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Potentialities and Impacts of Biomass Energy in the Brazilian Northeast Region

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Abstract: In Northeast Brazil, the use of biomass for energy generation is settled on traditional productive arrangements, such as a sugarcane production system in the humid Atlantic coastal area and firewood extraction from native tropical dry forests in the west. In parallel, substantial amounts of other biomass sources, such as residues from agricultural or urban processes, are still little used or wholly wasted, fudging the opportunity to generate new value chains based on these biomass sources. We hypothesize that using these non-traditional biomass sources to produce biofuels would significantly increase the regional bioenergy supply. In this context, this article discusses the potential for the production and use of biofuels and bioenergy in Northeast Brazil and its effects on regional development, which may be useful for both private actors and policymakers in the energy sector. The use of biomass sources for energy in the region is significant, reaching approximately 8.8 million tons of oil equivalent (toe) per year, emphasizing the already consolidated production of sugarcane and its derivatives. The use of all biomass resources in the Northeast region could supply around 4% of the Brazilian national electrical energy demand, with an environmental footprint of 0.055 tCO_{2eq} per toe, which would contribute to reducing emissions from the Brazilian energy matrix generation. Regarding the spatial distribution of biomass sources, sugarcane prevails on the coast, firewood and livestock manure in the dryland area towards the west, and municipal solid waste is distributed throughout the region within urban areas. Different from what we expected, the potential energy recovery from municipal waste and animal manure would increase by only 17% the current bioenergy supply. In the future, since the majority of the region presents a semi-arid climate with limited rainfall, to increase the use of biomass as an energy source, there is a need to increase the supply of biomass sources with high efficiency in water use and good yields in drylands. For this, the cultivation and use of cacti and agave, for example, could contribute to making biorefineries viable in the region. Above all, public policies for harnessing bioenergy in NE Brazil must seek opportunities associated with the carbon/decarbonization economy, with studies being needed to assess the technical, economic, social, and environmental viability of future productive arrangements.

Keywords: bioeconomy; biomass resources; bioenergy; regional economy; biomass emissions

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1. Introduction

Humanity's advances have always been linked to its success in collecting and utilizing energy. The strong technological development and world economic growth over the last two centuries were only possible due to the high energy density, abundance, and low cost of fossil fuels. However, the intensive use of fossil fuels has had negative environmental and geopolitical consequences, which have worsened in recent decades [1,2]. As a result, there is a worldwide effort to expand the use of renewable energy sources, with an emphasis on solar, wind, and biomass energy [3].

The world energy supply in 2020 was 13.96 billion tons of oil equivalent (toe), a decrease of 3.82% compared to 2019 (14.52 billion toe). Exhaustible fuels represented 11.86 billion (84.95%) and renewable fuels 2.10 billion toe (15.05%) [4]. Biomass was the renewable resource with the greatest share in the global energy matrix. In 2020, biomass energy was 1.36 billion toe, a share of 9.61% of the world supply [4]. The importance of biomass has been increasing annually, and it is expected to reach 30% of the world's energy supply by 2050 [5].

In Brazil, biomass energy is mainly from the timber sector and the use of waste in the sugar and ethanol industries. The national supply of energy in 2021 was 301.5 million toe, with the transport (28.2%) and the industrial (28.1%) sectors the segments with the greatest demands [6]. Biomass represented about 25% of the internal supply, sugarcane corresponded to 49.4 million toe, and firewood and charcoal to 26.1 million toe. In addition to supplying the primary energy, approximately 8% of the electrical energy was obtained from biomass, with an emphasis on sugarcane bagasse and black liquor [6].

The Northeast Brazilian region has a large dependency on biomass energy, mainly ethanol from sugarcane, produced in the coastal area from the Rio Grande do Norte to Alagoas state, and biodiesel from soy, produced in the Cerrado area of Bahia, Piauí, and Maranhão states. In addition, the semi-arid area has historically depended on firewood and charcoal, both for domestic and industrial uses [7].

Traditional productive arrangements are still active, such as sugarcane and firewood from the semi-arid dry tropical forest native vegetation (known as "caatinga"), but their economic and environmental viability has gradually decreased, threatening their sustainability [8–10]. In parallel, substantial amounts of other biomass sources, such as waste from agricultural or urban processes, are still little used or completely wasted [11,12]. Therefore, there are open opportunities to generate new value chains based on these biomass sources. We hypothesize that using these non-traditional biomass sources to produce biofuels would significantly increase the regional bioenergy supply. In this context, the article discusses the potential for the production and use of biofuels and bioenergy in Northeast Brazil and its effects on regional development, which may be useful for both private actors and policymakers in the energy sector.

This article discusses the current use of biomass energy in the Northeast region of Brazil and the potential use of other biomass sources and their effects on regional development. Traditional resources, such as firewood and sugarcane, were considered, availability based on the potential energy recovery from municipal solid waste (MSW) and animal waste was also analyzed, and the potential of bioenergy crops adapted to dry regions was also discussed. Finally, an evaluation of the impact of biomass use on greenhouse gas emissions in the region was carried out.

2. The Historical Importance of Biomass Sources in the Brazilian Northeastern Economy

Before the arrival of the Europeans, the traditional peoples of the Northeast region used the forests as a source of food, medicinal products, wood to build homes, and making utensils and firewood. The abundant vegetation of the Atlantic Forest made possible the first economic activity carried out by the Europeans in the Brazilian territory: the extraction of wood from "pau-brasil" to obtain a valuable red dye. As colonization progressed, firewood continued to be the primary energy source, as it did in the rest of the world until the last couple of centuries. Sugarcane production substituted "pau-brasil" cutting as the main economic activity, and large areas of the Atlantic Forest were replaced by the crop. The reduction in forest area, the use of firewood in the sugar production process, and the increase in population resulted in an unsustainable extraction and use of biomass, restricting its availability in the last century. Thus, problems related to the unsustainable use of bioenergy are old in this and other regions of the world [13–15].

Sugar production has faced international competition since the end of the 17th century and strong national competition in the 20th century. However, the oil price shock in the 1970s led to a major incentive to produce fuel ethanol for the car fleet, with the establishment of the National Alcohol Program [16]. The program fostered a great expansion of sugarcane, mainly in the Southeast and Midwest regions, but it has remained the main agricultural crop in the coastal area of NE Brazil, from the Rio Grande do Norte to Alagoas state.

The colonization inland, towards the west, in the semi-arid area of the Northeast region, was driven by livestock activity, and the area became the main provider of work animals, meat, and leather to the coastal area. This activity depended on forage biomass produced by caatinga vegetation. Arboreal cotton, with its long fiber, became important from the 18th to the end of the last century, leading to reduced caatinga forest coverage, land fragmentation, and the increased expansion of towns and cities. Caatinga vegetation still covers almost half of the original area, and it is largely used to produce firewood and charcoal for the regional market. The end of the cotton cycle led to a reduction in the per capita production of agricultural biomass, aggravating the poverty situation of most of the population in the semi-arid area.

Therefore, biomass use played an important role in the generation of wealth and the occupation of the regional territory in the first centuries after European colonization, but there has been a gradual reduction in the profitability and/or environmental viability of the production of traditional biomass sources over the last few decades [17]. Without the emergence of new production chains for the use of biomass adapted to new markets, opportunities for strengthening the regional economy will be lost. We expect the discussions in the present paper will contribute to identifying some of these opportunities and suggest options to improve future bioenergy generation in this region.

3. Materials and Methods

3.1. Object of Study

The object of study was the most abundantly available sources of biomass in the Northeast region of Brazil (Figure 1). The Northeast region of Brazil is approximately 1.5 million km^2, encompassing nine states of Brazil; sixty percent of this area has a semi-arid climate hosting the Caatinga biome, a unique and highly biodiverse tropical dry forest ecosystem, nowadays threatened by livestock and fuelwood production [18]. Most of the 40% remaining areas have humid climates composed of the Atlantic Forest and coastal ecosystems. The Atlantic Ocean borders all states of the region, and their soils are rich in mineral resources such as salt, limestone, and granite.

According to the IBGE (Brazilian Institute of Geography and Statistics) data from 2021, the population of the Northeast region of Brazil is approximately 57 million inhabitants, with about 60% of this population living in cities [19]. Despite the significant population, the region has a low Human Development Index (HDI) compared to the rest of the country. The main rural economic activities in the area are agriculture, livestock, and fishing, highlighting sugarcane cultivation, which represents 5% of the ethanol produced in Brazil. Tourism and mining also contribute to the economy of the region. Although the region has made progress in recent years, the poverty rates remain high, and many families struggle to access essential services such as education and healthcare. Recent studies have demonstrated the necessity of improving the infrastructure and creating economic alternatives to promote the sustainable development of the region, especially in rural communities [20]. We believe that investments in the bioenergy sector could contribute to bringing socioeconomic progress to this region.

