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Assessment of Bioenergy Potential from Biomass Waste to Improve Access to Clean Energy for Cooking in Mali

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Abstract: A lack of access to clean cooking fuels and technologies in Mali is causing negative health and welfare impacts on the population. There is a need to transition to cleaner cooking systems, and the production of biofuels is one promising solution. In order to successfully use biofuels in Malian households, it is necessary to calculate the sustainable bioenergy potential of the country. The aim of this study, therefore, was to assess this potential to determine if it can meet the cooking energy demand. Statistical data were used to estimate the bioenergy potential from three different biomass resources: crop residues, livestock waste, and municipal solid waste (MSW). Surveys in urban and rural areas in Mali were performed to assess cooking fuel consumption in the residential sector. Bioenergy potential and cooking energy demand were compared regionally to find out if biomass is a feasible substitute for traditional cooking fuels in Mali. It was shown that while there is high biogas potential in most of the regions, urban Bamako has a lack of biomass resources to cover the demand. Therefore, other clean alternatives like electric cooking should be considered for urban areas.

Keywords: biomass conversion technologies; cooking energy; rural energy transition; energy efficiency; waste to energy

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1. Introduction

During recent decades, fossil fuels have represented around 80% of the global energy demand [1]. The widespread reliance on fossil fuels for energy presents two major challenges. On the one hand, the combustion of fossil fuels is linked with environmental degradation and the emission of greenhouse gases (GHGs), which are the main contributors to climate change [2]. On the other hand, fossil fuels are non-renewable resources, so they are subject to running out. The depletion of fossil fuels is one of the main concerns in global energy policy, as it directly affects prices and supply [3]. Due to these reasons, a transition is needed toward cleaner ways of generating and using energy through renewable resources.

Although fossil fuels still have the largest share of global energy demand, the use of renewable energy is growing faster. From 2009 to 2020, renewable energy demand increased by 4.6% per year, compared to 0.9% of fossil fuels and 1.2% of global energy demand [1]. This has led to an increase in modern renewables' share of global energy demand from 8.7% in 2009 to 12.6% in 2020. Moreover, bioenergy plays an important role in the decarbonization and diversification of energy systems as part of modern renewables. The same REN21 report [1] specifies that in 2020, 5.4% of global energy demand was supplied by modern bioenergy, representing 47% of all modern renewable energy.

Bioenergy is a form of renewable energy that is produced from organic matter, which is known as biomass. This biomass is generated from plants or is plant-derived, including waste from agriculture, forestry, livestock, sewage, municipal solid waste (MSW), and energy crops. Traditionally, biomass has been used for heat generation through the direct combustion of firewood and charcoal, as well as agricultural residues and dung. The primary technology for the traditional use of biomass in the Global South is inefficient stoves, which are still widely used for cooking and heating in the residential sector [1]. In contrast, modern bioenergy can be used for different end-use applications (i.e., heating, power, and transport) with different biomass fuel types (i.e., solid, liquid, and gas) and at higher efficiency levels. A transition toward clean renewable energy requires the modernization of bioenergy systems as they can contribute to reducing the demand for fossil fuels in all sectors bringing economic and environmental benefits [4].

Sub-Saharan Africa is the region with the largest reliance on the traditional uses of biomass in the world. When looking at just the cooking sector in this region, 923 million people have no access to clean cooking fuels [5]. The use of solid biomass in traditional stoves is related to high levels of indoor air pollution, exposing women and children to numerous health issues [6]. Moreover, a lack of access to clean cooking fuels has other impacts, such as a reduction in women's time for income activities and their exposure to dangers while gathering fuel [7], or high deforestation rates and landscape degradation, which contribute to the increase in GHG emissions [8]. Modernizing the use of bioenergy in Sub-Saharan Africa would tackle these impacts while increasing access to clean energy. However, the transition to modern bioenergy use varies across countries due to diverse geographical, socio-economic, and cultural factors [9]. Therefore, issues such as policy development, cross-sectoral approaches, financing, research, or capacity building have to be considered for each context, while the harmonization of standards and policy frameworks can enhance regional cooperation. Moreover, Maishanu et al. [9] pointed out that a definition of information systems to determine sustainable bioenergy potential at the state and province level is essential to developing modern bioenergy systems.

One of the Sub-Saharan countries with the highest dependence on traditional biomass use is Mali. Located in the Sahel region, Mali is characterized by three different climate areas: tropical savanna in the south, hot semi-arid regions in the center, and hot desert in the north [10]. Most people in Mali live in the southern part of the country, where annual precipitation variation is high during the rainy season, which develops from April to October. As of 2021, the estimated population in Mali was 21.9 million, an increase of more than 10 million in the previous 10 years [11]. Although most of the population lives in rural areas, it was estimated that the share of people living in cities increased from 29.1% to 44.7% in the same period [12]. This population growth and urbanization rate have resulted in the country experiencing an increase in energy demand in recent years, especially for traditional fuels [13]. By 2020, biomass represented around 64% of the total energy supply, followed by oil at 33% and hydro at 3%, with solar, coal, and others being practically insignificant. However, when looking at electricity generation, hydro accounts for 57% of it, followed by oil at 38% and other fossil fuels, solar, and biomass at just around 3% [14]. Only around 53% of the population has access to electricity. Moreover, there is a huge difference between urban and rural populations, as electricity access in urban areas is around 97% compared to 18% in rural areas [15]. However, when comparing electrification to clean cooking fuel access, the latter is in a more critical situation.

Currently, Mali is one of the countries in the world with the lowest access to clean cooking fuels. The National Institute of Statistics (INSTAT) estimated that, as of 2020, 47.4% of the population used firewood as the primary source for cooking, 47% used charcoal, and around 3.3% used oil or animal waste [16]. When looking at access to clean cooking fuels and technologies as a whole, it is only around 0.9% of the population, with this value being stagnant during the last decade [15]. This reliance on polluting fuels highlights the importance of assessing the biomass waste resources in the country and their potential implementation for a transition toward modern bioenergy systems in the residential cooking sector. Mali is mainly an agricultural country, greatly dependent on this activity to sustain its socio-economic development [17]. Thus, there is considerable production of crop residues and livestock waste, which have not been quantified in detail so far. Moreover, MSW is poorly treated in the country. Waste disposal at uncontrolled open landfill sites is the most common practice. However, waste-to-energy technologies are preferred in the waste management hierarchy, as they are more socio-economically and environmentally beneficial [18]. Therefore, MSW could also be a potential source of bioenergy generation.

As mentioned above, low clean cooking access in Malian households makes a transition in this sector indispensable, with modern bioenergy systems being potential alternatives. To develop these systems in the country, it is essential to determine the quantity of available biomass resources and how they could contribute to bioenergy production for cooking. In the literature, the estimations of bioenergy potential have been focused on specific regions and/or crops, with little attention given to demand in the cooking sector [19,20]. Regarding livestock waste, Arthur and Baidoo [21] estimated the potential production of methane in the country by using animal manure, but without an energy-use perspective. These previous studies consider the entirely available biomass resources in the country, but without taking into account how the bioenergy resources for each waste stream can be applied in the cooking sector. In some cases where the bioenergy potential of a specific crop is quantified, its use for electricity production is prioritized. Using bioenergy for cooking could reduce the electric demand of rural households for their basic needs, thus helping to expand faster and in a more affordable way the electrification of the country [22].

The aim of the present study, therefore, is to assess the potential production of bioenergy from crop residues, livestock waste, and MSW, considering the specific end products for each biomass resource to meet the cooking needs of Malian households. Moreover, the estimation of biomass resources and their respective bioenergy products is presented geographically, considering the differences between the regions of Mali. This differentiation helps to determine to what extent each biomass resource can contribute to the cooking demand of each region. For this purpose, the useful energy cooking demand per region in Mali is also estimated. It should be noted that an economic analysis of bioenergy fuel applications is not considered as it is outside the scope of this study. The reason is the lack of data for estimating feedstock prices and supply costs in the country, thereby increasing its complexity.

The present work is the first study to comprehensively assess sustainable biomass potential in Mali, which is a crucial step for promoting bioenergy systems. In order to determine the potential production of cooking biofuels, the proposed methodology compared different production routes for the available biomass. This means that one biomass resource can be used for the production of different biofuels. This is a different approach to other similar studies, where normally only one route of biomass resource to bioenergy end product is considered. This approach can allow technology developers to compare the efficiency of different production systems while considering alternative biofuels to meet the cooking energy demand. This can also raise awareness about the availability of biomass for cooking and if other energy systems are required to achieve a clean cooking transition.

This paper is structured as follows: The next section presents the methodology of the study, followed by the results and discussion section, where the main findings of the study are presented and discussed. Finally, the conclusion constitutes the last section.

