.}$/year, equivalent to reducing GHG emissions to 33% to 34% of the current emissions estimated for firewood.

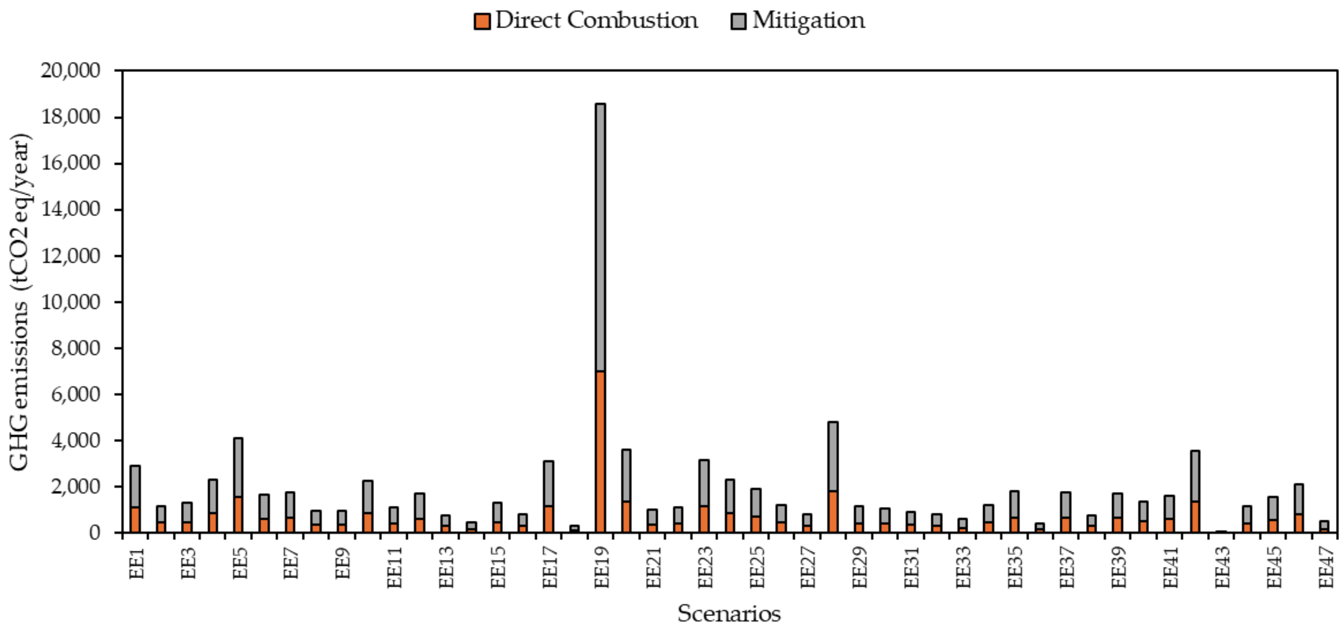

Figure 21. Estimation of GHG emissions of electricity from direct combustion technologies to replace firewood.

Direct combustion can reduce firewood's GHG emissions by 55,852 to 58,495 $t_{CO2eq.}$/year (i.e., 64% to 67% of the current emissions from firewood).

3.6. Mitigation of PM Emissions

Mitigation of PM emissions is achieved by substituting firewood with the evaluated technologies (Figure 22).

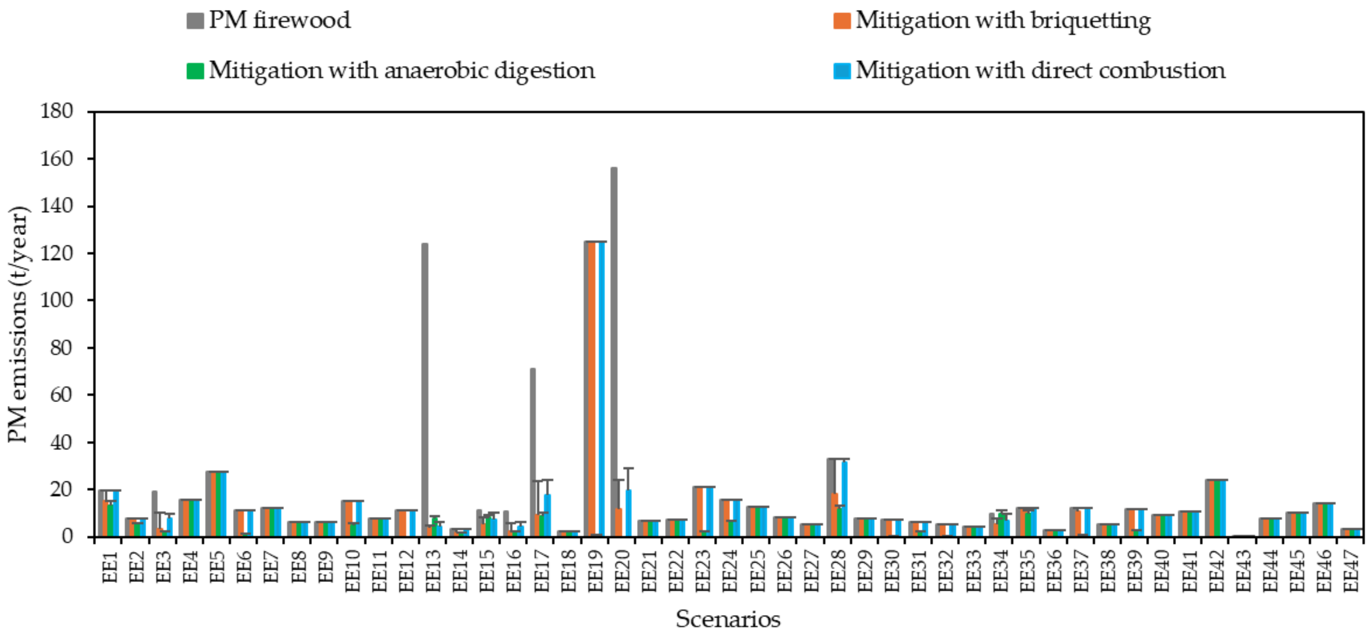

Figure 22. Mitigation of PM emissions through the substitution of firewood with the studied energy alternatives.

Using direct combustion technologies to generate electricity can reduce between 64% and 67% of the yearly 940 tons of PM emissions from firewood cooking. Furthermore, biogas from anaerobic digestion could reduce particulate matter by 34% to 35%, while briquettes could reduce between 59% and 66% of PM emissions. These alternatives provide significant solutions for reducing pollutant emissions and improving air quality in the region, especially in rural areas where firewood use is predominant.