In the present paper, data on the energy availability from sugarcane were based on the Municipal Agricultural Production (PAM), from firewood based on the Production of Vegetal Extraction and Silviculture (PEVS), and from animal waste based on the Municipal Livestock Survey, all produced by the Brazilian Institute of Geography and Statistics

(IBGE) [19]. Municipal solid waste data were obtained from the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE) [21]. The environmental and social impacts that energy recovery from these resources could represent in the Brazilian scenario were analyzed. Social impacts were qualitatively assessed based on the main individual impacts discussed in the literature.

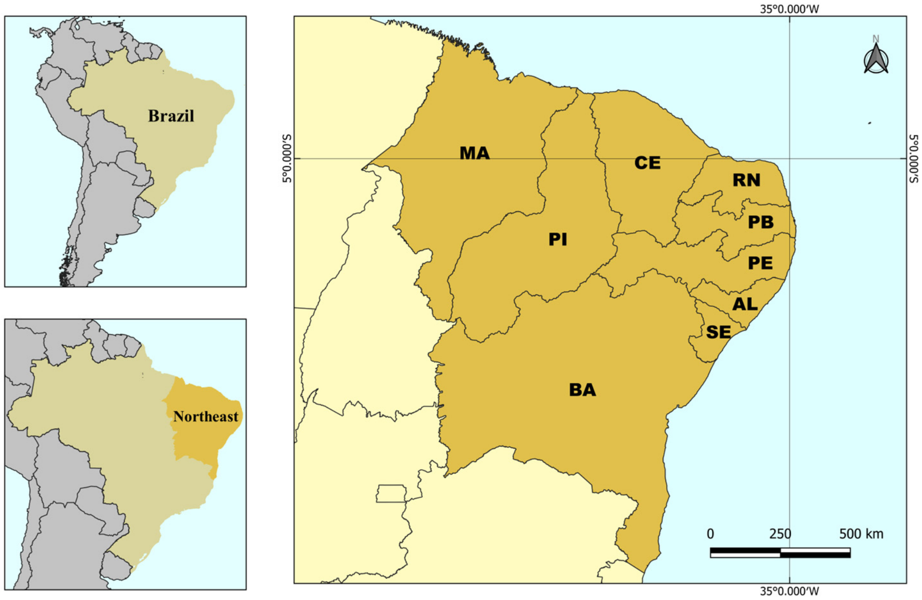

Figure 1. Location of the study region (Northeast Brazil and its respective states). Source: [19].

3.2. Energy Potential Estimates

3.2.1. Sugarcane

Energy products were considered: electricity, ethanol, and biogas. The biomass fractions considered were straw, sugarcane bagasse, and vinasse, obtained from ethanol production.

It was estimated that straw production was 250 kg of dry weight per ton of sugarcane fresh culms, of which only 12.5% can be used for energy generation without causing damage to the cultivation of a new rotation of this crop [22,23]. Sugarcane bagasse with a humidity of up to 50% was estimated to be 280 kg/t of the sugarcane culms [24]. The calorific value of the straw was considered equal to that of sugarcane bagasse at 50% moisture.

According to ÚNICA [25], 58.2% of the sugarcane produced in the Northeast region is destined to produce first-generation ethanol (1G). The production ratio used was 85 L of ethanol per tons of sugarcane. Vinasse, obtained in the 1G ethanol distillation towers, is a byproduct corresponding to 12 L for every 1 L of ethanol produced [26–28]. Biogas can be produced from the biodigestion process of this residual material, 1 m^3 of vinasse (1000 L) generating between 10 and 26.24 m^3 of biogas, with an average of 18.2 m^3 [27]. The energy for each product is shown in Table 1.

Table 1. Energy obtained from the sugarcane biomass fractions.

Fraction	Unit	Energy (MJ)	Toe * $\times 10^{-3}$	Reference
Straw	kg	9.5186	0.227	Silva et al. [29]
Sugarcane bagasse	kg	9.5186	0.227	Silva et al. [29]
Ethanol	L	21.2	0.506	REN 21 [30]
Biogas	m^3	20.92	0.500	Salomon et al. [31]

* The conversion factor from MJ to toe is 2.38846 $\times 10^{-5}$, as shown by the Intergovernmental Panel on Climate Change (IPCC) [32].

The bioenergy potential was estimated using Equation (1).

$$E = \sum_{i=1}^{n} Produc(i,j) \times Energy(i)\ [toe\ year^{-1}] \quad (1)$$

where E is the bioenergetic potential of sugarcane in the municipalities of the Northeast Brazilian region, toe year^{-1}; *Produc* (*i*,*j*) is the potential of different products i in the municipalities (j), kg year^{-1}, L year^{-1} or m^3 year^{-1}; and *Energy* (i) is the energy value of product i, toe kg^{-1}, toe L^{-1}, or toe m^{-3}.

3.2.2. Firewood

The values in m^3 of firewood were converted to tons of dry mass (tDM), considering the average value of the species common in the caatinga forest, which is 0.214 tDM m^{-3} [7]. The corresponding energy (higher heating value) was 0.4590 toe tDM^{-1}. The bioenergy potential was estimated with Equation (2). The higher caloric value is the amount of thermal energy released during the combustion of dry firewood [7,33].

$$E = \sum FW(j) \times Energy(i) \left[toe\ year^{-1}\right] \quad (2)$$

where *FW* (j) is the firewood produced in the municipalities (j) of the Northeast Brazilian region, tDM year^{-1}; Energy (i) is the energy value of product i, toe tDM^{-1}; and E is the bioenergetic potential of firewood in Northeast Brazil (toe year^{-1}).

3.2.3. Animal Waste

To estimate the generation of waste in the animal protein production chain, the herds of cattle (beef and dairy), pork, chicken, sheep, and goat in each municipality were taken into account. The daily manure production of each species was obtained from the specialized bibliography [34]. The energy potential was estimated by taking into account the generation of biogas from each waste, according to its species, and the ability to transform this biogas into electricity. The bioenergy potential was estimated using Equation (3) [34,35].

$$E = D(i) \times R(i) \times Q(i) \times mf \left[toe\ year^{-1}\right] \quad (3)$$

where E is the bioenergetic potential of the manure biomass in each municipality in Northeast Brazil, toe year^{-1}; $D(i)$ is the daily production of manure per animal of each species, tons year^{-1}; $R(i)$ is the effective number of animals of each species in the municipalities; $Q(i)$ is the amount in m^3 of biogas produced per tons of residual biomass; and mf is a multiplier factor to obtain the energy quantity (1.22 $\times$ 10^{-4} toe m^{-3}). For the conversion rates of biogas into energy, 1.43 kWh m^{-3} was used [36]. This index was considered for all residues, but it is known that there may be variations according to the substrate used. For conversion from kWh to toe, 86 $\times$ 10^{-6} was used [35].

3.2.4. Municipal Solid Waste (MSW)

Municipal solid waste generation rates were obtained for the Northeastern states and multiplied by the population of the respective cities [37]. In total, the region is home to approximately 58 million people, whose waste is composed of 45.3% organics [21]. When decomposed anaerobically, this fraction is the main one responsible for methane emissions from the waste sector. As the most common treatment for MSW in Brazil is landfilling, the landfill gas production rate was estimated considering the local climate conditions and the IPCC methodology [38]. Finally, the MSW energy potential is considered to be the landfill gas energy potential based on its lower heating value (LHV) (Equation (4)).

$$E = Pop(i) \times WG \times BG \times LHV_{LFG} \left[toe\ year^{-1}\right] \quad (4)$$

where E is the amount of energy in toe year^{-1}, $Pop(i)$ is the estimated population of each municipality (i) in the region, WG is the waste generation rate in tons hab^{-1} year^{-1}, BG is the biogas generation rate in m^3 tonnes^{-1}, and LHV_{LFG} is the lower heating value in toe per m^3.