2. Materials and Methods

In order to assess the bioenergy potential of the country and compare it with the cooking energy demand, the methodology was based on two main parts: desk research and fieldwork. The desk research included gathering data from official reports of the National Institute of Statistics, scientific papers, and other reports from governmental and international agencies. Those data and the data obtained after the fieldwork were analyzed. In the fieldwork, surveys of households in Bamako and a selected rural village were conducted regarding cooking practices and fuel consumption. This was complemented by separate interviews with local experts about the fuel market and energy demand.

The methodology is structured into three subsections. In the first subsection, the estimation of biomass resource potential is presented, including crop residues, livestock waste, and MSW. Subsequently, the estimation of bioenergy potential is presented, focusing on the production of briquettes, biogas, and bioethanol. Finally, the methodology for estimating the cooking energy demand in the Malian residential sector is presented.

2.1. Estimation of Biomass Resource Potential

In the literature, the potential of biomass resources for energy production is defined in several ways, encompassing theoretical potential, technical potential, economic potential, and sustainable potential [23]. Some even consider ecological potential or implementation potential [24]. Those terms are presented in the literature with different definitions, and in some cases, they might overlap. For example, Batidzirai et al. [24] presented economic potential as a subset of technical potential, with this being a subset of theoretical potential.

This study is focused on the concept of sustainable potential, understood as the fraction of produced biomass waste at a given time that can be obtained without negative social or ecological effects. It means the share of biomass waste that is disposed of or burned, which could be collected. This is especially relevant for crop residues, as agricultural waste has many purposes in the Malian context, e.g., animal fodder or soil fertilizer. Waste already employed for feeding animals or incorporated into soil is not available for bioenergy production.

The estimation of sustainable biomass resource potential was calculated for different regions according to the country's division before 2016 [25]. The selected regions are Bamako, Gao, Kayes, Kidal, Koulikoro, Mopti, Ségou, Sikasso, and Tombouctou. Consequently, the current regions of Taoudénit and Ménaka are part of Tombouctou and Gao, respectively. The choice of the previous division for the estimation of sustainable biomass resource potential was due to easier data access, while the new division's effect on the geographical distribution is not very significant. This previous division is also used for estimating bioenergy potential and cooking energy demand in the following sections. Figure 1 shows cropland use in the country together with the administrative division, aiding in understanding the effect of climate areas on the distribution of agricultural land.

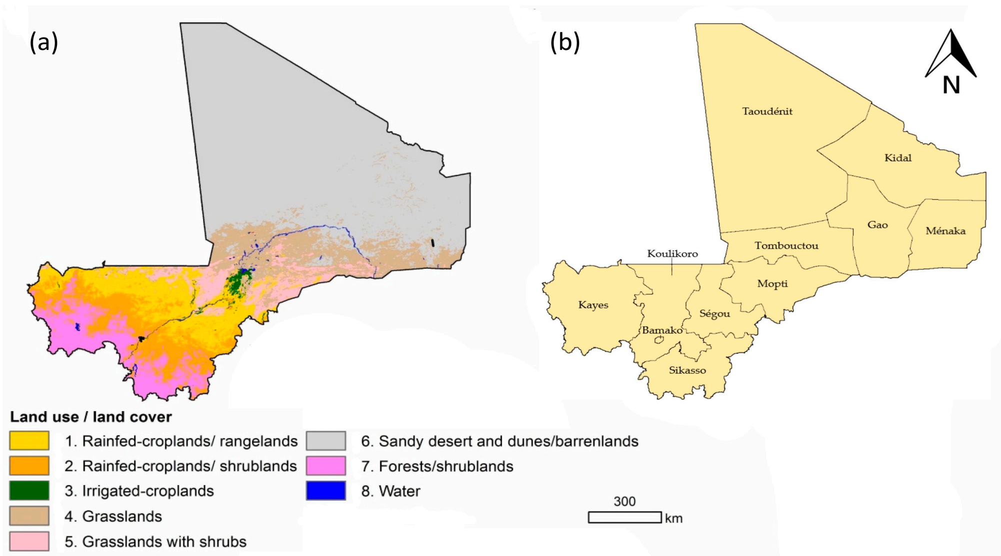

Figure 1. (**a**) Map of land use distribution in Mali. (**b**) Map of the administrative division of Mali [26].

2.1.1. Crop Residues

Cereals are the major type of crop produced in Mali. The main crops grown for subsistence are millet, sorghum, rice, and maize (corn), representing almost 75% of total crop production for food in the country. When the production of cowpea, groundnut, and sweet potato is considered, this share increases to around 82% [27]. Fruit crops like mango, banana, and orange also contribute significantly to food production. With their addition, more than 90% of the crops for food production in the country are included. Further, the country's two main cash crops are also considered in this study. One is sugarcane, which has a high production potential in the Ségou region [20]. The other is cotton, a major export and considered a key crop for socio-economic development, according to the Malian government [28].

To estimate the crop waste potential, crop production quantities were obtained from the 2015 Statistical Yearbook of the Rural Development Sector published by the Malian Ministry of Agriculture [27]. This statistical report is the most recent of its kind in the country. The equations and procedures used to estimate biomass resource potential in this study are based on similar cases for other countries in the literature [29–32]. These procedures rely on two main parameters associated with crop residues. The first is the residue-to-product ratio (RPR), which determines the mass of crop residue compared to the same type of crop production. The second is the surplus residue fraction (SRF), also known as the surplus availability factor [30] or recoverability fraction [32], among other terms. The SRF indicates the share of crop waste available for bioenergy production and not being used for other purposes, like animal fodder or bedding. Although animal bedding can be reused for energy purpose, its use as fertilizer is widespread in Sub-Saharan Africa [33]. Therefore, animal bedding is not considered here for energy purposes. Equation (1) shows how the crop residue potential is calculated for each region of the country:

$$SCRP(j) = \sum_{i=1}^{n} CP(i,j) \times RPR(i) \times SRF(i) \quad (1)$$

where *SCRP(j)* is the sustainable crop residue potential at the *j*th region (t/y); *n* is the total number of crops considered; *CP(i,j)* is the crop production of the *i*th crop at the *j*th region (t/y); *RPR(i)* is the residue to product ratio of the *i*th crop (-); and *SRF(i)* is the surplus residue fraction of the *i*th crop (%).

To determine the RPR and SRF values for the selected crops, studies in Mali were prioritized. When this was not possible, the values were assumed using studies for the given crops in other Sub-Saharan regions. RPR and SRF were determined for the main residue types for each crop. Table 1 shows the input parameters used in the estimation of the sustainable crop residue potential. It should be noted that the waste produced by cowpea crops is commonly used as fodder for animals, so it was not considered for bioenergy production [34].

Table 1. RPR and SRF values for selected crop residues in Mali.

Crop	Crop Waste	RPR	Reference	SRF	Reference
Millet	Millet straw	2.00	[35]	37%	[34]
Sorghum	Sorghum straw	2.00	[35]	29%	[34]
Rice	Rice straw	0.75	[19]	10%	[19]
	Rice husk	0.21	[36]	10%	[19]
Maize	Maize stalk	1.20	[36]	9%	[20,34]
	Maize cobs	0.65	[36]	9%	[20,34]
Mango	Mango pruning	1.80	[32]	80%	[32]
Banana	Banana leaves	0.35	[32]	80%	[32]
	Banana stem	5.60	[32]	80%	[32]
	Banana peels	0.25	[32]	80%	[32]
Orange	Orange pruning	0.29	[32]	80%	[32]
Cowpea	Cowpea waste			0%	[34]
Groundnut	Groundnut stalk	2.30	[35]	9%	[34]
	Groundnut husk	0.42	[35]	9%	[34]
Sweet Potato	Leaves and peel	0.50	[32]	80%	[32]
Cotton	Cotton stalk	2.00	[37]	60%	[20,34]
Sugarcane	Sugarcane bagasse	0.23	[32]	5%	[20]

The use of average parameters adds uncertainty to the estimation of sustainable biomass potential, not only for crop residues but also for livestock waste and MSW. Nygaard et al. [19] already pointed out this problem in their study of the rice waste potential in the Office du Niger, showing a lack of scientific data regarding parameters used, such as the RPR. Although in the current study the use of data from the studied country or region was prioritized, the results have to be taken to some extent with a degree of uncertainty. Moreover, when data on potential estimates were available for certain crops or regions, the results were compared to observe if there were significant deviations.

2.1.2. Livestock Waste

Livestock waste refers to the dung produced by farm animals. According to the 2015 Statistical Yearbook data [27], the main types of animals are cattle, sheep, goats, horses, donkeys, camels, pigs, and poultry. In this same report, the total number of heads for the different livestock types in all the regions of the country is given. The equations and procedures to estimate the biomass resource potential from livestock waste are based on similar previous studies for different regions [30].