3.7. Assessment of the Technology Performance

Table 6 shows the evaluation criteria used in assessing the performance of the alternative options to firewood.

Table 6. Assessment of the technology performance.

Criteria	Parameters	Technologies			Reference
		Anaerobic Digestion	Direct Combustion	Briquetting	
Technical	Useful energy (TJ/year)	13.5–14.1	26.7–28.0	24.7–27.5	Own elaboration
Economic	LCOE (USD/kWh)	0.06–0.15	0.07–0.29	0.096–0.106	[147–156]
	Economic savings from replacing firewood. (10^6 USD/year)	4.6–4.8	9.1–9.5	8.4–9.4	Own elaboration
Environmental	GHG emissions (kg_{CO2eq}/kg_{wastes})	0	1–3	1.6	[157–160]
	PM into the atmosphere (mg/kg_{waste})	0	1	1	
	GHG mitigation (t_{CO2eq}/year)	28,277–29,554	55,852–58,495	51,522–57,542	Own elaboration

	Mitigation of PM emissions (t/year)	320–334	604–633	558–623	Own elaboration
Social	Stakeholders' acceptance (Completely Acceptable, Difficult to Accept, Rejection).	Acceptable	Acceptable	Acceptable	[161–163]
	Households that could replace firewood	3,721–3,560	7,032–7,365	6,487–7,245	Own elaboration

Figure 23 compares the technologies shown in Table 6 based on technical, economic, environmental, and social aspects.

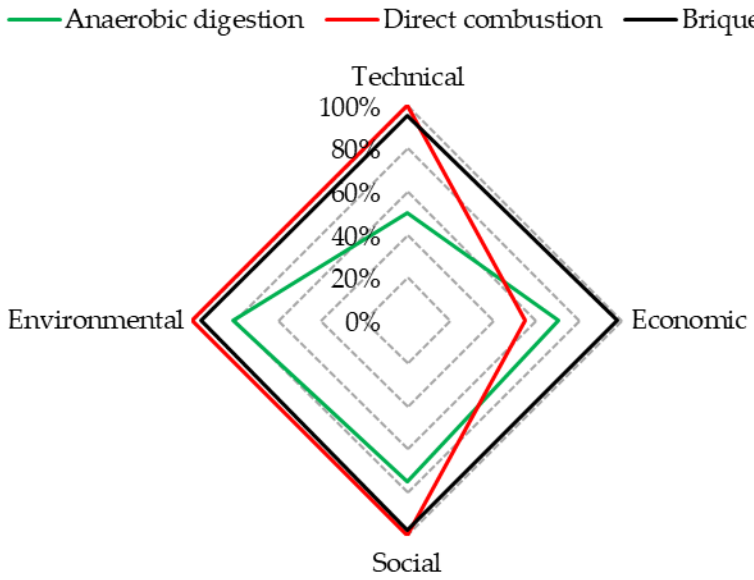

Figure 23. Performance evaluation criteria.

The results show that direct combustion stands out for its high technical and social performance, with the highest energy potential to benefit most households. However, its economic performance is limited, with an LCOE ranging from 0.07 to 0.29 USD/kWh, the highest among the evaluated technologies.

On the other hand, anaerobic digestion has the lowest technical and social impact due to its low energy production and limited capacity to replace firewood. However, it stands out for its excellent environmental performance, generating low particulate emissions and greenhouse gasses, establishing it as the most eco-friendly alternative. These results must be carefully considered when implementing anaerobic digestion in clusters where this technology is competitive with direct combustion and briquetting.

Briquetting, on the other hand, balances the different criteria, offering considerable energy production, good environmental performance, and positive economic and social impact. Its sustainability, cost-effectiveness, and ease of implementation make it the most balanced option for replacing firewood.

4. Discussion

Some studies in Colombia have discussed the bioenergy potential of biomass [23,56,73,164–166]. However, these studies did not consider the geolocation of biomass, limiting their ability to accurately highlight the potential of biomass as a fuel source for residential, transportation, industrial, or other applications.

Geographic information system (GIS) methods have shown that 5.1% to 5.7% of the 127,364 households relying on firewood in La Guajira (i.e., between 6487 and 7245 households) have sufficient agricultural wastes to replace firewood using briquetting technologies. Moreover, direct combustion technologies could benefit 7032 to 7365 households, while anaerobic digestion technologies could be used in between 2.8% and 2.9% of the households. These findings highlight the need to discuss alternatives to firewood further.

No biomass potential exists to replace firewood in indigenous reservations where no agricultural activity occurs. Transporting biomass from 'Baja Guajira' to 'Alta y Media Guajira' is unfeasible since it involves moving biomass over 50 km, which is over the economic and environmental feasibility limit defined in the literature [117–121]. In the indigenous reservations of "Alta y Media Guajira", housing 91% of the Wayuu population, the dispersion of indigenous communities further complicates access to clean and modern energy [15].

Since the characteristics of agricultural wastes vary with the crops, energy solutions must be tailored for every location. Figure 24 shows the areas more suitable for biomass combustion and briquetting.