3.3. Estimates of Greenhouse Gas Emissions

To estimate the emissions, the bottom-up approach (sectoral approach) was used, considering the energy generation potential of each biomass type. The guidelines of the Energy Research Company of Brazil for emissions from the national matrix were used [39]. For fuels not identified in the EPE guidelines, we used the values of the IPCC, which provides standardized data for the emission of greenhouse gases due to the stationary combustion of different fuels [40]. One of the positive aspects of biomass is biogenic CO_2 emissions, which were considered in the baseline scenario (for all forms of energy analyzed: sugarcane products, firewood, and biogas, both from animal origin and from urban waste), which makes this resource considered to have a low environmental impact compared to fossil energy sources [41].

The emissions were calculated by multiplying the energy availability of each biomass fuel (in thousand toe) by the respective emission factors (in thousand tCO_{2eq} per thousand toe) according to Equation (5).

$$kgCO_{2eq} = \sum_{i=1}^{n} (P(i) \times PCO_2 \times GWP_{CO_2}) + \sum_{i=1}^{n} (P(i) \times PCH_4 \times GWP_{CH_4}) + \sum_{i=1}^{n} (P(i) \times PN_2O \times GWP_{N_2O}) \quad (5)$$

where $P(i)$ is the energy potential in toe year^{-1} of each municipality in the region; PCO_2 is the default emission factor of CO_2 performing stationary biogas combustion; GWP_{CO2} is the global warming factor for CO_2 (GWP_{CO2} = 1); PCH_4 is the default emission factor of CH_4 performing stationary biogas combustion; GWP_{CH4} is the global warming factor for CH_4 (GWP_{CH4} = 28); PN_2O is the default emission factor of N_2O performing stationary biogas combustion; and GWP_{N2O} is the global warming factor for N_2O (GWP_{N2O} = 265) [39].

3.4. Locational Quotient

The Locational Quotient (LQ), expressed in Equation (6), relates the relative participation of energy availability from the biomass form, due to the relative participation of this availability in a reference macro-region. The LQ was used to identify intermediate states and regions specialized in biomass sources in Northeast Brazil [42,43]. The intermediate regions are divisions of the Brazilian territory carried out by the IBGE based on the national political–administrative network, which aims to facilitate government action for the allocation of resources and implementation of projects in the grouped municipalities [44].

$$LQ = \frac{\frac{E_{ij}}{E_j}}{\frac{E_i}{E}} \quad (6)$$

where E_{ij} = available energy, in toe year^{-1}, from each biomass type (i), sugarcane, firewood, MSW, or animal waste in each state or intermediate region (j); E_j = available energy, in toe year^{-1}, of the total biomass, in each state or intermediate region (j); E_i = available energy, in toe year^{-1}, from biomass (i), sugarcane, firewood, MSW, or animal waste in the reference region (j) (state or Northeast region), and E = available energy, in toe year^{-1}, of the total biomass in each state or Northeast region. The LQ was classified as follows: state with high specialization ($LQ \geq 1.00$), with moderate specialization ($0.50 \leq LQ < 1.00$), and with weak specialization ($LQ < 0.5$) [45].

4. Results and Discussion

4.1. Biomass Availability

The amounts of biomass generated in the Northeast region (Table 2) highlight the potential of sugarcane, biomass historically cultivated in the region, and manure from growing livestock herds in the region.

Table 2. Distribution of biomass types by states in the Northeast Brazilian region in millions of tons (10^6 t) [19,21].

State	Sugarcane	Firewood	MSW *	Animal Waste
Alagoas (AL)	15.294	0.004	0.885	9.324
Bahia (BA)	5.450	0.360	4.894	60.261
Ceará (CE)	0.588	0.629	3.243	22.613
Maranhão (MA)	2.838	0.343	1.939	45.648
Paraíba (PB)	5.674	0.132	1.115	10.611
Pernambuco (PE)	14.827	0.400	2.811	19.946
Piauí (PI)	1.002	0.464	1.073	10.996
Rio Grande do Norte (RN)	3.913	0.166	0.844	8.487
Sergipe (SE)	2.058	0.002	0.593	6.817
Northeast	51.643	2.501	17.398	194.706

* MSW = municipal solid waste.

The energy use of sugarcane biomass is historically important in the region, due to its productivity and high versatility, including ethanol, bagasse, straw, and vinasse. Alagoas and Pernambuco stand out in the region with the highest production (>30 million tons in 2020), approximately 60% of the total regional production, but Bahia and Paraíba also produce considerable values, around 5.5 million tons in 2020.

The highest production of MSW is found in states where the population is higher. Bahia stands out as the biggest producer, with a production of almost 5 million tons in 2019, followed by Ceará (3.2 million tons) and Pernambuco with (2.8 million tons). Together, they create more than 60% of MSW production in the region.

Ceará, Piauí, and Pernambuco stand out as the states that produce the most firewood in the region: 2.9, 2.1, and 1.9 million cubic meters, respectively. The three states comprise more than 40% of all woody biomass in the region. Almost all of this wood comes from the caatinga, the dry tropical forest native to the semi-arid area of NE Brazil. Firewood extraction from native forests creates an intense debate about the energy use of firewood, its sustainability, and legality, reinforcing the need for public policies and strategies to develop projects that meet the legal and socioenvironmental requirements.

The Northeast region produces 8.8% of the beef in Brazil, 1.2% of the pork, and 4.5% of the chicken [19]. There is an expectation of an annual increase of approximately 3% by 2032 in the herds of these three species, which highlights the need to propose solutions to use the waste produced by these production chains. Bahia produces the highest volume of manure, followed by Maranhão, the two states accounting for 54% of the production in the region. It is important to highlight that a large part of the manure is produced in non-urban areas of the municipalities, which generally have less electricity supply. Therefore, generation centers located in these areas may promote greater energy security for the producers. A positive aspect to the increase in energy supply is the to of produce goods with greater added values, for example, in the milk production chain.

4.2. Energy Availability

Traditional sources of biomass have maintained prominence in the supply of primary energy, representing 30% of the regional supply in Northeast Brazil. However, there has been the establishment of new biomass production arrangements; the use of sources already available (MSW, vinasse, and manure); and strategies for the integral valorization of the different fractions in modern approaches, such as first-generation biorefineries based on sugar.

Some types of biomasses, such as manure, for example, are produced in large quantities, but only part can be collected for processing; therefore, only this fraction that can be processed was considered for the estimation of energy use.

Various types of biomasses are produced in the region, but some are still not used as an energy source. Sugarcane, produced mainly in the coastal Zona da Mata, and firewood, extracted mainly from the native vegetation (caatinga) in the semi-arid area, are still the most used biomass energy sources. Animal manure and MSW stand out in terms of their potential as non-traditional biomass sources. However, the feasibility of using energy from some other sources depends on the relationship between the production location and energy demand, and often, transport over long distances makes their use unfeasible. The utilization strategy of biomass produced in a decentralized manner—that is, in small amounts distributed over large areas—should focus on processing at the local scale in small processing units. Therefore, it is important to understand the spatial distribution of the biomass energy potential in the region (Figures 2 and 3).