In order to determine the livestock waste potential, it is necessary to determine the quantity of manure produced by each type of animal. This quantity depends on different factors such as animal age, feeding habits, type of fodder, and even temperature. Moreover, the availability factor is used to estimate the total quantity of livestock waste suitable for bioenergy production. This factor represents the share of waste that can be collected and is not used for other purposes. Equation (2) shows how the sustainable livestock waste potential for bioenergy production is estimated for each region:

$$SLWP(j) = \sum_{i=1}^{n} N_A(i,j) \times Y_M(i) \times AF(i) \times D_y \quad (2)$$

where $SLWP(j)$ is the sustainable livestock waste production at the jth region (t/y); $N_A(i,j)$ is the number of heads of the ith animal at the jth region; $Y_M(i)$ is the daily manure yield of the ith animal in [t/(day·animal)]; $AF(i)$ is the availability factor for the ith animal (-); and D_y is a conversion factor representing the number of days in a year (d/y), i.e., 365.

Due to the lack of literature data on livestock waste production in Mali, different worldwide studies for manure yield and available factor values were considered (Table 2). As these values are affected by the different aforementioned conditions, average values were assumed for the Malian context. The manure yield for cattle and camels was considered 15 kg per day and head, 10 kg for horses and donkeys, 1.6 kg for sheep and goats, 3.12 kg for pigs, and 0.05 kg for poultry. In the case of the availability factor, it was chosen as 0.35 for cattle; 0.25 for sheep and goats; 0.5 for horses, donkeys, and camels; 0.9 for pigs; and 0.75 for poultry.

Table 2. Manure yield and availability factor values.

Animal	Manure Yield (kg/(Day × Head))	References	Availability Factor	References
Cattle	10–22.5	[38–40]	0.2–0.5	[39,40]
Sheep	1.2–2	[38–40]	0.2–0.33	[39,40]
Goats	1.5–2	[38–40]	0.2–0.33	[39,40]
Horses	10	[40]	0.5	[40]
Donkeys	10	[40]	0.5	[40]
Camels	15–22.5	[40,41]	0.5	[40]
Pigs	3.12–3.6	[39,42]	0.9	[42]
Poultry	0.02–0.1	[38–40]	0.5–0.99	[39,40]

2.1.3. Municipal Solid Waste

For the estimation of biomass resource potential from MSW, there are different approaches in the literature. While some studies consider the entire population [30], others only consider urban areas [43]. In this study, urban population is used for estimating MSW generation, as there are no known strategies for waste collection in rural areas of the country, and usually, the waste generated per capita in these areas is low. Data on the total population for 2015 was available from the 2015 Statistical Yearbook [27]. The share of urban population was estimated using data from the last official census from the National Institute of Statistics (INSTAT) in 2009 [44] and using an average increase in urban population of 0.8% annually between 2009 and 2015 [45]. According to the INSTAT census, urban populations consist of urban municipalities with at least 5000 inhabitants. The estimated values of the population are shown in Table 3.

Table 3. Total population and share of urban population in Mali in 2015. Data source: [27,44,45].

Region	Population (2015)	Urban Population, % (2015)
Bamako	2,480,320	100%
Gao	658,938	41%
Kayes	2,450,662	30%
Kidal	87,206	43%
Koulikoro	3,064,739	36%
Mopti	2,445,538	22%
Ségou	2,808,415	26%
Sikasso	3,268,023	35%
Tombouctou	819,922	26%
Total	18,083,763	40%

With the urban population defined, Equation (3) is used to estimate the sustainable MSW potential for bioenergy production:

$$SSMSWP(j) = UP(j) \times MSW_G(j) \times RC(j) \times D_y \tag{3}$$

where *SMSWP(j)* is the sustainable MSW potential at the *j*th region (t/y); *UP(j)* is the urban population at the *j*th region; $MSW_G(j)$ is the MSW generation at the *j*th region [t/(person·day)]; *RC(j)* is the rate collection at the *j*th region; and D_y is a conversion factor representing the number of days in a year (d/y), i.e., 365. For the generation of MSW, it was determined a value of 0.65 kg/(person·day) ($6.5 \cdot 10^{-4}$ t/(person·day)) for the entire country, while the average rate collection in Mali is 85% according to the literature [46,47].

2.2. Estimation of Bioenergy Potential

The sustainable biomass resource potential of Mali can be a source for the production of bioenergy, thus helping to increase access to energy for its population. Although the contribution of biomass to the production of clean cooking fuel is low in Mali, there are some existing applications both in the commercial and pilot-scale phases. The main bioenergy fuels used in the country, besides firewood, are solid briquettes for improved cook stoves (ICSs), biogas, and bioethanol [48]. The following subsections show the methodology used to estimate their potential production from biomass resources.

2.2.1. Briquettes Potential

Briquettes are formed in different shapes by the compression of biomass, such as agricultural waste. The compression of biomass allows it to have a longer burning time and an improved density for handling it. Therefore, briquettes substitute charcoal and firewood in many countries for cooking purposes [49]. In order to estimate the potential of briquettes in Mali, only the application of crop residue and its densification is considered. With this assumption, a calculation can be performed using the heating content of the biomass resources, as was conducted in previous similar cases [29]. A lower heating value (LHV) is used. Equation (4) is used to determine the bioenergy potential for each region:

$$E_{briquettes}(j) = \sum_{i=1}^{n} SRCP(i,j) \times LHV(i) \tag{4}$$

where $E_{briquettes}(j)$ is the briquette bioenergy potential at the jth region (TJ/y); $SRCP(i,j)$ is the sustainable residue crop potential of the ith crop at the jth region (t/y); and $LHV(i)$ is the low heating value of the ith crop (TJ/t). The values of LHV were obtained from the literature from case studies in Sub-Saharan Africa, as shown in Table 4.

Table 4. LHV values for different crop residues.

Crop Residue	LHV (GJ/t)	Reference
Millet straw	15.51	[35]
Sorghum straw	14.40	
Rice straw	16.02	
Rice husks	19.93	
Maize stalks	15.51	
Maize cobs	16.63	
Mango pruning	17.50	[32]
Banana leaves	11.37	
Banana stems	12.38	
Banana peels	15.83	
Orange pruning	18.10	
Groundnut stalks	14.40	[35]
Groundnut husks	15.56	
Cotton stalks	18.61	[50]
Sugarcane bagasse	18.10	

All crop residues were considered except for sweet potato waste. According to Bot et al. [51], sweet potato waste is not suitable for the production of briquettes due to its properties, which is consistent with the lack of studies on briquette production from this biomass resource. Therefore, sweet potato waste was only considered for biogas and bioethanol potential.

2.2.2. Biogas Potential

Biogas is a mixture of methane, carbon dioxide, and other gases in small proportions. The relatively high methane content of biogas makes it suitable for energy purposes; however, the quantity of methane depends on different parameters, with the feedstock being one of the most relevant. The production of biogas is based on the anaerobic digestion of organic matter, including biomass such as crop residues, livestock waste, or MSW [52]. In this work, all biomass resources were considered for the estimation of the biogas potential. Concerning crop residues, the potential bioenergy from anaerobic digestion was determined using the methane yield of different crop wastes, following a similar procedure to Kemausuor et al. [39]. Equation (5) shows bioenergy potential estimation from the anaerobic digestion of crop residues:

$$E_{biogas,cr}(j) = \sum_{i=1}^{n} SRCP(i,j) \times DM(i) \times Y_{CH4}(i) \times U_{CH4} \tag{5}$$

where $E_{biogas,cr}(j)$ is the biogas energy potential at the *j*th region (TJ/y); *SCRP(i,j)* is the sustainable residue crop potential for the *i*th crop at the *j*th region (t/y); *DM(i)* is the dry matter content of the *i*th crop (-); Y_{CH4} is the methane yield of the *i*th crop (m^3 CH_4/t DM); and U_{CH4} is the energy density of methane in (TJ/m^3). The energy density of methane was considered to be 36 MJ/m^3 [53]. The values for dry matter (DM) and methane yield were obtained from the literature, as shown in Table 5.

Table 5. Methane yield and DM values for crop waste.