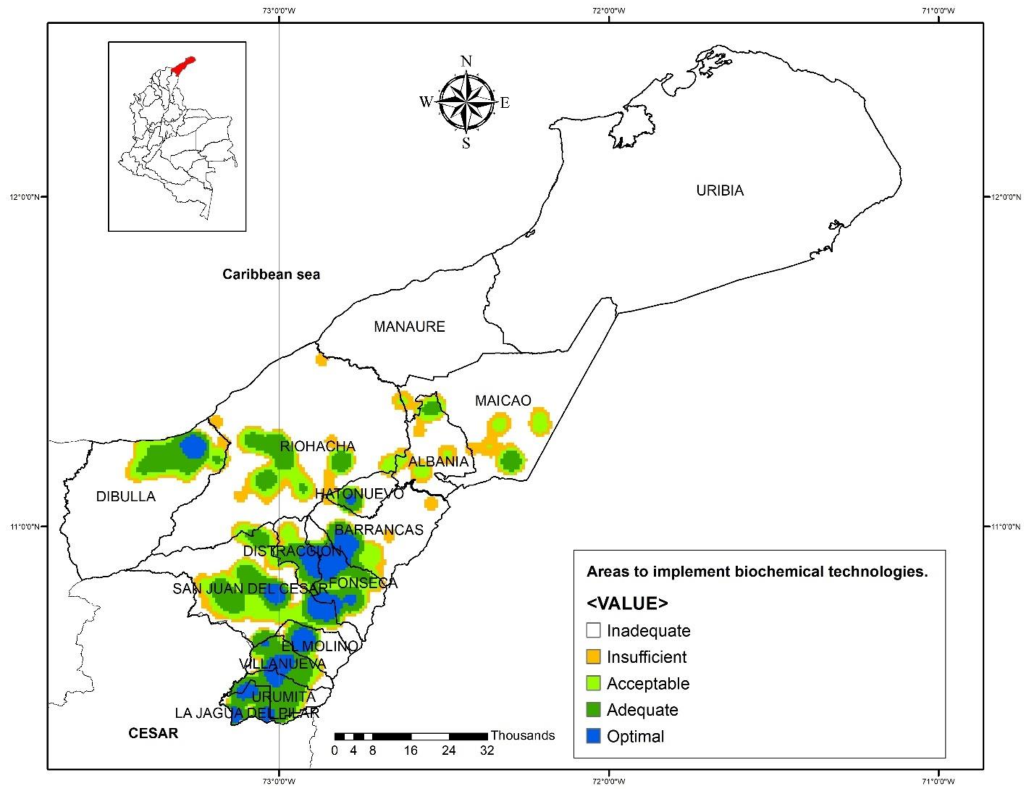

Figure 24. Areas to implement thermochemical technologies.

The figure shows that some locations in Baja Guajira have optimal conditions for thermochemical technologies, which should be discussed in more detail in further studies to assess the possibility of exploiting biomass plants in energy clusters.

Figure 25 identifies areas adequate for implementing anaerobic digestion.

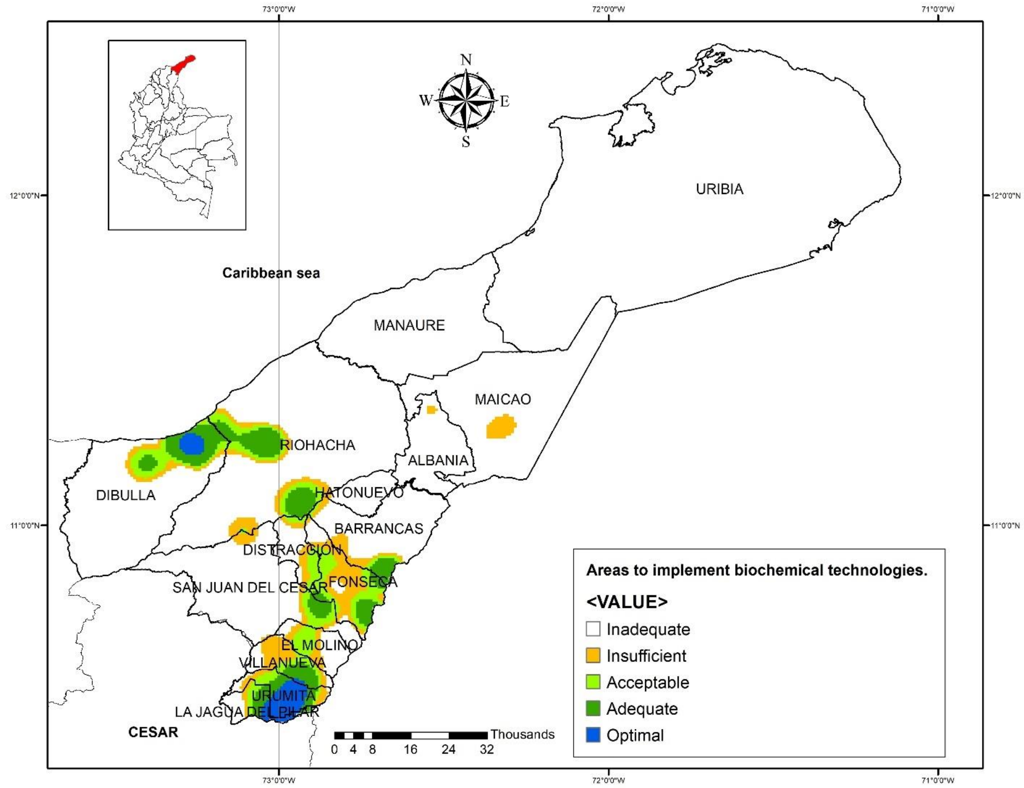

Figure 25. Areas to implement biochemical technologies.

The figure shows two locations optimal for anaerobic digestion and some with adequate biomass availability. Thus, biomass combustion and briquetting generally have a higher energy potential in the department.

Overall, 36% of agricultural waste is generated far from firewood-demanding communities, particularly for indigenous communities. However, there is a potential to reduce energy poverty in the department. Yet, governmental support is required to develop adequate policies and invest in infrastructure and projects to exploit the energy potential of agricultural wastes. It is essential to foster collaboration between stakeholders like farmers and local authorities to ensure the success of these initiatives. Exploiting the technical potential of biomass sources faces several barriers in Colombia [167]:

- High capital cost: Direct combustion technologies have a capital cost ranging from 800 to 4500 USD/kW, which is only possible through subsidies in La Guajira [168]. Furthermore, the taxes for importing technologies further affect these investments [169].
- Insecurity: the possibility of armed attacks in rural areas hinders investments.
- Poor coordination between public and private agencies.
- Energy infrastructure: non-interconnected zones (ZNI) in La Guajira highlight a shortage of energy infrastructure. In the department, 78% of the population has access to electricity, which reduces to 9 and 15% in Uribia and Manaure, with the highest demand for firewood [170].

5. Conclusions

The departmental demand for firewood for cooking is estimated at 640 kt per year, corresponding to some 4242 hectares of forest deforestation. This study shows that using agricultural biomass wastes and more efficient technologies can significantly reduce this issue. Briquette stoves could reduce the energy demand from traditional three-stone firewood cooking by 27% to 47%. Similarly, biogas from anaerobic digestion could decrease the demand for firewood from 10% to 12%. In comparison, direct combustion technologies for medium-scale electricity production combined with electric stoves could reduce it by between 55% and 75%. Given the scale, economic costs, and efficiencies of the technologies discussed, briquetting surfaced as the most indicated alternative for cooking with biomass waste fuels.

Some 47 potential energy clusters were identified considering a 5 km radius where agricultural biomass wastes overlap with firewood-demanding communities. Depending on their characteristics, the clusters where the different technologies discussed can be implemented are as follows:

- Direct combustion: scenarios EE1, EE2, EE4, EE5, EE6, EE7, EE8, EE9, EE10, EE11, EE12, EE18, EE19, EE21, EE22, EE23, EE24, EE25, EE26, EE27, EE29, EE30, EE31, EE32, EE33, EE35, EE36, EE37, EE38, EE39, EE40, EE41, EE42, EE43, EE44, EE45, EE46, and EE47.
- Anaerobic digestion: scenarios EE4, EE5, EE7, EE8, EE9, EE11, EE18, EE21, EE22, EE25, EE26, EE27, EE29, EE33, EE36, EE38, EE40, EE41, EE42, EE43, EE44, EE45, EE46, and EE47.
- Briquetting: scenarios EE2, EE4, EE5, EE7, EE8, EE9, EE10, EE11, EE12, EE18, EE19, EE21, EE22, EE23, EE24, EE25, EE26, EE27, EE29, EE30, EE31, EE32, EE33, EE35, EE36, EE37, EE38, EE39, EE40, EE41, EE42, EE43, EE44, EE45, EE46, and EE47.