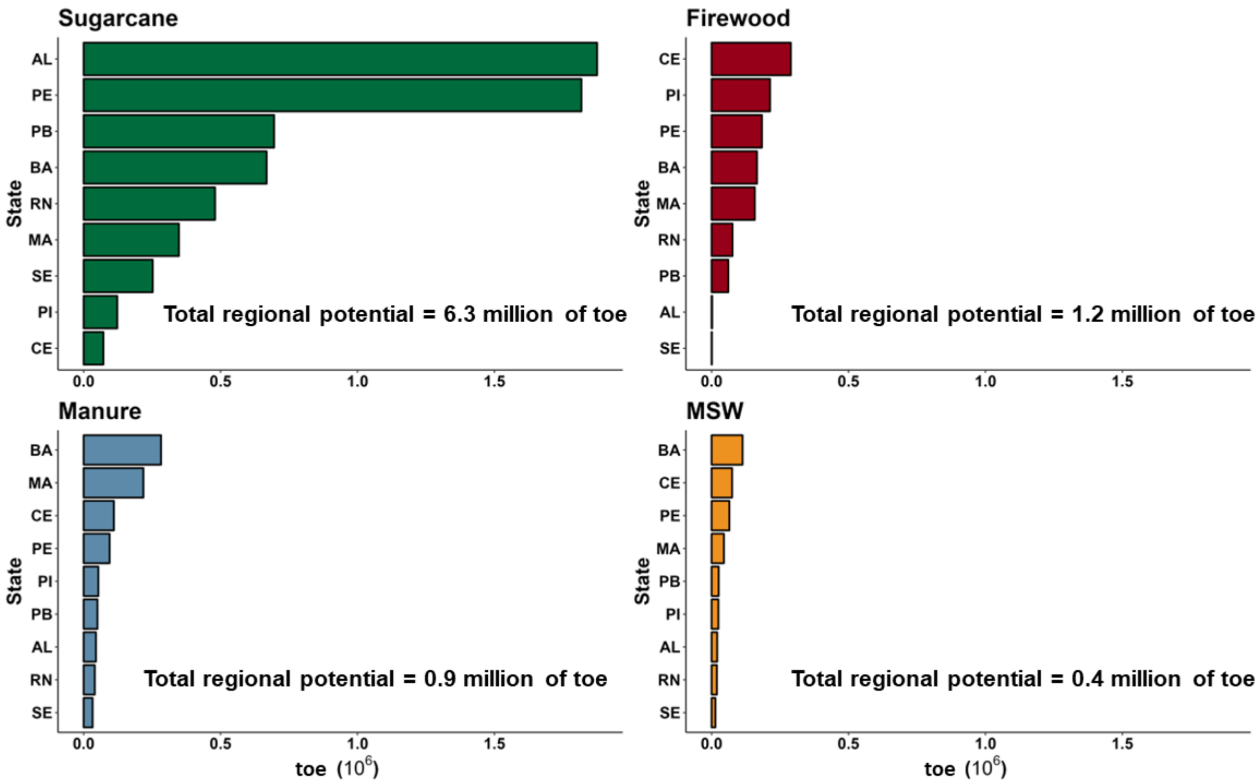

Figure 2. Estimates of potential energy use, in tons of oil equivalent (toe), from biomass sources produced in the Northeast region of Brazil. Cane (sum of fractions, bagasse, straw, ethanol, and vinasse); firewood (produced firewood); manure (sum of manure from beef and dairy cattle, sheep, goats, and poultry); and MSW (municipal solid waste).

4.2.1. Sugarcane Derivatives (Bagasse, Ethanol, Straw, and Vinasse)

From sugarcane, it is possible to obtain up to 6.33 million toe in the Northeast region. Of this value, sugarcane bagasse would be the main vector with 51.96% of the energy offered, followed by straw (23.19%), ethanol (20.44%), and vinasse biogas (4.42%). Among the states, Alagoas would be the main highlight with 1.87 million toe and 29.61% of the supply, followed by the state of Pernambuco with 1.82 million toe and 28.71%. The states with the lowest generation of biomass energy from sugarcane would be Ceará and Piauí.

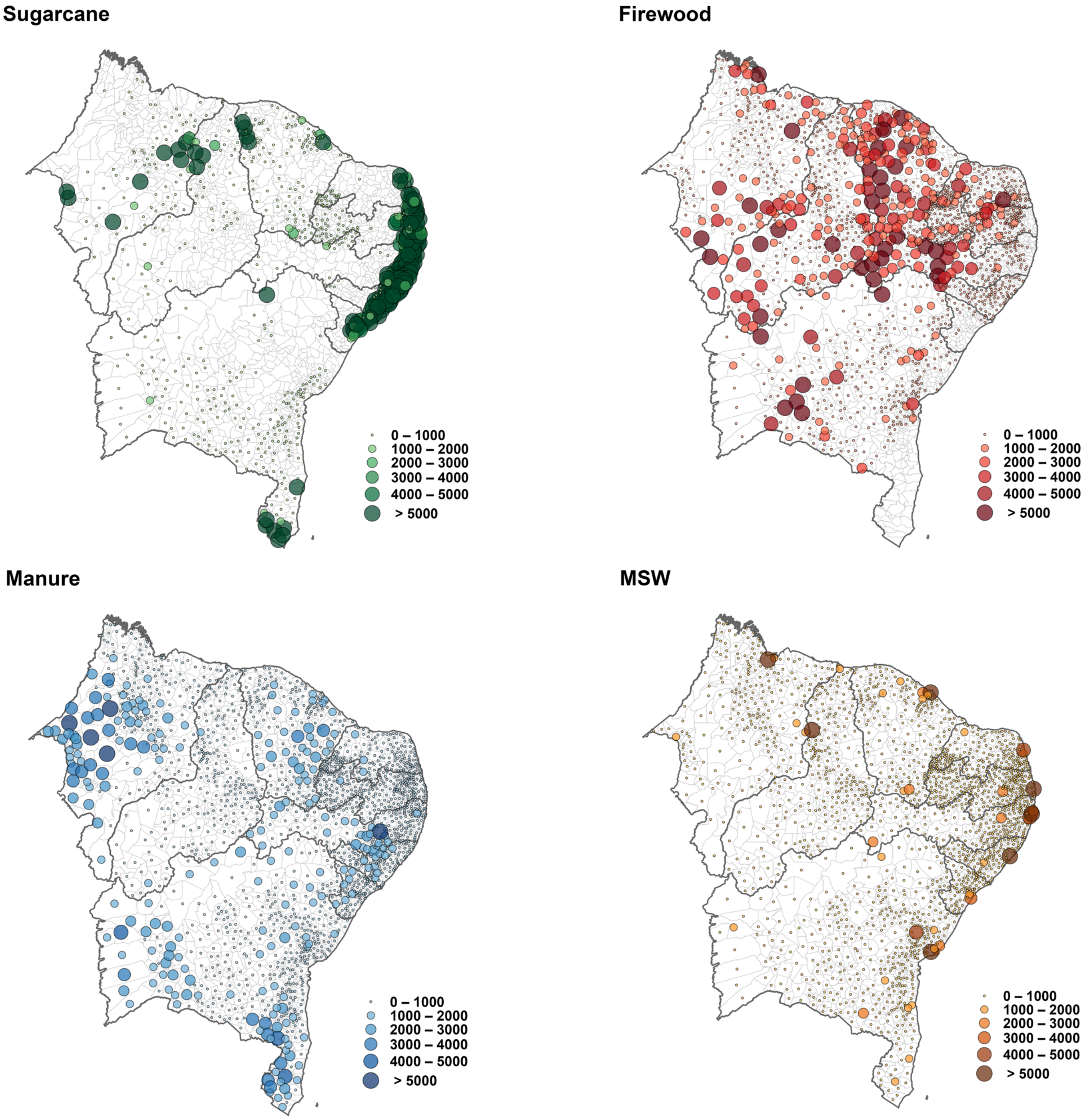

Figure 3. Estimation of the spatial distribution of biomass sources with potential for energy use, in tons of oil equivalent (toe), expressed for each municipality in the NE region of Brazil. Sugarcane (sum of fractions, bagasse, straw, ethanol, and vinasse); firewood (produced firewood); manure (sum of manure from beef and dairy cattle, sheep, goats, and poultry); and MSW (municipal solid waste).

Sugarcane is the highest supply of biomass energy in the region. Ethanol generated from the fermentation of sugarcane juice (first-generation ethanol) is the main source of low-cost, low-emission, renewable energy for the national car fleet. In addition to ethanol, the bagasse generated in the industrial processing of sugarcane, when the stalks are pressed to extract the juice, has great potential for energy production. In the 21st century, bagasse became the most important agro-industrial residue in Brazil, generating electricity and heat in all sugarcane processing units. Currently, the Northeast region produces 51.4 million tons of cane stalks, around 6% of the national production, with an installed capacity of 887 MW.

However, not all sugarcane residues are used to produce energy. Vinasse and straw are incipiently used and correspond to about a quarter of the energy contained in the plant. Vinasse, a liquid residue of ethanol production, is generated in large quantities (12–15 L for each L of ethanol); according to the calculations performed, this could mean an additional 0.28 million toe from anaerobic digestion and biogas production [27,31]. It is expected that vinasse use will increase in the coming years as a strategy to improve the environmental efficiency rating of the plants and the commercialization of carbon credits in the context of the RENOVABIO program (a Brazilian governmental policy to reduce emissions from the biofuel production chain). Furthermore, vinasse has been tested as a promising source to produce H_2 and other value-added products. Straw, the leaves remaining in the field at harvesting, are burned or left to decompose on the ground. If 50% of the straw were harvested for energy use, as calculated in our study, based on Silva et al. [29], there would be an increase of 1.47 million toe in the energy supply of the sugarcane sector. Currently, heavy investments are being made to develop economically viable processes to produce what is called second-generation ethanol from bagasse and straw. When effective, they will increase the energy efficiency and profitability of sugarcane biomass.