Feedstock	Methane Yield (m^3 CH_4/t DM)	Reference	DM Ratio	Reference
Millet straw	181	[39]	0.92	[54]
Sorghum straw	285		0.87	
Rice straw	264		0.91	
Rice husks	232		0.92	
Maize stalks	268		0.8	
Maize cobs	348		0.9	
Mango pruning	159		0.85	[55]
Banana leaves	213		0.21	[56]
Banana stems	213		0.07	
Banana peels	213		0.154	[57]
Orange pruning	159		0.85	[55]
Groundnut stalks	154		0.91	[54]
Groundnut husks	227		0.91	
Sweet potato waste	253		0.89	
Cotton stalks	225		0.9	
Sugarcane bagasse	221		0.91	

For the potential biogas production from livestock waste, first the volume of biogas produced is calculated using Equation (6). The production of biogas depends on the quantity of total solids (TSs) present in a given kind of livestock dung [40]. Once the volume of biogas per livestock waste is estimated, it is possible to determine the bioenergy potential through its methane content:

$$V_{biogas,lw}(j) = \sum_{i=1}^{n} SLWP(i,j) \times TS(i) \times Y_{biogas}(i) \quad (6)$$

where $V_{biogas,lw}(j)$ is the volume of biogas from livestock waste at the *j*th region (m^3/y); *SLWP(i,j)* is the sustainable livestock waste potential of the *i*th waste at the *j*th region (t/y); *TS(i)* is the total solids of the *i*th waste (-); and Y_{biogas} is the biogas yield of the *i*th waste (m^3/t TS). Table 6 shows the considered values for TS and biogas yield according to the literature. Different literature was reviewed, selecting average values for the Malian context. For TS, it was selected a value of 0.2 for cattle and pigs; 0.25 for sheep, goats, horses, donkeys, and camels; and 0.29 for poultry. For biogas yield, 0.6 m^3/t TS was chosen for cattle, horses, donkeys, and camels and 0.4 for the rest.

Table 6. Values on TS and biogas yield for livestock waste.

Animal	TS	References	Biogas Yield (m^3/t TS)	References
Cattle	0.12–0.25	[39,40,58]	0.6–0.8	[40,41,58]
Sheep	0.2–0.29	[39,40,58]	0.33–0.6	[40,41,58]
Goats	0.2–0.29	[39,40,58]	0.33–0.6	[40,41,58]
Horses	0.25	[40]	0.6	[40]
Donkeys	0.25	[40]	0.6	[40]
Camels	0.25	[38,40,41]	0.6–0.8	[40,41]
Pigs	0.11–0.25	[39,58,59]	0.37–0.4	[58,60]
Poultry	0.25–0.29	[39–41,58]	0.15–0.8	[40,41,58]

Equation (7) shows how the bioenergy potential from the anaerobic digestion of livestock waste is estimated:

$$E_{biogas,lw}(j) = \sum_{i=1}^{n} V_{biogas,lw}(i,j) \times c_{CH4}(i) \times U_{CH4} \quad (7)$$

where $E_{biogas,lw}(j)$ is the bioenergy potential produced from the anaerobic digestion of livestock waste at the jth region (TJ/y); $V_{biogas,lw}(j)$ is the volume of biogas from livestock waste at the jth region (m^3/y); $c_{CH4}(i)$ is the content of methane in biogas for the ith livestock waste (%); and U_{CH4} is the energy density of methane (TJ/m^3). The energy density of methane was considered to be 36 MJ/m^3 [53]. In terms of methane content, it was considered that poultry waste has a share of 50%, while for the dung of other animals, the share is 60% [40].

In the case of MSW, its organic biodegradable fraction was considered for the production of biogas, as this is a correct practice according to the literature [61]. Equation (8) shows how the bioenergy potential from the anaerobic digestion of MSW is calculated:

$$E_{biogas,MSW}(j) = \sum_{i=1}^{n} SMSWP(j) \times OF \times VS \times Y_{CH4} \times U_{CH4} \quad (8)$$

where $E_{biogas,MSW}(j)$ is the bioenergy potential from the anaerobic digestion of MSW at the jth region (TJ/y); $SMSWP(j)$ is the sustainable MSW potential at the jth region (t/y); OF is the organic biodegradable fraction of MSW (%); VS is the volatile solid (VS) content of MSW (%); Y_{CH4} is the methane yield of MSW (m^3/t VS); and U_{CH4} is the energy density of methane (TJ/m^3).

The average values for the organic biodegradable fraction in MSW at the country level in Mali are between 18 and 21% [46,62]. For this study, an average value of 20% was considered. For the case of VS content, a value of 23% was chosen, with an average methane yield of 415 m^3/t VS for MSW [63].

2.2.3. Bioethanol Potential

Biothanol is a biofuel with a high octane number, which is the result of the fermentation of simple sugars in diverse plant biomass, such as agricultural residues. The most commonly used feedstock for the production of bioethanol is lignocellulosic biomass [64]. In the case of MSW, a previous study showed that its use for ethanol production is less advantageous than for biogas [65]. Similarly, Kemausuor et al. [39] only selected MSW for biogas production and not for bioethanol in a study in Ghana. Therefore, only crop residues were considered for the production of bioethanol in the present study.

In order to produce bioethanol through fermentation, the lignocellulosic biomass has to be converted into glucose. This conversion requires a pre-treatment process, which usually involves a hydrolysis step [66]. Following a similar procedure to Kemausuor et al. [39], the stoichiometric yields and conversion efficiencies of the process were considered. Equation (9) shows how the bioenergy potential of bioethanol is calculated:

$$E_{bioethanol}(j) = \sum_{i=1}^{n} SCRP(i,j) \times DM(i) \times c_{glu}(i) \times y_{hyd} \times y_{eth} \times \eta_{pre} \times \eta_{enz} \times U_{eth} \quad (9)$$

where $E_{bioethanol}(j)$ is the bioenergy potential from bioethanol production at the jth region (TJ/y); $SCRP(i,j)$ is the sustainable crop residue potential for the ith crop residue at the jth region (t/y); $DM(i)$ is the dry matter content of the ith crop residue (-); $c_{glu}(i)$ is the concentration of glucan at the ith crop residue (g/g TS); y_{hyd} is the glucose yield during hydrolysis (g/g); y_{eth} is the ethanol yield during fermentation (g/g); η_{pre} is the efficiency in the conservation of glucan in the pre-treatment (%); η_{enz} is the efficiency of the enzymatic conversion of glucan (%); and U_{eth} is the energy content of bioethanol (TJ/t).

The selected values of DM content per crop residue are shown in Table 5, while the concentration of glucan per crop residue is shown in Table 7. The selected indices used in Equation (9) were obtained from the study of Kemausuor et al. [39] in Ghana. The glucose yield during hydrolysis was considered 1.11 g/g, while the yield of glucose converted into ethanol during fermentation was 0.51 g/g. For the efficiency values, 90% was assumed for the pre-treatment and 80% was assumed for the enzymatic conversion of glucan. The energy content of bioethanol was considered at 26 MJ/kg [67].

Table 7. Glucan content per type of crop residue. Data source: [39].

Feedstock	Glucan Content (g/g TS)
Millet straw	0.269
Sorghum straw	0.416
Rice straw	0.378
Rice husks	0.313
Maize stalks	0.368
Maize cobs	0.34
Mango pruning	0.21
Banana leaves	0.34
Banana stems	0.34
Banana peels	0.34
Orange pruning	0.21
Groundnut stalks	0.372
Groundnut husks	0.357
Sweet potato waste	0.198
Cotton stalks	0.42
Sugarcane bagasse	0.36

2.3. Estimation of the Cooking Energy Demand of Malian Households

The demand for cooking energy in the residential sector of Mali was compared with the bioenergy potential of the country. The demand was estimated based on the share of the population without access to clean cooking fuels in the country. While the population in Mali is given in Table 3, the share of people without access to clean cooking is 99.1% [15]. Although firewood has been the predominant fuel for cooking, charcoal consumption has increased in the last few years, especially in urban areas. As the rate of access to clean cooking is very low in Mali, it can be assumed that almost all households consume either firewood or charcoal. The share of consumption of each fuel per region according to INSTAT [16] is shown in Table 8, considering only the population without access to clean cooking fuels.

Table 8. Type of fuel consumed per region among the population without access to clean cooking fuels. Data estimated from [16].

Region	Firewood Consumption (%)	Charcoal Consumption (%)
Bamako	4.8%	95.2%
Gao	38.0%	62.0%
Kayes	50.5%	49.5%
Kidal	12.7%	87.3%
Koulikoro	60.7%	39.3%
Mopti	77.6%	22.4%
Ségou	41.9%	58.1%
Sikasso	59.9%	40.1%
Tombouctou	29.7%	70.3%
Total	47.4%	58.2%

When observing the type of fuel consumed for cooking in urban or rural areas, it is noticed that firewood is still predominant in rural areas, with comparatively little charcoal consumption. Therefore, it is crucial to target fuel consumption per capita in Mali according to differences between urban and rural regions. In this regard, a structured questionnaire-based survey was conducted in Bamako and a rural village with the help of local university staff to facilitate the interaction with the population. The survey in Bamako addressed 360 households, including households from all six different communes that form the city. For the small rural village, Katibougou was selected, which is located in the Koulikoro region, around 70 km northeast of Bamako. This village was selected because it represents a typical rural Malian village, and its location is optimal to perform the fieldwork. In this village, 25 (out of 100) households were surveyed. These surveys helped to estimate the population distribution per household and their size, the type of stoves and fuels used for cooking, and the quantity of fuel used and their costs.