It is observed that some clusters (e.g., EE4, EE5) can support more than one technology. Therefore, a more detailed analysis is needed to define the best alternative.

The methodology developed in this study can be used in other regions of Colombia or globally, facing similar challenges to identify existing potentialities. Identifying the energy potentialities will improve energy sustainability, reduce deforestation, and mitigate climate change towards widespread access to clean energy.

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Appendix A. Figures

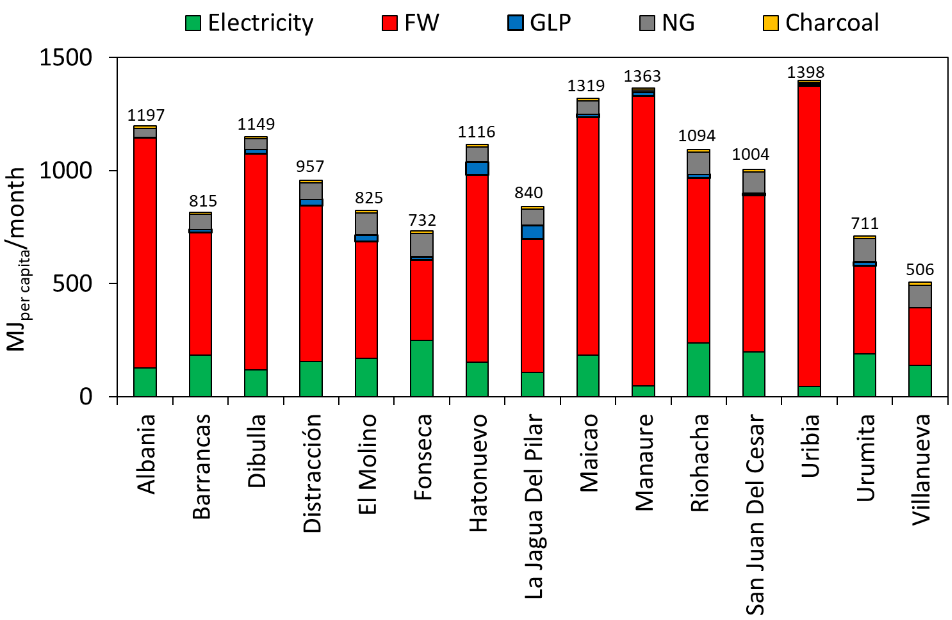

Figure A1. Consumption per capita by municipality [15,32].

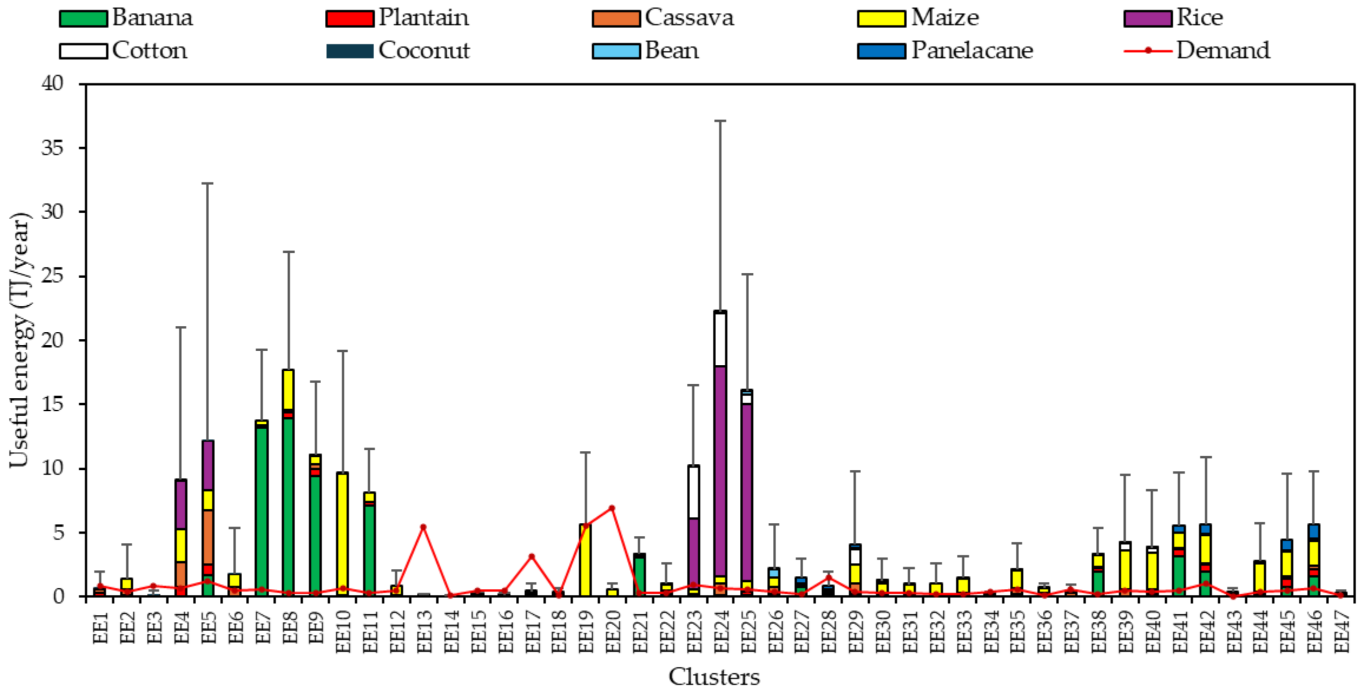

Figure A2. Useful energy potential for replacing firewood with briquetting technologies.