4.2.2. Firewood

Dependence on wood fuels is a historical fact in the region, and it is currently associated with low-income households; local multiple small industries, such as bakeries, cassava flour-producing plants, and ceramics; and larger localized industrial units, such as plaster and steel. The production of firewood in the region in 2020 was around 2.5 million tons (IBGE 2022), with an energy availability of up to 1.15 million toe. Among the Brazilian states, Ceará had the highest proportion with 289.29 thousand toe at 25.15%. Next was Piauí with 213.35 thousand toe (18.55%) and Pernambuco with 183.91 thousand toe (15.99%). The two main states demonstrate the complementarity of sugarcane with firewood.

For comparative purposes, this energy is equivalent to around 11% of the regional residential electricity consumption, considering losses of 75% in the conversion of firewood into electricity. Due to the cost of firewood and the low efficiency of the conversion process into electricity, only three thermoelectric plants use charcoal (or its residual gas) to generate electricity in the region.

Up to 60% of the energy used for cooking food in the region comes from firewood, a share that has increased due to the crisis generated by the COVID-19 pandemic and the current problems in the global energy supply [46,47]. Approximately 80% of the firewood produced in the region comes from the caatinga vegetation, which has been reduced to less than 50% of its original coverage, a worrying fact from the point of view of sustainability [7]. Due to its energy density, it is not feasible to transport firewood over long distances, but the feasibility of transport increases with the conversion of firewood into charcoal, which contributes to the extraction of firewood in more distant locations.

The extraction and use of firewood can be carried out with greater environmental efficiency, based on Sustainable Forest Management Plans (PMFS) and/or authorized cutting without changes in land use, which guarantee the recovery of the vegetation. Studies aimed at more efficient uses of firewood and, in the case of residential consumption, less impact on people's health deserve greater attention from researchers and public policymakers.

4.2.3. Animal Waste

The Northeast region of Brazil stands out with high production herds of chickens, cattle, goats, and sheep, the latter being traditional species in the region. The cattle herds stand out mainly in the state of Bahia, with a total of more than 10 million heads, including dairy and beef cattle, and in the state of Maranhão with almost 9 million heads. The total manure generated in the two mentioned regions is 120 ktons day^{-1}, which produces a theoretical volume of 4.5 million m^3 of biogas daily. The state of Pernambuco stands out in the production of goats and sheep, with almost 6.5 million heads. The daily production of waste of all kinds is 54 ktons daily in the state with a potential for biogas generation of 2.1 million m^3. The state of Ceará has a daily production of animal waste of 62 ktons, with a potential for the generation of biogas of 2.4 million m^3 daily.

From an energy point of view, the states with the greatest potential are Bahia, Maranhão, Ceará, and Pernambuco; consequently, these states produce the largest volumes of waste, totaling 406 ktons daily. Bahia has the highest theoretical energy potential, around 283 ktoe, followed by the state of Maranhão with 218 ktoe, the state of Ceará with 110 ktoe, and the state of Pernambuco with 94 ktoe. It is important to note that the high volume of manure produced, which, if improperly disposed of in the environment, can cause serious environmental damage, and, in addition, studies such as this one should draw attention to the need to rethink the current production models of the production chains of animal protein. Stimulating energy recovery projects from animal waste can have a positive impact on regions with low economic activity, generating jobs, income, and development.

It is important to highlight that a large part of animal protein production is located in non-urban regions of the municipalities, places that generally suffer more from a lack of electricity and heat; therefore, the implementation of bioenergy production facilities located in these regions may promote greater energy generation and security for producers. The meat industry generates more than 6 million jobs and contributes significantly to the generation of employment and income, especially in regions with low industrial activity [48,49].

4.2.4. Municipal Solid Waste

For MSW, the available energy would be 0.4 million toe, coming from landfill biogas. It is important to emphasize the close relationship between the population and energy availability for this resource; as a result, the state of Bahia presented the greatest contribution with 112.88 thousand toe (28.13% of the total) to be exploited, followed by Ceará with 74.81 thousand toe (18.64%) and Pernambuco with 64.85 thousand toe (16.16%).

Due to urbanization, increases in the population, and changes in consumption habits in recent decades, MSW has become an important source of residual biomass. In the Northeast, in 2020, around 18 million tons of waste were generated, mainly in the large urban areas of the state capitals. Most of it is still not used for energy generation, due to a lack of segregation, failures in the collection, and the absence of processing units.

The use of MSW as an energy source brings numerous benefits. In addition to mitigating the environmental impacts arising from incorrect disposal, it reduces municipal budget costs, especially with transport and infrastructure. Additionally, it is a renewable and decentralized resource.

The technology used for MSW energy recovery in Brazil is currently landfill gas combustion, which can be used in thermal applications of electricity generators. If all the waste produced in the Northeast region was sent to landfills and used to produce biogas, it would be possible to obtain around 0.41 million toe from its burning. If power is the priority, this number can reach 0.14 million toe or 1642.5 GWh per year, which is enough energy to meet 5.3% of the residential demand for electricity in the region.

4.3. Municipal Specialization

Figure 4 presents the Locational Quotient (LQ) of the energy availability from biomass (sugarcane, firewood, MSW, and manure) in Northeast Brazil. For the state level, Northeast Brazil was used as the reference region, while, for the intermediate ones, the reference was their respective states.

For sugarcane, at the state level, the states of Alagoas, Sergipe, Pernambuco, Paraíba, and Rio Grande do Norte were the most specialized. As expected, Alagoas, Sergipe, and Pernambuco had the highest rates for LQ specialization at 1.34, 1,17, and 1.17, respectively, due to the high productivity shown in Section 4.1. The sugar–alcohol supply chains are well developed in these regions, although the state of Pernambuco has shown a decrease in production in the last decade. Pedroso, Lages, and Silva [50] verified the decline of sugarcane cultivation and the beginning of its replacement by other activities. As for Alagoas, it highlighted the need for technological improvement in cultivation because of the high dependence on the state for this crop.

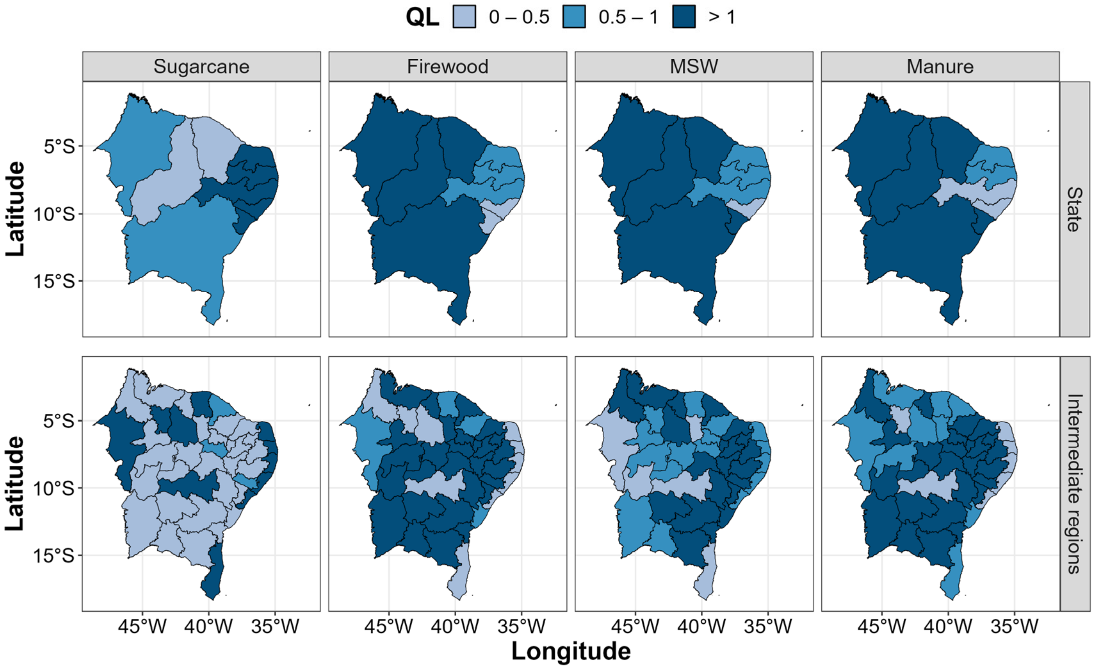

Figure 4. Locational Quotient (LQ) of the energy availability from biomass, by states and intermediate regions, in Northeast Brazil.