Among all the households that were surveyed in the urban area of Bamako, 30% had up to ten family members, 33% had between eleven and twenty family members, and 37% had more than twenty members. Regarding the types of fuels used, 32% of the households relied only on charcoal, 28% relied on a combination of charcoal and firewood, and 25% relied on a combination of charcoal, firewood, and butane gas. The households using only firewood comprised 3%, and only 1% cooked without traditional cooking fuels (butane gas). In order to determine the average charcoal and firewood consumption, only households that were not using modern cooking fuels were considered, comprising 229 households in the sample. This was conducted to avoid possible bias from households using electricity or butane gas, as the consumption of firewood and charcoal depends on cooking practices. On average, the firewood consumption per capita was calculated as 0.498 kg per person per day, while for charcoal, it was 0.334 kg per person per day.

For the households surveyed in Katibougou, 28% had up to 10 family members, 48% had between eleven and twenty, and 24% had more than twenty members. Concerning the types of fuels used, most of the population relied on firewood as their main source of energy for cooking. In total, 72% of the households relied only on firewood for cooking, while 28% used a combination of firewood and charcoal. Even in this second case, all the households presented higher consumption values for firewood than for charcoal. This helped to validate the assumption that only firewood can be considered in the estimation of the cooking energy demand in rural areas. Therefore, when calculating the firewood demand per capita, only 72% of the households using firewood as the only resource were considered. On average, the firewood consumption per capita was determined to be 1.081 kg per person per day.

In the literature, previous studies have targeted the fuel consumption per capita in Mali according to differences between urban and rural regions. Morton [68] targeted rural areas in a survey to define firewood consumption as 1.041 kg per person per day. Although fuelwood demand in rural areas has not shown an important variation in the last 20 years, in urban areas, a huge part of the population has shifted from firewood to charcoal [16]. Therefore, most surveys conducted a long time ago reflect different cooking fuel consumption practices that exist nowadays in those regions. One recent survey regarding this topic was carried out by the French Agricultural Research Centre for International Development (CIRAD) [69]. In their report, they estimated the firewood consumption per capita in rural areas for cooking food and heating water as 1.320 kg per person and day. For urban areas, this rate was 0.400 kg per person and day. For charcoal, only urban areas were considered, with an average consumption value of 0.203 kg per person per day.

The values from our own survey were compared with those in the literature. For firewood consumption in rural areas, these values were similar to Morton [68], but lower than CIRAD [69]. For firewood and charcoal consumption in urban areas, values from our own survey were slightly higher than those from the literature. In order to choose the values that better reflect the average consumption of the population, interviews with local experts were conducted. When transforming consumption per capita into consumption per household, local experts noticed that values from our own survey could better reflect average family expenditures on cooking fuels. Therefore, the consumption rates from the performed survey were preferred for the calculation of the cooking energy demand.

Knowing the population per region, its distribution per rural and urban areas, and the average consumption rates, it is possible to estimate the annual cooking fuel demand with Equations (10) and (11):

$$C_{firewood}(j) = P_{ncc}(j) \cdot r_{firewood}(j) \cdot (c_{fw,u}(j) * UP(j) + c_{fw,r}(j) * RP(j)) \quad (10)$$

where $C_{firewood}(j)$ is the annual firewood consumption at the jth region (t/y); $P_{ncc}(j)$ is the population with no access to clean cooking fuels at the jth region; $r_{firewood}(j)$ is the share of people consuming firewood at the jth region (%); $c_{fw,u}(j)$ is the annual consumption of firewood in urban areas per capita at the jth region [t/(person·y)]; $c_{fw,r}(j)$ is the annual consumption of firewood in rural areas per capita at the jth region [t/(person·y)]; $UP(j)$ is the share of the urban population at the jth region (%); and $RP(j)$ is the share of the rural population at the jth region (%). And for Equation (11):

$$C_{charcoal}(j) = P_{ncc}(j) \times r_{charcoal}(j) \times c_{ch}(j) \quad (11)$$

where $C_{charcoal}(j)$ is the annual charcoal consumption at the jth region (t/y); $P_{ncc}(j)$ is the population with no access to clean cooking fuels at the jth region; $r_{charcoal}(j)$ is the share of people consuming charcoal at the jth region (%); and $c_{ch}(j)$ is the annual consumption of firewood per capita at the jth region [t/(person·y)].

Once the annual consumption of charcoal and firewood per region is estimated, it is possible to calculate the energy demand in two different ways. The first option is to calculate the final energy demand, which is equivalent to the product of the annual consumption and the energy content of the fuel. However, to compare different fuels, it is required to consider the different efficiencies of stoves. Therefore, in this case, the useful energy demand is calculated using Equations (12) and (13):

$$E_{d,firewood}(j) = C_{firewood}(j) \times U_{firewood} \times \eta_{tr,stove} \quad (12)$$

where $E_{d,firewood}(j)$ is the useful energy demand from firewood at the jth region (TJ/y); $C_{firewood}(j)$ is the annual firewood consumption at the jth region (t/y); $U_{firewood}$ is the energy content of firewood (TJ/t); and $\eta_{tr,stove}$ is the efficiency of traditional cooking stoves in Mali (%). For the energy content of firewood, its LHV was used, assuming a value of 16 MJ/kg [70]. The efficiency of the traditional cooking stove for firewood was considered 12%, as traditional three-stone stoves are still common in the country [71]. For Equation (13):

$$E_{d,charcoal}(j) = C_{charcoal}(j) \times U_{charcoal} \times \eta_{ch,stove} \quad (13)$$

where $E_{d,charcoal}(j)$ is the useful energy demand from charcoal at the jth region (TJ/y); $C_{charcoal}(j)$ is the annual charcoal consumption at the jth region (t/y); $U_{charcoal}$ is the energy content of charcoal (TJ/t); and $\eta_{ch,stove}$ is the efficiency of traditional charcoal cooking stoves in Mali (%). In this case, the LHV for charcoal was used for the energy content, assuming a value of 31.8 MJ/kg [70]. For the efficiency of the traditional charcoal stove, a value of 19% was assumed, according to the literature [71].

Moreover, to compare the useful energy demand with the useful energy potential in the cooking sector, the values from the bioenergy potential have to be multiplied by the efficiency of their respective stoves. In order to enhance the use of briquettes and improve the cooking conditions of the population, ICSs are considered. Different programs have been launched in Mali to increase the use of these ICSs. A value of 30% was selected, which is equivalent to an ICS compatible with briquettes that have already been implemented in areas of the country [72]. For biogas and bioethanol stoves, an efficiency of 55% was considered [73,74].

3. Results and Discussion

3.1. Biomass Resource Potential

3.1.1. Crop Residues

In order to present the potential generation of sustainable biomass resources from crop residues per region in Mali, the crop residues are divided according to different categories. The values for cereal crop waste are shown in Table 9, for fruit crops in Table 10, and for other diverse crops in Table 11. It was estimated that the total sustainable biomass resource from crop residues in Mali is 5516 kt/y. Cereal crops are the major source of these sustainable biomass crop residues, with 2981 kt/y (Table 9), followed by fruit crops, with 1716 kt/y (Table 10), and other crops, with 819 kt/y (Table 11). Moreover, millet straw is the largest sustainable crop residue produced in Mali, with 1380 kt/y. It is followed by the pruning of mango trees and sorghum straw, with 1007 and 886 kt/y, respectively.

In Table 9, the regional distribution of cereal crop waste generation is presented. It is observed that Sikasso and Ségou have the highest generation, with 714 and 706 kt/y. Although their production is similar, Sikasso has a bigger production of maize and sorghum waste, while in Ségou, millet predominates. Moreover, a major part of the Office du Niger is located in Ségou, which has the largest production of rice in the country. Other regions, like Koulikoro, Mopti, and Kayes, also have a large production of cereal crop residues. However, northern regions, like Gao, Tombouctou, and Kidal, have no or little generation of these kinds of residues. This is the same case in Bamako, where the production of cereal crop waste is negligible.

Table 9. Sustainable biomass resource potential of cereal crop waste per region in Mali.