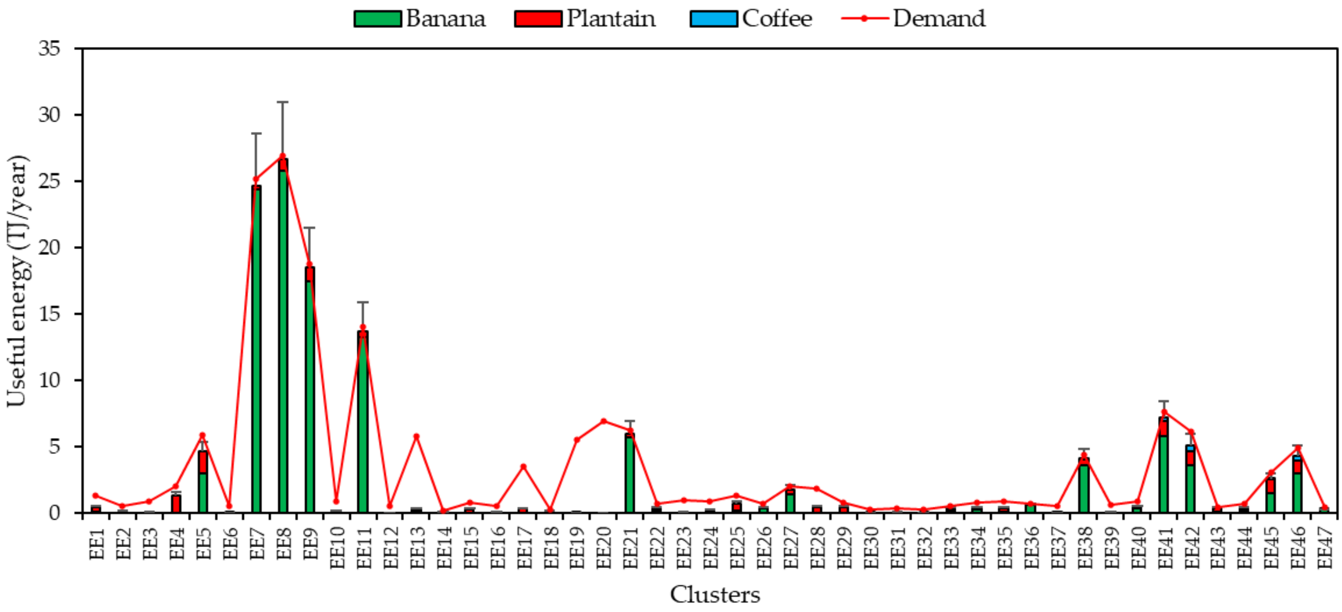

Figure A3. Useful energy potential for replacing firewood with anaerobic digestion technologies.

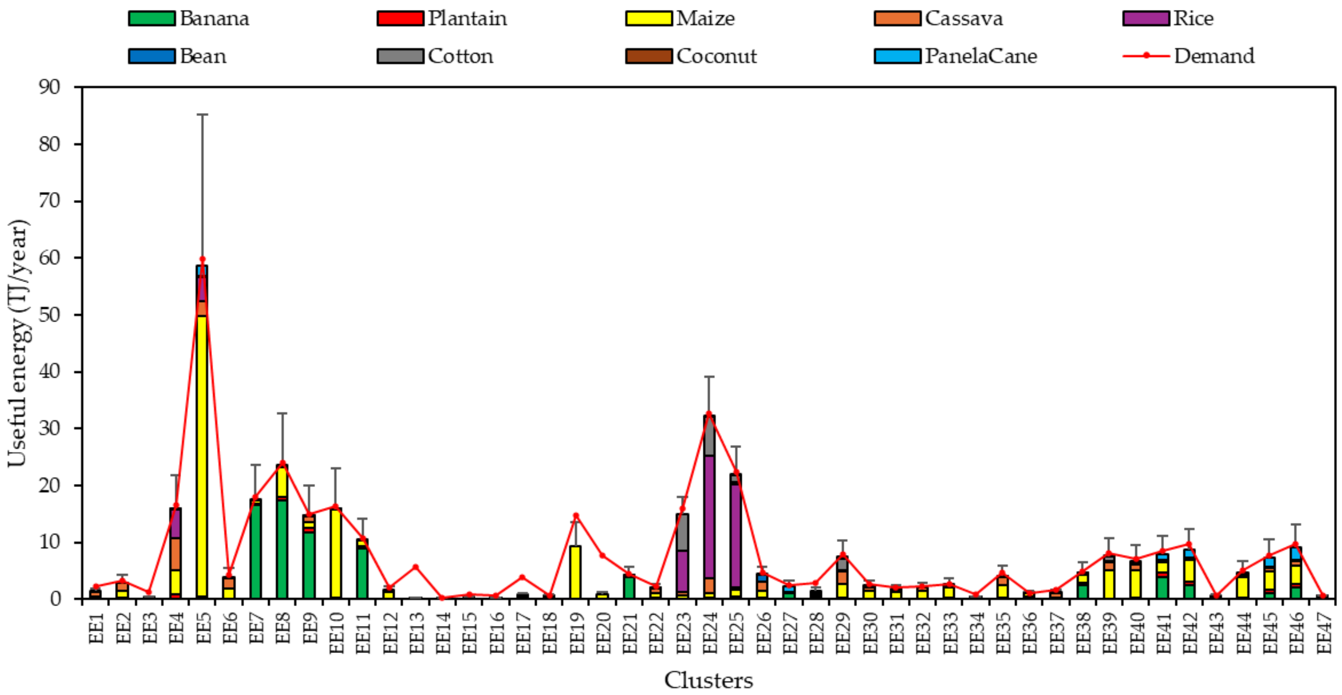

Figure A4. Useful energy potential for replacing firewood with direct combustion technologies.

Appendix B. Tables

Table A1. Characterization of agricultural biomass wastes.