Still, regarding the high specialization of Alagoas and Pernambuco, Santos Júnior [51] highlighted the two states with the largest number of thermoelectric plants installed in the Northeast region of Brazil. Currently, there are 20 plants in each state, together totaling 74.1% of the regional thermoelectric plants.

It should be noted that Sergipe is only the seventh (7th) largest sugarcane producer in the Northeast region (3.75% of production) and has a strong specialization in this resource, demonstrating the low offer from the other biomass sources when compared to the reference region.

Concerning intermediate regions, it was possible to visualize areas with good energy availability from sugarcane, even outside the main states, such as the case of the intermediary of Sobral (CE), which represented 68.14% of the sugarcane energy potential in the entire state of Ceará, demonstrating a much higher availability than its reference region. Other prominent areas were Teresina (PI), Caxias (MA), and Juazeiro (BA), the latter representing 47.49% of the availability in Bahia. It is also in the intermediary of Juazeiro (BA) that the only thermoelectric plant using sugarcane bagasse in the state is installed, Agrovale, with 12.00 MW of the installed capacity [52].

For firewood energy, the states to the north of the study region were the ones with the greatest specialization, with Ceará, Piauí, and Maranhão as the greatest exponents. Ceará covered 25.15% of the energy from firewood in the Northeast region. According to the North East Plant Association [7], one of the species that makes the state so relevant is the cashew trees. The authors point out that the need for pruning for fruiting interferes with the production of a large amount of sustainable biomass. The states with less specialization were Sergipe and Alagoas, corroborating the spatial patterns identified by Coelho Junior et al. [53].

Of the intermediate regions, the main offers were in the interior of the Northeast, except for the coast of Ceará, where cashew crops stand out. The immediate ones with greater specialization in firewood energy were Petrolina (PE), Serra Talhada (PE), and Patos (PB), where most of the demand for thermal energy by the red ceramic industries is concentrated [53]. The intermediate region of Arapiraca (AL), with the fourth highest LQ index, is an example of a region that differs from the reference in the case of firewood;

although it presents only 1% of the entire regional supply from firewood, the region contains 55% of the energy from firewood in the state of Alagoas.

For animal waste, most states had a strong concentration of the available energy. Unlike other biomasses, the supply of animal waste comprises several sources—that is, different types of livestock, which makes most states highly available for this bioenergy source. Only Rio Grande do Norte, Paraíba, Pernambuco, and Alagoas did not show strong specialization. In general, these states have a very high supply of sugarcane and firewood, which reduces the impact of the energy supply of manure.

The intermediaries of Caruaru (PE), Souza-Cajazeiras (PB), and Arapiraca (AL) were the most specialized. In the case of Caruaru (PE), up to 72.38% of the biomass available in the region could be obtained from animal waste; with the perspective of the entire state, of the 297 thousand toe available based on animal waste, 52.2% is in Caruaru.

Finally, a specialization for MSW, as expected, had higher rates in Ceará and Bahia, the two Northeastern states with the largest populations and consequently higher generations of waste. For the intermediate ones, a greater specialization in the metropolitan areas to the capitals, where there was a greater population density, was expected; however, in the states of RN, PB, PE, AL, and SE, this phenomenon was not observed due to the high availability of energy from sugarcane, which demonstrates the degree of development for obtaining energy from sugarcane.

Although Ceará and Bahia have the highest supply of this resource, only the state of Bahia has a MSW thermoelectric plant connected to the National Interconnected System, the Salvador Plant, with 19.73 MW granted, which has been in operation since 2010, using biogas generated by urban waste. Paraíba, Pernambuco, and Maranhão also have one thermoelectric plant each. The production of energy from MSW in Northeast Brazil, is still under development [52].

4.4. Socio-Environmental Impacts

Brazil's domestic energy supply in 2021 was 301.47×10^6 toe, and the associated emissions were 445.4 million tons of carbon dioxide equivalent [39]. Of this total, 55.3% were from fossil fuels, representing approximately 86% of the total emissions. The national emissions were approximately 1.47 t CO_{2eq} for each toe offered. An increased use of renewable biomass in the energy matrix would reduce the carbon emissions [54]. The full use of biomass resources in the Northeast region could supply around 4% of the national amount, and the present use corresponds to 0.055 t CO_{2eq} per toe. However, it is important to point out that processing losses and the difficulty in raising funds make full use unfeasible at this time. The source with the greatest emission impact was firewood from the caatinga, used mainly to supply heat in the residential sector and in the ceramics and plaster industries, with a contribution of 0.07 t CO_{2eq} per toe, while MSW and animal waste had an emission of 0.002 t CO_{2eq} per toe from the combustion of biogas. Sugarcane products had a factor of 0.06 t CO_{2eq} per toe, with straw and bagasse combustion the fuels with the highest environmental footprints. It should be noted that the use of biomass collaborates strongly with the reduction of emissions in Brazil's energy matrix.

If all the energy potential of biomass stipulated in the previous sections were used, the states of Pernambuco, Alagoas, and Bahia would lead the regional production, while Pernambuco would have the greatest contribution to greenhouse gas emissions (Figure 5), due to the intensive use of sugarcane and firewood. Maranhão and Bahia would have the lowest proportional emissions, considering their low supply of sugarcane and significant production of biogas.

The case of firewood production, mostly in the semi-arid area, is a complex issue. The indiscriminate use of the resource, without proper reforestation, means that a significant part of what is produced is not considered renewable. Approximately 78% of the firewood produced in the region is obtained sustainably, whether from forest management plans, extraction without changing land use, fruit tree pruning, and others [7].

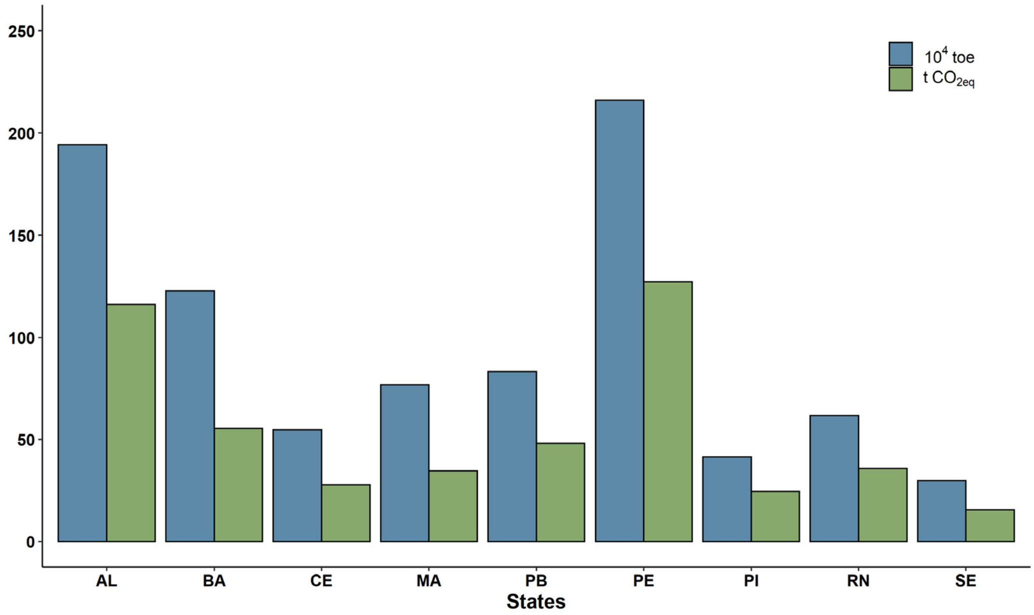

Figure 5. Estimates of the annual energy potential (10^4 toe) by biomass and associated GHG emissions (t CO_{2eq} year^{-1}) in the states of the Northeast Brazil region.

Investments in renewable energy sources, in addition to environmental benefits, create local value chains, generating jobs and leveraging regional development [4]. The renewable energy sector employed more than 12 million people worldwide, 3.4 million only in the bioenergy sector from biomass, and the expectation is that, in 2030, more than 38 million people are employed in the sector in a scenario of energy transition and with significant investments [1]. The use of biomass as an energy source stands out, as it has a greater capacity to use local inputs in its transformation process than other renewable sources, such as solar and wind. Therefore, most of the values generated in the biomass supply chain value tend to remain in the region.

The animal production chain brings possibilities of even greater social and economic impacts, since a good part of its production is found in rural areas, places with low-intense jobs and low electricity supplies. Energy security in these areas could foster the development of new or improved production chains, adding value to local production. The use of manure to produce energy could change the reality of these areas.