Region	Sustainable Biomass Resource Potential of Cereal Crop Waste in kt/y						
	Millet Straw	**Sorghum Straw**	**Rice Straw**	**Rice Husks**	**Maize Stalks**	**Maize Cobs**	**Total**
Bamako	0	0	0	0	0	0	0
Gao	12	0	10	3	0	0	26
Kayes	52	177	3	1	21	21	276
Kidal	0	0	0	0	0	0	0
Koulikoro	193	314	9	3	50	50	620
Mopti	457	32	40	11	1	1	542
Ségou	448	152	71	20	8	8	706
Sikasso	155	200	21	6	166	166	714
Tombouctou	61	11	20	6	0	0	98
Total	1380	886	175	49	246	246	2981

For fruit crop waste, most of the production is concentrated in Sikasso, with the pruning of mango trees being the biggest potential source. In total, only in Sikasso, the sustainable biomass resource potential from fruit crop waste is 985 kt/y. The Koulikoro region also has great potential, with banana residues being predominant. Moreover, fruit crop residues are practically the only ones available in the Bamako region, especially thanks to the production of mangoes. Furthermore, like for other crops, the northern regions of the country have practically inexistent production of sustainable biomass resources from fruit crop waste.

Table 10. Sustainable biomass resource potential of fruit crop waste per region in Mali.

Region	Sustainable Biomass Resource Potential of Fruit Crop Waste in kt/y					
	Mango Pruning	Banana Leaves	Banana Stems	Banana Peels	Orange Pruning	Total
Bamako	166	2	31	1	0	201
Gao	0	0	0	0	0	0
Kayes	12	1	11	0	1	25
Kidal	0	0	0	0	0	0
Koulikoro	139	15	247	11	3	415
Mopti	13	0	8	0	0	22
Ségou	32	2	30	1	1	67
Sikasso	644	18	294	13	16	985
Tombouctou	0	0	0	0	0	0
Total	1007	39	621	27	21	1716

Diverse crop waste in Table 11 encompasses some of the waste from important food crops, such as groundnut and sweet potato, with cash crops, such as sugarcane and cotton. The total sustainable biomass resource potential from cotton stalk in the country is 588 kt/y, with more than half of this potential concentrated in the Sikasso region. Moreover, this region also has great potential for the production of sweet potato waste, with 110 kt/y. The Kayes, Ségou, and Koulikoro regions also have considerable potential for sustainable biomass from cotton and groundnut waste. It must be mentioned that the potential from sugarcane bagasse is concentrated in Ségou, with just 6 kt/y, which is due to its low recoverability. Bamako and the northern regions of the country present low sustainable biomass generation values.

Table 11. Sustainable biomass resource potential of diverse crop waste per region in Mali.

Region	Sustainable Biomass Resource Potential of Diverse Crop Waste in kt/y					
	Groundnut Stalks	Groundnut Husks	Sweet Potato Waste	Cotton Stalks	Sugarcane Bagasse	Total
Bamako	0	0	0	0	0	0
Gao	0	0	0	0	0	0
Kayes	34	6	0	41	0	82
Kidal	0	0	0	0	0	0
Koulikoro	24	4	6	106	0	141
Mopti	4	1	0	0	0	5
Ségou	10	2	0	59	6	76
Sikasso	15	3	110	382	0	510
Tombouctou	0	0	5	0	0	5
Total	87	16	122	588	6	819

The sustainable crop residues generated annually per region in Mali were estimated according to the main crops produced in each region. The biomass resource potential from crops is linked to different climate areas in the country, as they define the agro-ecological characteristics of the regions. Northern regions, like Tombouctou, Kidal, and Gao, are located in the Saharan zone, experiencing a hot desert climate. Under this condition, agricultural production is very limited in these regions, resulting in very low crop residue production. Consequently, agricultural production is concentrated in the central and southern regions. Sikasso, the most southern region in Mali, has a tropical savannah climate and the greatest annual crop waste potential in the entire country, with 2.2 million tons. This represents 40% of the total potential production of sustainable biomass resources from crop waste in Mali.

Concerning Bamako, the region covers only around 0.2% of the total country area. Due to its urban nature and high population density, Bamako has limited agricultural land compared to other regions. However, the availability of the banks of the Niger River and the increased consumption of fruits and vegetables have led to significant horticultural production in the capital [75]. In this sense, Bamako has the potential to produce 201 kt/y of sustainable biomass resources from fruit crop residues, making it the region with the third-highest potential for these types of crops.

As mentioned in the Introduction, there is a lack of information in the literature on bioenergy potential in Mali. Few studies have considered the biomass resources potential, being focused on specific crops. FAO [20] published a report in which the sustainable biomass potential of some of the main crops in the country was determined. However, the methodology to obtain the potential was not defined. In that study, the potential from rice husks was around 22 kt/y, from maize waste, 110 kt/y (without considering cobs); from cotton stalks, 1280 kt/y; and from sugarcane bagasse, 20 kt/y. Compared with the values from the present study (Tables 9 and 11), it is noticeable that the estimation of potential from food crops is higher than in the FAO study, while for cash crops, the potential is smaller. These differences may not only be because of the different levels of production in the year considered but also because of different considerations of the RPR and SRF parameters. In the case of Nygaard et al. [19], which focused on rice straw in the Office du Niger, a similar methodology was applied to estimate the potential in 2020. For this case, the business-as-usual and realistic scenarios estimated a sustainable biomass resource potential of 57-118 kt/y. This is within the range estimated in the present study, as the Office du Niger comprises the Ségou region, which has an annual sustainable rice straw potential of 70 kt.

3.1.2. Livestock Waste

The sustainable biomass potential of livestock waste in Mali is presented in Table 12. The total production in the country is 91,237 kt/y, with 58,159 kt produced by cattle dung. Pigs have the lowest production, with around 94 kt/y. For other animals, the range is between 764 and 12,315 kt/y. In terms of regional distribution, Mopti has the largest potential, with 21,068 kt/y. The lowest production is found in Bamako, with only 415 kt/y. Farming and livestock are mainly concentrated in rural areas of the country [21], leaving the relatively small area of Bamako with low sustainable biomass resources in comparison. For the other regions, the annual values do not differ largely, being in the range between 6160 and 11,388 kt/y.

When comparing the geographic distribution of biomass, variations emerge in the predominant type of livestock per region. While northern regions, like Gao, Kidal, and Tombouctou, generate significant amounts of camel dung, the southern and central regions have more potential for cattle and poultry manure production. In the case of sheep and goat manure, its production is significant throughout the country, being the two main sources of sustainable biomass potential after cattle dung.

Table 12. Sustainable biomass potential of livestock waste per region in Mali.

Region	Sustainable Biomass Potential of Livestock Waste in kt/y								
	Cattle	Sheep	Goats	Horses	Donkeys	Camels	Pigs	Poultry	Total
Bamako	192	34	21	2	2	0	0	164	415
Gao	5013	1799	2380	84	647	1282	0	5	11,211
Kayes	6194	1024	1037	634	316	15	0	122	9342
Kidal	413	1070	1353	26	375	2921	0	2	6160
Koulikoro	8346	738	1307	336	403	57	39	162	11,388
Mopti	16,285	1631	2351	133	522	90	5	51	21,068
Ségou	6560	772	1223	327	335	4	37	69	9327
Sikasso	9271	656	786	8	280	0	13	183	11,196
Tombouctou	5886	1120	1857	416	695	1150	0	5	11,129
Total	58,159	8844	12,315	1966	3575	5521	94	764	91,237

3.1.3. Municipal Solid Waste

Table 13 presents the total MSW generated in Mali and the share of organic biodegradable MSW that is available for bioenergy production. In urban regions, 1721 kt/y of MSW is generated, and just 17% is organic biodegradable waste available for energy production. Geographically comparing MSW generation reveals that most of its production is concentrated in Bamako. The capital has the largest urban population in the country, contributing significantly to MSW production. Other regions with important urban centers, such as Sikasso or Koulikoro, also generate considerable amounts of MSW. In contrast, northern regions, such as Kidal, Tombouctou, or Gao, have fewer cities and populations, resulting in lower quantities of MSW generated.

Table 13. Sustainable biomass potential of MSW per region in Mali.

Region	MSW Generation (kt/y)	Organic Biodegradable MSW (kt/y)
Bamako	588	100
Gao	64	11
Kayes	174	30
Kidal	9	2
Koulikoro	260	44
Mopti	129	22
Ségou	175	30
Sikasso	273	46
Tombouctou	50	8
Total	1721	293

During the estimation of potential organic biodegradable MSW, a relatively high rate of collection was considered for Mali. This is attributed to the existing market for recyclables from organic waste for soil conditioning and pork fodder [47]. This established infrastructure can facilitate the development of bioenergy infrastructure, utilizing the organic biodegradable fraction of MSW for biogas production, with soil fertilizer as a by-product. However, the use of waste as animal fodder could create competition for feedstock use. As it is reportedly used for pigs, the numbers of which are relatively low in the country, with some regions even without this species [27], this competition was not considered.