Crop	Waste	Lignocellulosic Components (%)			Physicochemical Properties (%)				Heating Value (MJ/Kg)		Reference
		X_H	X_H	X_H	MC	MV	Ash	CF	LHV	HHV	
Banana/Plantain	Pseudo-Stem	20.20	35.20	13.90	92.40	-	-	-	-	-	[171]
		25.36	38.48	5.77	79.80	89.43	9.36	1.21	13.63	15.04	[83]
		23.50	32.50	13.00	-	-	-	-	-	-	[172]
		-	-	-	-	-	-	-	13.63	16.16	[173]
		-	-	-	-	76.00	19.00	5.00	12.96	15.60	[174]
		14.98	32.50	15.07	-	80.60	12.50	6.90	10.80	12.40	[80]
		29.05	38.36	17.81		76.50	8.64	14.86	-	-	[175]
		19.62	60.84	17.26	-	-	-	-	-	-	[82]
		36.09	49.12	8.22	-	-	-	-	-	-	[176]
		16.00	54.00	21.00	90.00	88.80	-	-	-	-	[79]
	Rachis	11.20	23.00	10.80	-	-	29.90	-	-	-	[76]
		10.20	26.40	9.40	-	-	26.60	-	10.00	-	[77]
		22.30	36.50	26.2	93.58	-	-	-	-	-	[78]
		8.80	32.10	19.0	93.60	-	23.0	-	12.88	13.53	[165]
		9.80	26.20	8.60	-		9.95	-	-	-	[75]
		-	-	-	-	57.78	26.02	5.73	11.22	-	[177]
		-	-	-	-	59.30	5.24	19.59	9.91	-	[178]
		17.00	53.00	16.00	93.60	79.10	11.00	8.80	11.17	14.40	[179]
		10–20	37.81	10–20	-	70.5–75.2	17.3–22.7	-	10.9–12.8	14.5–15.7	[180]
	Leaves	34.34	43.34	15.00	-	-	12.40		-	-	[75]
		32.59	29.39	15.35	-	-	-	-	-	-	[181]
		12.80	21.90	21.50	-	-	15.70	-	16.50	-	[77]
		25.8–28.5	26.7–53.5	15.4–17.0	12.38	77.79	10.90	11.31	14.69	15.90	[84]
		-	-	-	40.0	-	-	-	11.37	12.12	[68]
		26.70	25.80	17.00	7.80	78.20	6.20	15.60	15.60	17.10	[182]
									15.73	17.51	[48]
		23.46	35.58	10.58	6.67	83.35	9.05	7.60	16.16	17.57	[83]
		14.63	31.40	22.36	7.46	78.13	7.47	7.48	-	17.22	[183]
Maize	Cob	34.00	46.00	17.00	-	-	1.35	-	-	-	[184]
		30.14	27.41	21.03	12.72	-	1.94	-	-	-	[64]
		33.12	45.01	13.81	-	-	3.10	-	-	-	[65]
		35.00	45.00	15.00	8.70	-	1.36	-	12.60	-	[53]
		-	-	-	7.53	-	-	-	16.30	-	[68]
		-	-	-	15.00	-	-	-	15.50	18.50	[72]
		-	-	-		80.79	1.81	17.40	17.97	19.34	[67]
		-	-	-	10.52	65.23	7.71	16.54	15.08	16.50	[185]
		-	-	-	9.29	71.83	1.67	17.21	15.51	17.35	[186]
		-	-	-	13.10	67.00	3.50	16.40	17.34	19.30	[187]
	Husk	-	-	-	11.10	-	-	-	17.27	-	[72]
		-	-	-	11.11	-	-	-	15.56	-	[68]
		-	-	-	-	-	-	-	16.37	19.90	[48]
		-	-	-	-	-	-	-	12.6–15.6	-	[70]
		12.72	43.14	23.00	-	-	-	-	-	-	[188]
		25.00	40.00	14.00	7.00	-	-	-	15.96	-	[24]

		35.72	43.14	23.00	12.12	82.66	2.52	7.94	16.60	-	[189]
		24.63	29.19	15.44	-	-	-	-	-	-	[190]
		19.10	39.00	15.10	6.06	75.17	4.30	19.25	16.44	17.65	[191]
		28.10	32.60	16.60	5.90	79.61	9.70	20.39	17.41	18.69	
	Stalk	-	-	-	5.50	71.69	10.10	12.71	17.50		[192]
		-	-	-	6.8	73.1	7.4	12.7	15.30	16.6	[193]
		25.52	49.77	8.69	-	-	-	-	-	-	[194]
		-	-	-	2.86	64.49	6.58	28.93	13.49	-	[95]
		20–30	40–50	10–15	-	-	-	-	-	-	[195]
		21.16	32.32	18.70	-	-	-	-	-	-	[196]
		20.10	37.10	17.10	-	-	4.20	-	-	-	[197]
		-	-	-	3.55	73.93	5.51	17.01	15.74	-	[198]
		30.88	51.53	17.59	15.00	-	-	-	16.30	-	[53]
		21.37	34.65	20.51	-	-	-	-	-	-	[199]
Cassava	Stalk	-	-	-	15.50	79.90	6.00	14.10	-	-	[179]
		-	-	-	8.50	69.70	7.10	14.70	16.80	18.10	[200]
		31.61	33.70	27.04	-	-	-	-	-	-	[201]
		21.12	28.86	30.62	-	-	7.34	-	-	-	[202]
		28.80	22.80	22.10	15.50	79.90	-	-	13.40	-	[56]
		-	-	-	15.50	64.90	4.70	14.40	14.28	15.76	[203]
		24.30	35.20	15.00	-	-	-	-	-	-	[204]
		-	-	-	15.00	-	-	-	16.99	-	[68]
		31.61	33.70	27.04	20.00	-	-	-	13.10	-	[53]
		-	-	-	15.50	79.90	6.00	14.10	17.60	18.00	[205]
	Rizhome	-	-	-	8.30	77.80	4.10	18.20	-	-	[179]
		-	-	-	1.80	81.50	3.60	14.90	18.80	20.30	[206]
		-	-	-	10.60	70.70	5.20	13.50	17.10	-	[52]
		11.00	49.00	20.00	-	-	-	-	-	-	[203]
		13.81	52.52	21.45	-	-	-	-	-	-	[207]
		13.17	48.01	26.31							
		10.57	33.89	23.91	-	-	4.77	-	-	-	[208]
		15–35	40–50	18–35	-	-	-	-	-	-	[209]
		-	-		8.80	65.00	11.20	15.00	15.90	17.10	[200]
		27.80	39.70	21.70	8.30	71.30	3.70	16.70	-	-	[210]
		-	-	-	8.30	77.70	4.10	18.20	18.50	23.70	[205]
		-	-	-	-	81.90	7.30	10.70	20.00	21.70	[211]
		17.00	34.00	28.00	8.30	-	-	-	10.61	-	[24]
		11.07	63.13	25.80	-	-	3.60	-	13.10	-	[53]
		-	-	-	8.60	74.70	0.74	15.96	15.37	-	[212]
Rice	Straw	20.00	32.00	25.00	-	-	-	-	-	-	[184]
		-	-	-	5.60	65.20	12.60	16.60	14.40	-	[213]
		-	-	-	9.8	76.32	13.91	9.08	15.76	-	[93]
		-	-	-	6.43	76.84	10.86	12.30	14.40	-	[214]
		-	-	-	10.29	67.87	8.69	13.15	13.06	-	[156]
		-	-	-	7.93	54.68	19.19	18.2	12.65	13.89	[187]
		18.00	35.00	20.89	-	-	10.20	-	-	-	[215]
		23.73	39.17	21.50	-	71.78	14.41	13.81	-	19.01	[216]
		31.82	37.65	6.18	8.08	69.99	8.79	13.40	14.21	-	[217]
		19.73	33.14	13.1	-	-	-	-	-	-	[218]
		19.7–35.7	32.0–38.6	13.5–22.3	-	-	10 –17	-	-	-	[219]
		-	-	-	-	70.41	13.80	15.79	15.39	-	[217]