Energy recovery of the MSW brings up the possibility of communicating with other segments, generating jobs in waste selection and processing, and stimulating cooperatives that work with the non-organic recyclable fraction. In large urban centers, the immediate social impact would be great, while smaller cities would benefit from cooperation between municipalities, creating communal processing centers. The development of mechanisms to produce energy from these residues would enable the employment of trained professionals and could stimulate the development of courses directed toward this energy sector. This could benefit the production of local knowledge, technology, and innovation, from local schools to institutes of education and universities.

5. Conclusions and Future Trends

The present study evaluated the availability of biomass energy for the Northeast region of Brazil, considering the supply of sugarcane, firewood, urban solid waste, and livestock manure. A high potential for energy production was observed, reaching estimates of approximately 8.8 million toe, highlighting the already consolidated production of sugarcane and its derivatives.

Different from what we hypothesized, energy recovery from non-traditional bioenergy sources, such as municipal waste and animal manure, would not significantly improve the current bioenergy supply, since these sources would bring about an increase of only up to 17% for the current regional bioenergy supply if all the available biomass from those sources were used for bioenergy generation, which is unlikely.

Therefore, to increase the regional supply of bioenergy in a significant manner, there is a need to investigate the feasibility of other options, such as bioenergy crops adapted to drylands with high efficiency in water use and high biomass yields, such as cacti and agave, to be produced in the semi-arid area of NE Brazil. Several studies have pointed out the potential of these crops to reach high biomass productivity under limited rainfall and the possibility to convert this biomass into different biofuels. The widespread production of such crops would make it viable to establish biorefineries beyond the coastal zone to produce biofuels and value-added compounds, which could have important regional socioeconomic benefits on the local population. These benefits may also be useful in other similar regions of the world, located in underdeveloped countries with tropical dry climates, given the extreme capability of cacti and agave to produce biomass productivity in arid and semi-arid zones.

The potential spatialization analysis yielded interesting results, indicating the priorities of the biomass types for the different areas within NE Brazil. First, we observed the clear complementarity among the main biomass sources, with sugarcane on the coast, firewood and manure in the drylands, and solid waste distributed throughout the region within the urban areas. The Locational Quotient highlighted the states of Alagoas, Pernambuco, Sergipe, Paraíba, and Rio Grande do Norte for sugarcane; Ceará and Piauí for firewood; Ceará and Bahia for MSW; and Maranhão and Bahia for animal waste. It is clear that, in some situations, such as remote, low-populated areas, the establishment of small, decentralized bioenergy processing units for electricity generation may bring about significant economic benefits and energy security to the local economy.

From the environmental assessment, the full use of biomass resources in Northeast Brazil could supply around 4% of the Brazilian national energy demand. Most importantly, these sources presented an environmental footprint of 0.055 $tCO2_{eq}$ per toe, values well below the environmental impact of the Brazilian energy matrix, which shows that the increase in bioenergy sources would reduce even further the emissions from the energy sector in NE Brazil.

In the near future, we believe that new opportunities will benefit bioenergy generation in Brazil and other countries with similar environmental and socioeconomic conditions, given the strengthening of the bioeconomy and carbon markets worldwide. Therefore, the academic sector needs to focus on identifying the technical, economic, social, and environmental viability of the different productive arrangements in these regions to support the establishment of strong market chains that will improve the lives of millions of people.

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References

1. Vogel, J.; Steinberger, J.K.; O'Neill, D.W.; Lamb, W.F.; Krishnakumar, J. Socio-economic conditions for satisfying human needs at low energy use: An international analysis of social provisioning. *Glob. Environ. Chang.* **2021**, *69*, 102287. [CrossRef]
2. González-Eguino, M. Energy poverty: An overview. *Renew. Sustain. Energy Rev.* **2015**, *47*, 377–385. [CrossRef]
3. Owusu, P.A.; Asumadu-Sarkodie, S. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng.* **2016**, *3*, 1167990. [CrossRef]
4. International Energy Agency. Data Browser. Available online: https://www.iea.org/statistics/ (accessed on 10 April 2023).
5. Guo, M.; Song, W.; Buhain, J. Bioenergy and biofuels: History, status, and perspective. *Renew. Sustain. Energy Rev.* **2015**, *42*, 712–725. [CrossRef]
6. Empresa de Pesquisa Energética (Brasil). Brazilian Energy Balance 2022 year 2021. *Braz. Energy Dep.* **2022**, *1*, 292.
7. Brasil. Ministério do Meio Ambiente. Biomassa Para Energia no Nordeste: Atualidade e Perspectivas [Recurso Eletrônico]/Ministério do Meio Ambiente, Programa das Nações Unidas Para o Desenvolvimento. 2018. Available online: https://www.undp.org/sites/g/files/zskgke326/files/migration/br/Livro_APNE_NE_AGO20.pdf (accessed on 1 September 2022).
8. Herreras Martínez, S.; van Eijck, J.; Pereira da Cunha, M.; Guilhoto, J.J.M.; Walter, A.; Faaij, A. Analysis of socio-economic impacts of sustainable sugarcane–ethanol production by means of inter-regional Input–Output analysis: Demonstrated for Northeast Brazil. *Renew. Sustain. Energy Rev.* **2013**, *28*, 290–316. [CrossRef]
9. Cardoso, T.F.; Watanabe, M.D.B.; Souza, A.; Chagas, M.F.; Cavalett, O.; Morais, E.R.; Nogueira, L.A.H.; Leal, M.R.L.V.; Braunbeck, O.A.; Cortez, L.A.B.; et al. A regional approach to determine economic, environmental and social impacts of different sugarcane production systems in Brazil. *Biomass Bioenergy* **2019**, *120*, 9–20. [CrossRef]
10. de Arruda, H.L.S.; dos Santos, J.F.O.; Albuquerque, U.P.; Ramos, M.A. Influence of Socioeconomic Factors on the Knowledge and Consumption of Firewood in the Atlantic Forest of Northeast Brazil. *Econ. Bot.* **2019**, *73*, 1–12. [CrossRef]
11. Alfaia, R.G.d.S.M.; Costa, A.M.; Campos, J.C. Municipal solid waste in Brazil: A review. *Waste Manag. Res. J. A Sustain. Circ. Econ.* **2017**, *35*, 1195–1209. [CrossRef]
12. Forster-Carneiro, T.; Berni, M.D.; Dorileo, I.L.; Rostagno, M.A. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. *Resour. Conserv. Recycl.* **2013**, *77*, 78–88. [CrossRef]
13. Bolaji, B.O. Effects of Unsustainable Use of Biomass Energy for Cooking and Strategies for Their Reduction in Developing Countries. *Dev. Ctry. Stud.* **2012**, *2*, 19–26.
14. Hakizimana, E.; Wali, U.G.; Sandoval, D.; Venant, K. Environmental Impacts of Biomass Energy Sources in Rwanda. *Energy Environ. Eng.* **2020**, *7*, 62–71. [CrossRef]
15. Majeed, M.T.; Luni, T.; Tahir, T. Growing green through biomass energy consumption: The role of natural resource and globalization in a world economy. *Environ. Sci. Pollut. Res.* **2022**, *29*, 33657–33673. [CrossRef]
16. De Oliveira, F.C.; Coelho, S.T. History, evolution, and environmental impact of biodiesel in Brazil: A review. *Renew. Sustain. Energy Rev.* **2017**, *75*, 168–179. [CrossRef]
17. Butnar, I.; Broad, O.; Solano Rodriguez, B.; Dodds, P.E. The role of bioenergy for global deep decarbonization: CO_2 removal or low-carbon energy? *GCB Bioenergy* **2020**, *12*, 198–212. [CrossRef]
18. Benevenuto, R.; Caulfield, B. Measuring access to urban centres in rural Northeast Brazil: A spatial accessibility poverty index. *J. Transp. Geogr.* **2020**, *82*, 102553. [CrossRef]
19. Instituto Brasileiro de Geografia e Estatística. Sistema IBGE de Recuperação Automática. Available online: https://sidra.ibge.gov.br/home (accessed on 1 September 2022).
20. Howard, D.B.; Soria, R.; Thé, J.; Schaeffer, R.; Saphores, J.-D. The energy-climate-health nexus in energy planning: A case study in Brazil. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110016. [CrossRef]
21. Associação Brasileira Empresas de Limpeza Pública e Resíduos Especiais (ABRELPE). *Panorama dos Resíduos Sólidos no Brasil 2020*. São Paulo, Brazil: 2021. (In portuguese). Available online: www.abrelpe.org.br (accessed on 1 September 2022).
22. Singh, P.; Suman, A.; Tiwari, P.; Arya, N.; Gaur, A.; Shrivastava, A.K. Biological pretreatment of sugarcane trash for its conversion to fermentable sugars. *World J. Microbiol. Biotechnol.* **2008**, *24*, 667–673. [CrossRef]
23. Chandel, A.K.; da Silva, S.S.; Carvalho, W.; Singh, O.V. Sugarcane bagasse and leaves: Foreseeable biomass of biofuel and bio-products. *J. Chem. Technol. Biotechnol.* **2012**, *87*, 11–20. [CrossRef]
24. Hofsetz, K.; Silva, M.A. Brazilian sugarcane bagasse: Energy and non-energy consumption. *Biomass Bioenergy* **2012**, *46*, 564–573. [CrossRef]