Mali still maintains a high percentage of the rural population relying on farming and livestock for living. Consequently, most of the country's sustainable biomass potential comes from animals and crops, while MSW is concentrated only in regions with more urban areas, such as Bamako. For the rest of the country, livestock waste can be found in all regions, making it appropriate for local energy production. However, crop residues are only found in central and southern regions, limiting their use in the northern regions of the country.

3.2. Bioenergy Potential

3.2.1. Briquette Potential

In order to improve cooking energy access for the population, diverse biofuels are recommended in this study. One that is already common in the country, even on a commercial scale, is briquettes from agricultural residues. Tables 14–16 show the energy potential derived from the combustion of different crop wastes through briquette production. This energy, obtained from the LHV of waste residues, represents the heat that can be used for cooking purposes. The total energy potential from briquette combustion in Mali is 83,090 TJ/y. This value represents the final energy potential of the biofuels. It should be noted that most of the energy potential comes from cereal crop waste, such as millet and sorghum straw. In total, cereals can produce up to 43,958 TJ/y (Table 14). Other crop wastes, such as mango pruning or cotton stalks, also have great potential for energy production through briquettes.

As mentioned, cereal crop waste has the greatest potential for the generation of energy from briquette combustion. As seen in Table 14, more than 75% of the energy potential from cereal waste comes from millet straw and sorghum straw, as they can generate 21,397 and 12,757 TJ/y in the form of briquettes. Geographically, most of the potential is concentrated in the regions of Ségou, Sikasso, Koulikoro, and Mopti, with energy potentials that range from 8439 to 10,860 TJ/y. In contrast, Bamako and the northern regions exhibit the lowest values, and in some cases, their potential is even negligible.

Table 14. Energy potential from briquette combustion of cereal crop waste per region in Mali.

Region	**Energy Potential from Combustion of Cereal Crop Waste in TJ/y**						
	Millet Straw	**Sorghum Straw**	**Rice Straw**	**Rice Husks**	**Maize Stalks**	**Maize Cobs**	**Total**
Bamako	0	0	0	0	0	0	0
Gao	190	1	166	58	0	0	415
Kayes	812	2544	53	19	329	191	3948
Kidal	0	0	0	0	0	0	0
Koulikoro	2989	4526	150	52	779	453	8950
Mopti	7094	456	646	225	11	6	8439
Ségou	6956	2188	1132	394	121	70	10,860
Sikasso	2411	2884	335	117	2568	1491	9806
Tombouctou	946	158	318	111	4	2	1540
Total	21,397	12,757	2801	976	3813	2214	43,958

For energy potential from the combustion of fruit crop waste briquettes, it is estimated that the total value for the country is 26,575 TJ/y (Table 15). Most of this potential comes from mango pruning and banana stems, with 17,616 and 7694 TJ/y, respectively. Geographically, more than half of the energy potential is concentrated in Sikasso, with 15,608 TJ/y. Other central regions, like Koulikoro and Bamako, also have considerable energy potential, with 5892 and 3350 TJ/y, respectively. Similar to cereals, production in northern regions, like Gao, Kidal, or Tombouctou, is practically nil.

Table 16 shows the energy potential from the combustion of briquettes made from sources other than the main food and cash crops of Mali, which were not previously mentioned. While the total energy potential of the considered crops is 12,557 TJ/y, only 10,948 TJ comes from cotton stalks. This gives an idea of the considerable sustainable potential of this crop waste. Most of the cotton production is concentrated in the Sikasso region, with an annual energy potential of 7372 TJ. In Koulikoro, Ségou, and Kayes, the values range between 1361 and 2390 TJ/y.

Table 15. Energy potential from briquette combustion of fruit crop waste per region in Mali.

Region	Energy Potential from Combustion of Fruit Crop Waste in TJ/y					
	Mango Pruning	Banana Leaves	Banana Stems	Banana Peels	Orange Pruning	Total
Bamako	2911	22	388	22	7	3350
Gao	0	0	0	0	0	0
Kayes	217	8	131	7	13	376
Kidal	0	0	0	0	0	0
Koulikoro	2426	175	3056	174	61	5892
Mopti	232	6	98	6	0	341
Ségou	560	22	377	21	21	1001
Sikasso	11,265	209	3644	208	282	15,608
Tombouctou	6	0	0	0	0	7
Total	17,616	442	7694	439	384	26,575

Table 16. Energy potential from briquette combustion of other main crop waste per region in Mali.

Region	Energy Potential from Combustion of Other Main Crop Waste in TJ/y				
	Groundnut Stalks	Groundnut Husks	Cotton Stalks	Sugarcane Bagasse	Total
Bamako	1	0	0	0	1
Gao	0	0	0	0	0
Kayes	496	98	766	0	1361
Kidal	0	0	0	0	0
Koulikoro	350	69	1971	0	2390
Mopti	57	11	0	0	69
Ségou	138	27	1095	104	1364
Sikasso	213	42	7116	0	7372
Tombouctou	1	0	0	0	1
Total	1258	248	10,948	104	12,557

The quantity of energy potential in the form of briquettes is directly related to the availability of sustainable biomass resources in the country. Therefore, northern regions, like Kidal, Gao, or Tombouctou, exhibit little to no potential. In contrast, central and southern regions have the opportunity to produce significant energy potential in the form of briquettes. In the case of Bamako, this potential comes almost entirely from fruit crop residues.

Another parameter that has an important effect on the bioenergy potential from briquettes is the LHV. Although the combustion characteristics of the briquettes can be affected by the production process or the use of binders, this study primarily employs the type of feedstock to define the potential. For example, briquettes produced from banana waste have a relatively low energy content. This explains why the bioenergy potential from banana stems is lower than for cotton stalks, even with higher annual residue production nationwide. Woody residues from pruning and cotton stalks have good calorific values for briquette production. Straws and stalks from cereals, while abundant in Mali, have lower energy levels when compared to other crop residues. Regarding residues from fruit and vegetables (excluding pruning), briquette production is less preferable due to their lower LHVs.

3.2.2. Biogas Potential

The annual biogas potential in Mali was calculated considering three feedstock types, namely, crop residues, livestock waste, and MSW. Tables 17–19 show the biogas energy potential from cereal, fruit, and other main crop residues; Table 20 shows the potential from livestock waste; and Table 21 shows the potential from MSW. Livestock waste has the greatest potential for biogas production, with 83,450 TJ/y, followed by 32,769 TJ/y from crop residues and only 1001 TJ/y from MSW. The potential from crop residues is divided into those generated by cereal crop waste, with 21,465 TJ/y; fruit crop waste, with 5430 TJ/y; and other main crop waste, with 5874 TJ/y. For the total biogas potential, most comes from cattle waste, with 52,762 TJ/y.

The biogas potential from cereal crop residues is shown in detail in Table 17. Out of a total potential of 21,465 TJ/y, 8270 TJ comes from millet straw and 7908 TJ comes from sorghum straw, the two major crops. When the different regions are compared, the southern and central parts of the country have the highest potential. The potential in Kayes, Mopti, Koulikoro, Ségou, and Sikasso is between 2220 and 5234 TJ/y. Although Tombouctou has a potential of 682 TJ/y, the anaerobic digestion potential of cereal crops in northern regions and Bamako is very low or almost non-existent.

Table 17. Energy potential from anaerobic digestion of cereal crop waste per region in Mali.

Region	Energy Potential from Anaerobic Digestion of Cereal Crop Waste in TJ/y						
	Millet Straw	**Sorghum Straw**	**Rice Straw**	**Rice Husks**	**Maize Stalks**	**Maize Cobs**	**Total**
Bamako	0	0	0	0	0	0	0
Gao	73	1	90	22	0	0	186
Kayes	314	1577	29	7	164	130	2220
Kidal	0	0	0	0	0	0	0
Koulikoro	1155	2806	81	20	388	307	4757
Mopti	2742	283	349	87	5	4	3470
Ségou	2688	1356	611	152	60	48	4915
Sikasso	932	1788	181	45	1278	1011	5234
Tombouctou	366	98	172	43	2	2	682
Total	8270	7908	1512	376	1897	1501	21,465

The biogas potential from fruit crop residues is shown in Table 18. In this case, almost all potential comes from mango pruning, i.e., 4898 TJ out of a total of 5430 TJ/y. As mango plantations are especially common in the Sikasso, Koulikoro, and Bamako regions, most of the potential from fruit crop waste is concentrated in these areas. The energy potential from anaerobic digestion is 3411 TJ/y for Sikasso and 861 and 833 TJ/y for Koulikoro and Bamako, respectively. For the rest of the central and southern regions, the potential is quite low, whereas in the northern regions, it is practically negligible.