		23.0–25.9	29.2–34.7	17.0–19.0	-	-	-	-	-	-	[220]
		30.00	35.00	18.00	-	-	-	-	-	-	[75]
		-	-	-	9.00	70.83	11.07	18.10	16.41	-	[69]
		26.40	38.20	24.10	9.50	63.00	8.10	19.40	12.77	14.37	[221]
		21.30	38.57	21.10	7.73	64.20	12.57	15.50	15.39	-	[217]
		22.0–29.7	28.6–43.3	19.2–24.4	-	-	17–20	-	-	-	[219]
	Husk	-	-	-	-	76.56	9.48	14.02	14.21	-	[222]
		-	-	-	10.1	52.3	14.2	23.4	12.84	14.09	[187]
		21.34	36.06	21.16	-	-	10.99	-	12.90	-	[53]
		12.0–29.3	28.7–35.6	15.4–20.0	-	-	-	-	-	-	[220]
		-	-	-	3.31	69.12	16.20	14.69	11.66	-	[95]
		-	-	-		-	-	-	15.5–17.44	-	[70]
		-	-	-	12.40	-	-	-	12.90	-	[72]
		19.60	21.40	10.20	6.30	72.70	6.20	21.10	16.41	17.30	[223] [224]
		-	-	-	4.50	-	-	-	14.70	-	[53]
Bean	Straw	19.60	21.40	10.20	10.63	69.10	6.80	24.10	15.47	17.60	[225]
		-	-	-	10.00	-	-	-	12.38	-	[68]
		-	-	-	15.00	-	-	-	14.90	-	[72]
		-	-	-	-	-	-	-	14.65	17.20	[70]
		16.00	38.00	16.00	-	75.30	5.93	18.77	16.24	17.46	[191]
		9.20	35.60	-	80–82	-	-	-	-	-	[226]
		2.30	63.00	17.50	-	-	-	-	-	-	[63]
		4.37	25.84	12.46	-	-	-	-	-	-	[227]
		3.60	20.70	14.30	82.44	-	-	-	-	-	[228]
		27.80	43.98	6.88	-	-	-	-	-	-	[229]
		19.03	24.80	19.35	-	-	-	-	-	-	[230]
		28.66	32.56	26.40	-	-	-	-	-	-	[231]
	Pulp	11.00	18.60	17.20	-	-	7.10	-	-	-	[61]
Coffee		7.00	43.00	9.00	15.00	-	2.50	-	15.90	-	[53]
		-	-	-	-	69.48	6.55	21.23	14.95	16.28	[232]
		17.35	20.33	21.04	-	53.19	8.53	33.08	13.49	14.79	[62]
		-	-	-	57.90	34.73 82.50	-	7.19 17.09	8.56	10.65	[191]
		-	-	-	83.60			-	-	-	[233]
		-	-	-	-	-	-	-	12.60	15.90	[70]
	Mucilage	-	-	-	97.56	-	-	-	2.00	-	[59,228]
		20–25	33–45	27–32	-	-	5–9	-	-	-	[184]
		23–32	40	18–23	11.00	85.30	6.70	8.00	17.00	19.40	[234]
		27	46.00	23.00	-	-	1.94	-	17.80	-	[53]
		28–32	25.0–45.0	15.0–25.0	-	-	-	-	-	-	[220]
		-	-	-	50.0	-	-	-	9.30	17.2	[56]
		-	-	-	9.9	76.00	4.00	10.00	13.86	17.32	[235]
Pan-	Bagasse	-	-	-	21.0	82.50	2.50	15.00	17.60	-	[236]
elacane		370	42.00	21.00	50.00	-	-	-	7.50	-	[237]
		-	-	-	5.92	88.40	2.31	9.12	15.96	18.29	[86]
		-	-	-	50.00	79.06	2.94	18.00	16.10	18.50	[87]
		-	-	-	50.00	-	2.20	-	7.50	-	[88]
		-	-	-	50–75	-	-	-	8.6–15.40	-	[72]
		-	-	-	-	-	-	-	17.90	20.00	[70]
	Leaves	-	-	-	6.70	79.00	5.70	8.60	17.00	18.40	[200]

		-	-	-	50.00	-	-	-	15.80	-	[49]
		32.00	39.70	21.70	-	-	4.70	-	-	-	[53]
		32.99	43.55	21.76	40.00	-	-	-	7.40	17.30	[56]
		-	-	-	3.50	76.5	7.4	16.10	16.80	17.80	[89]
		33.28	39.81	21.63	8.42	86.64	3.85	9.51	15.72	18.61	[90]
		30.4–30.8	40.5–44.5	12.3–22.8	-	80.6–84.5	3.7–7.5	11.6–15.7	-	17.40	[91]
		-	-	-	-	-	-	-	17.90	-	[70]
		-	-	-	9.20	68.00	6.10	16.90	-	-	[54]
Cotton	Stalk	-	-	-	7.88	75.18	4.67	20.15	15.94	17.5	[238]
		-	-	-	7.49	61.21	6.18	25.12	15.21	-	[198]
		-	-	-		75.56	6.61	17.83	16.69	17.84	[239]
		-	-	-	4.66	74.96	4.59	15.80	11.63	-	[240]
		-	-	-	4.55	78.61	2.74	18.65	15.97	-	[95]
		-	-	-	8.60	69.90	4.60	16.9	17.06	18.32	[241]
		20–28	32–46	-	-	73.29	5.51	21.20	17.10	-	[85]
		13.70	36.40	25.50	-	-	-	-	-	-	[199]
		16.00	48.70	21.80	6.80	69.83	1.34	22.03	-	-	[242]
		32.00	38.00	21.00	7.00	-	-	-	15.85	17.23	[24]
		20–28	39.85	23.92	8–9	-	-	-	-	-	[243]
		14.40	32.00	24.50	-	-	-	-	-	-	[244]
		11.90	45.50	18.20	-	-	-	-	-	-	[245]
		12.50	43.70	28.60	-	-	-	-	-	-	[246]
		17.40	48.80	25.30	-	-	-	-	-	-	[247]
		-	-	-	12.00	-	-	-	14.6–18.20	-	[72]
Coconut	Husk	25.50	31.60	35.10	-	-	-	-	-	-	[176]
		25.42–27.81	29.58–54.00	25.02–42.00	0.18–11.28	72.60–84.13	0.92–3.95	5.88–15.54	15.83	18.15	[248]
		15.20	37.60	41.30	-	-	2.50	-	-	-	[249]
		-	-	-	-	-	3.10	-	19.02	20.27	[250]
		-	-	-	7.50	85.30	5.30	14.70	-	-	[251]
		-	-	-	8.50	61.50	5.39	-	18.22	19.31	[252]
		17.33	21.26	46.36		-	-	-	-	-	[253]
		-	-	-	7.25	71.01	4.07	17.68	18.00	-	[177]
		-	-	-	10.30	-	-	-	18.60	-	[68]
		20.00	39.00	37.00	10.00	-	-	-	18.62	20.95	[24]
	Leaves/fronds	10.66	56.71	28.44	2.55	83.32	6.97	7.16	17.67	18.37	[254]
		8.45	59.39	27.97	-	-	-	-	-	-	[255]
		22.49	39.05	21.46	-	89.96	4.67	5.37	-	-	[256]
		-	-	-	4.77	80.75	6.33	12.92	19.71	20.83	[257]
		-	-	-	10.49	-	6.17	-	17.95	-	[257]
		31.58	43.91	18.15	7.08	78.03	4.96	17.01	17.77	19.00	[258]
		22.49–31.58	39.05–43.91	18.15–21.46	-	-	4.96	-	-	-	[259]
		-	-	-	4.77–7.08	78.03–87.75	4.96–6.33	12.92–17.01	16.80–19.36	17.77–20.83	[248]