25. União da Indústria de Cana-de-Açúcar e Bioenergia. Setor Sucroenergético. Available online: https://unica.com.br/setor-sucroenergetico/etanol/ (accessed on 1 September 2022).
26. de Souza Dias, M.O.; Maciel Filho, R.; Mantelatto, P.E.; Cavalett, O.; Rossell, C.E.V.; Bonomi, A.; Leal, M.R.L.V. Sugarcane processing for ethanol and sugar in Brazil. *Environ. Dev.* **2015**, *15*, 35–51. [CrossRef]
27. Parsaee, M.; Kiani, M.K.D.; Karimi, K. A review of biogas production from sugarcane vinasse. *Biomass Bioenergy* **2019**, *122*, 117–125. [CrossRef]
28. Nadaleti, W.C.; Lourenço, V.A.; Filho, P.B.; dos Santos, G.B.; Przybyla, G. National potential production of methane and electrical energy from sugarcane vinasse in Brazil: A thermo-economic analysis. *J. Environ. Chem. Eng.* **2020**, *8*, 103422. [CrossRef]
29. da Silva, M.B.; dos Santos Morais, A. *Avaliação Energética do Bagaço de Cana em Diferentes Níveis de Umidade e Graus de Compactação*; XXVIII Encontro Nacional de Engenharia de Produção: Rio de Janeiro, Brazil, 2008.
30. REN 21. Energy Units and Conversion Factors. Available online: https://www.ren21.net/gsr-2018/pages/units/units/ (accessed on 9 November 2022).
31. Salomon, K.R.; Silva Lora, E.E. Estimate of the electric energy generating potential for different sources of biogas in Brazil. *Biomass Bioenergy* **2009**, *33*, 1101–1107. [CrossRef]
32. Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 1—General Guidance and Reporting*; Annex 8A.1 Prefixes, units and abbreviations, standard equivalents; IPCC: Geneva, Switzerland, 2006.
33. Sheng, C.; Azevedo, J.L.T. Estimating the higher heating value of biomass fuels from basic analysis data. *Biomass Bioenergy* **2005**, *28*, 499–507. [CrossRef]
34. Melikoglu, M.; Menekse, Z.K. Forecasting Turkey's cattle and sheep manure based biomethane potentials till 2026. *Biomass Bioenergy* **2020**, *132*, 105440. [CrossRef]
35. De Oliveira, A.C.L.; de Oliveira Resende, M.; Silva, E.G.M.; dos Santos Renato, N.; Martins, M.A.; Sequinel, R.; Machado, J.C. Evaluation and optimization of electricity generation through manure obtained from animal production chains in two Brazilian mesoregions. *J. Clean. Prod.* **2021**, *316*, 128270. [CrossRef]
36. Ferreira, L.R.A.; Otto, R.B.; Silva, F.P.; De Souza, S.N.M.; De Souza, S.S.; Junior, O.A. Review of the energy potential of the residual biomass for the distributed generation in Brazil. *Renew. Sustain. Energy Rev.* **2018**, *94*, 440–455. [CrossRef]
37. Instituto Brasileiro de Geografia e Estatística. Estimativas de População Residente no Brasil e Unidades da Federação Com Data de Referência em 1° de Julho de 2021. Available online: https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?=&t=resultados (accessed on 1 December 2022).
38. Towprayoon, S.; Tomonori, I.; Chiemchaisri, C.; Abdel-Aziz, A.O. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 5 Waste, Ch. 3 Solid Waste Disposal*; IPCC: Geneva, Switzerland, 2019.
39. Empresa de Pesquisa Energética—EPE Informativo Técnico. 011/2022, EPE/DEA/SMA Dez/2022, 13. Technical Report. Available online: https://www.epe.gov.br/sites-pt/areas-de-atuacao/estudos-socioambientais/SiteAssets/Paginas/Emissoes-de-Gases-de-Efeito-Estufa/Informativo%20Tecnico_11-2022_fatores%20de%20emiss%C3%A3oSMA.pdf (accessed on 1 December 2022).
40. Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2—Energy*; Ch 2. Stacionary Combustion; IGES: Kanagawa, Japan, 2006.
41. Liu, W.; Zhang, Z.; Xie, X.; Yu, Z.; von Gadow, K.; Xu, J.; Zhao, S.; Yang, Y. Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. *Sci. Rep.* **2017**, *7*, 39857. [CrossRef]
42. Júnior, E.P.S.; da Silva, M.V.B.; Simioni, F.J.; Junior, P.R.; Menezes, R.S.C.; Junior, L.M.C. Location and concentration of the forest bioelectricity supply in Brazil: A space-time analysis. *Renew. Energy* **2022**, *199*, 710–719. [CrossRef]
43. Bichel, A.; Telles, T.S. Spatial dynamics of firewood and charcoal production in Brazil. *J. Clean. Prod.* **2021**, *313*, 127714. [CrossRef]
44. Instituto Brasileiro de Geografia e Estatística. *Divisão Regional do Brasil em Regiões Geográficas Imediatas e Regiões Geográficas Intermediárias: 2017*; IBGE Coordenação de Geografia, Ed.; IBGE Coordenação de Geografia: Rio de Janeiro, Barzil, 2017; ISBN 9788524044182.
45. Piacenti, C.A.; Alves, L.R.; De Lima, J.F. O Perfil Locacional do Emprego Setorial no Brasil. *Rev. Econ. Nordeste* **2008**, *39*, 481–502.
46. Santos, S.C.J.; Gomes, L.J. Consumo e procedência de lenha pelos estabelecimentos comerciais de Aracaju-SE. *Rev. Fapese* **2009**, *5*, 155–164.
47. GIODA, A. Características e procedência da lenha usada na cocção no Brasil. *Estud. Avançados* **2019**, *33*, 133–150. [CrossRef]
48. Eduardo Luiz, G. Rios Neto. Indicadores IBGE—Estatística da Produção Pecuária. *Inst. Bras. Geogr. Estatística* **2021**, *1*, 91.
49. Embrapa Suínos e Aves (Brazilian Agricultural Research Corporation). *Annual Report 2019/Editors Monalisa Leal Pereira, Lucas Scherer Cardoso*; Embrapa Suínos e Aves: Concórdia, Brazil, 2020.
50. Pedroso, L.G.; Lages, A.M.G.; Silva, R.P. As estruturas canavieira e citrícola em Alagoas, Pernambuco e São paulo. *Rev. Política Agrícola* **2015**, *24*, 88–101.
51. Santos Júnior, E.P. Concentração e Distribuição Espacial da Oferta Brasileira de Bioeletricidade Florestal-1° Lugar-Categoria: Graduação; VI Prêmio Serviço Florestal Brasileiro em Estudos de Economia e Mercado Florestal. 2018. Available online: http://repositorio.enap.gov.br/handle/1/3826 (accessed on 6 March 2023).

52. Agência Nacional de Energia Elétrica. Sistema de Informações de Geração da ANEEL. Available online: http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm (accessed on 5 September 2018).
53. Coelho Junior, L.M.; Burgos, M.D.C.; Santos Júnior, E.P. Concentração regional da produção de lenha da Paraíba. *Ciência Florest.* **2018**, *28*, 1729. [CrossRef]
54. Rabaia, M.K.H.; Abdelkareem, M.A.; Sayed, E.T.; Elsaid, K.; Chae, K.-J.; Wilberforce, T.; Olabi, A.G. Environmental impacts of solar energy systems: A review. *Sci. Total Environ.* **2021**, *754*, 141989. [CrossRef]