Table A2. Scenario Evaluation.

Scenario	Geolocation		Briquettes	Biogas	Electricity	Firewood Demand	
	Latitude	Longitude	(kt/year)	(10^6 m^3/year)	(TJ/year)	Community	Households
EE1	11.1821	−73.4134	0.08–0.24	0.06–0.07	2.74–3.84	3	227
EE2	11.1998	−73.3311	0.17–0.50	0.02–0.03	5.80–8.39	2	93
EE3	11.2452	−73.4119	0.02–0.05	0.01–0.01	0.67–0.88	2	221
EE4	11.2531	−73.3013	1.12–2.58	0.16–0.19	31.83–43.47	4	181
EE5	11.2388	−73.2460	1.50–3.96	0.57–0.66	46.54–64.04	5	322
EE6	11.1812	−73.2720	0.22–0.66	0.01–0.01	7.54–10.92	4	131
EE7	11.2860	−73.1694	1.69–2.37	3.02–3.50	34.87–47.33	10	140
EE8	11.2618	−73.0646	2.18–3.30	3.26–3.79	47.34–65.33	7	75
EE9	11.2519	−73.0213	1.36–2.06	2.26–2.63	29.33–40.09	7	75
EE10	11.1576	−73.0357	1.17–2.35	0.02–0.03	31.41–46.19	12	176
EE11	11.0921	−72.9201	0.99–1.42	1.68–1.95	20.75–28.32	8	89
EE12	11.1770	−72.9773	0.10–0.25	0.00–0.00	3.08–4.50	9	133
EE13	11.4599	−72.9436	0.02–0.03	0.04–0.04	0.40–0.54	15	1444
EE14	11.2239	−72.8521	0.01–0.02	0.01–0.01	0.25–0.36	5	38
EE15	11.1071	−72.8242	0.03–0.05	0.04–0.04	0.65–0.90	3	130
EE16	11.2284	−72.4559	0.01–0.03	0.01–0.01	0.39–0.56	4	125
EE17	11.3525	−72.5343	0.05–0.13	0.04–0.05	1.57–2.13	3	828
EE18	11.3064	−72.3218	0.04–0.08	0.02–0.03	1.09–1.57	2	25
EE19	11.1981	−72.2871	0.69–1.39	0.00–0.00	18.50–27.21	4	1456
EE20	11.3135	−72.2082	0.07–0.13	0.00–0.00	1.74–2.56	6	1818
EE21	10.8644	−72.6713	0.40–0.57	0.73–0.84	8.39–11.37	3	79
EE22	10.8659	−72.7464	0.12–0.32	0.04–0.05	3.83–5.48	3	86
EE23	10.9291	−72.8070	1.25–2.03	0.01–0.01	29.87–35.91	4	247
EE24	10.8901	−72.8536	2.72–4.56	0.03–0.03	64.05–78.40	3	182
EE25	10.8974	−72.9266	1.97–3.10	0.09–0.11	43.69–53.57	5	149
EE26	10.7822	−72.7844	0.27–0.69	0.04–0.05	8.53–11.50	3	96
EE27	10.7404	−72.7259	0.18–0.37	0.22–0.26	4.45–6.38	3	63
EE28	10.8089	−72.8961	0.10–0.24	0.05–0.06	2.81–3.93	5	383
EE29	10.7456	−72.8719	0.50–1.20	0.05–0.06	15.09–20.64	3	92
EE30	10.7556	−73.0206	0.15–0.36	0.00–0.00	4.54–6.49	3	82
EE31	10.8292	−73.0808	0.11–0.27	0.01–0.01	3.38–4.92	3	72
EE32	10.7843	−73.1447	0.13–0.31	0.00–0.00	3.91–5.71	3	64
EE33	10.9622	−73.0615	0.18–0.39	0.04–0.05	5.08–7.31	3	49
EE34	11.0279	−72.9432	0.03–0.04	0.05–0.05	0.62–0.85	7	113
EE35	10.6575	−72.9298	0.26–0.67	0.05–0.05	8.05–11.62	5	144
EE36	10.5994	−72.8622	0.08–0.14	0.08–0.09	1.99–2.83	3	33
EE37	10.6444	−73.0338	0.06–0.21	0.00–0.00	2.28–3.31	4	140
EE38	10.5343	−72.9349	0.40–0.65	0.51–0.59	9.14–12.77	4	62
EE39	10.5896	−72.9871	0.52–1.17	0.01–0.01	15.04–21.39	4	136
EE40	10.5446	−73.0093	0.47–1.02	0.06–0.07	13.21–18.93	4	109
EE41	10.5084	−72.9517	0.68–1.19	0.88–1.03	15.87–22.39	4	126
EE42	10.4679	−72.9685	0.70–1.33	0.62–0.73	17.23–24.71	6	281
EE43	10.4886	−72.8873	0.05–0.08	0.05–0.06	1.13–1.59	1	5
EE44	10.5089	−73.0750	0.34–0.71	0.05–0.05	9.38–13.47	4	92
EE45	10.4564	−73.0424	0.55–1.17	0.32–0.37	14.49–20.97	3	121

EE46	10.4242	−73.0077	0.70–1.49	0.53–0.62	18.34–26.43	3	165
EE47	10.4489	−73.1407	0.03–0.06	0.03–0.04	0.83–1.13	3	39

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