Table 18. Energy potential from anaerobic digestion of fruit crop waste per region in Mali.

Region	Energy Potential from Anaerobic Digestion of Fruit Crop Waste in TJ/y					
	Mango Pruning	**Banana Leaves**	**Banana Stems**	**Banana Peels**	**Orange Pruning**	**Total**
Bamako	809	3	17	2	2	833
Gao	0	0	0	0	0	0
Kayes	60	1	6	1	4	71
Kidal	0	0	0	0	0	0
Koulikoro	674	25	132	13	16	861
Mopti	65	1	4	0	0	70
Ségou	156	3	16	2	6	182
Sikasso	3132	30	158	16	76	3411
Tombouctou	2	0	0	0	0	2
Total	4898	63	334	33	103	5430

The biogas potential from other main crop waste is shown in Table 19. From a total estimated value of 5874 TJ/y from these main crops, 4288 TJ comes from cotton stalks. As this is the main cash crop in the country, the regions where cotton is cultivated have great potential. Sikasso has a total potential from other crop waste of 3775 TJ/y, while Koulikoro has 977 TJ, Ségou has 532 TJ, and Kayes has 524 TJ/y. It should be noted that sweet potato waste is also an important source of biogas generation in Sikasso, with a potential in this region of 893 TJ/y. Again, the potential from these other crop wastes in Bamako and the northern regions is low.

Table 19. Energy potential from anaerobic digestion of other main crop waste per region in Mali.

Region	Energy Potential from Anaerobic Digestion of Other Main Crop Waste in TJ/y					
	Groundnut Stalks	Groundnut Husks	Sweet Potato Waste	Cotton Stalks	Sugarcane Bagasse	Total
Bamako	0	0	0	0	0	1
Gao	0	0	0	0	0	0
Kayes	174	47	3	300	0	524
Kidal	0	0	0	0	0	0
Koulikoro	123	33	49	772	0	977
Mopti	20	5	0	0	0	26
Ségou	48	13	0	429	41	532
Sikasso	75	20	893	2788	0	3775
Tombouctou	0	0	40	0	0	40
Total	441	119	985	4288	41	5874

The energy potential from the anaerobic digestion of livestock waste is shown in Table 20. This is the largest type of bioenergy potential in the country, with 83,450 TJ/y. Of this total, 52,762 TJ/y can be produced only from cattle dung, as it is the feedstock with the highest potential for bioenergy production. Other livestock waste with high potential are as follows: camel dung: 8944 TJ/y, goat manure: 6650 TJ/y, donkey dung: 5792 TJ/y, sheep manure: 4776 TJ/y, and horse dung: 3184 TJ/y. Poultry and pig manure have lower values, at 1197 and 146 TJ/y, respectively. When different regions are compared, Mopti has the largest energy potential, with 18,219 TJ/y, while Bamako has only 468 TJ/y. For the rest of the regions, the differences are not very large, with all of them being in a range between 7068 and 10,618 TJ/y. Although the potential could seem more or less homogeneous among most of the regions, there are big differences in the available feedstock. The northern regions have greater potential from camel dung, while southern regions have more potential from cattle dung.

Table 20. Energy potential from anaerobic digestion of livestock waste per region in Mali.

Region	Energy Potential from Anaerobic Digestion of Livestock Waste in TJ/y								
	Cattle	Sheep	Goats	Horses	Donkeys	Camels	Pigs	Poultry	Total
Bamako	174	18	11	3	4	0	0	257	468
Gao	4548	971	1285	136	1049	2077	0	7	10,075
Kayes	5619	553	560	1027	511	25	0	191	8487
Kidal	375	578	731	42	607	4732	0	3	7068
Koulikoro	7571	399	706	545	652	93	61	254	10,281
Mopti	14,773	881	1269	215	846	146	7	80	18,219
Ségou	5952	417	660	529	543	7	57	108	8273
Sikasso	8410	354	424	13	454	0	19	287	9962
Tombouctou	5339	605	1003	674	1125	1863	0	8	10,618
Total	52,762	4776	6650	3184	5792	8944	146	1197	83,450

In Table 21, the biogas potential from MSW is shown. The total potential in the country is 1001 TJ/y, with more than one-third being generated in the urban region of Bamako, i.e., 342 TJ/y. Other regions with important cities, such as Sikasso, Koulikoro, Ségou, or Kayes, have potentials ranging from 101 to 159 TJ/y. The rest of the regions have values below 100 TJ/y. These values are directly related to the biodegradable MSW generated in these regions. It is estimated that 292 kt/y of biodegradable MSW is produced in urban areas of the country, generating almost 28 million m^3/y of methane that can be used for energy purposes.

Table 21. Energy potential from anaerobic digestion of MSW per region in Mali.

Region	Biodegradable MSW (kt/y)	Methane (m^3/y)	Energy (TJ/y)
Bamako	100	9,507,000	342
Gao	11	1,028,000	37
Kayes	30	2,809,000	101
Kidal	2	144,000	5
Koulikoro	44	4,194,000	151
Mopti	22	2,081,000	75
Ségou	30	2,831,000	102
Sikasso	46	4,409,000	159
Tombouctou	8	805,000	29
Total	293	27,807,000	1001

The biogas potential in Mali is affected by the geographical availability of feedstock. Concerning biogas produced from crop residues, the southern and central regions have higher biogas potential than the northern regions. When livestock waste is considered, all regions except Bamako display high potential, as animals can be found everywhere. In the case of biogas production from MSW, Bamako has the highest potential, being the biggest urban area in the country. Other regions with important cities, such as Sikasso or Koulikoro, also have considerable biogas production potential from MSW compared to northern regions, like Kidal or Tombouctou.

It is not only feedstock quantity that affects biogas production but also its quality. Different feedstock types have different properties, so the type of input used to produce biogas determines the quantity of methane generated and, thus, the heat content of the biogas. For biogas produced from crop residues, the differences between the methane yield and DM ratio among residues are pivotal. For example, banana waste has a very low DM compared to other crops (Table 5), making this residue less efficient for bioenergy production. Regarding methane yield, residues from maize or sorghum have great potential, while the pruning from fruit trees is observed as less favorable.

In general terms, biogas production from livestock waste has shown the greatest potential for bioenergy production in the country. Total solids and biogas yield are the substrate parameters with the greatest effect on biogas potential from livestock waste. Dung from large animals, such as donkeys, camels, and horses, has greater biogas potential than other animals. This favors northern areas, where cattle are less common and there is a major presence of camels and donkeys.

3.2.3. Bioethanol Potential

Bioethanol is a promising biofuel for cooking that has been developed in Mali on a small scale. Its production, derived from agricultural residues, has an estimated total potential production of 15,470 TJ/y, as shown in Tables 22–24. The highest bioethanol production in the country was derived from cereal crop residues, with 10,273 TJ/y (Table 22). Fruit crop residues have the potential to generate 2146 TJ/y of bioethanol (Table 23), while other main crop waste can produce 3051 TJ/y (Table 24).

In the case of bioethanol production from cereal crop residues (Table 22), millet and sorghum straw are the feedstock with the largest potentials, being 4889 and 3398 TJ/y, respectively. However, it must be mentioned that geographically, maize is quite important in the Sikasso region, leading to considerable potential for bioethanol production. On a smaller scale, rice residues also contribute in the Ségou and Mopti regions. In this sense, Ségou, Sikasso, Koulikoro, and Mopti have potentials ranging between 1928 and 2528 TJ/y.

This is followed by Kayes and Tombouctou, with potentials of 982 and 349 TJ/y, respectively. Other regions have small or practically non-existent potentials.

Table 22. Energy potential of bioethanol production from cereal crop waste per region in Mali.

Region	Energy Potential of Bioethanol Production from Cereal Crop Waste in TJ/y						
	Millet Straw	Sorghum Straw	Rice Straw	Rice Husks	Maize Stalks	Maize Cobs	Total
Bamako	0	0	0	0	0	0	0
Gao	43	0	38	9	0	0	90
Kayes	186	678	12	3	66	37	982
Kidal	0	0	0	0	0	0	0
Koulikoro	683	1206	34	8	157	88	2176
Mopti	1621	122	147	34	2	1	1928
Ségou	1589	583	257	60	24	14	2528
Sikasso	551	768	76	18	517	291	2220
Tombouctou	216	42	72	17	1	0	349
Total	4889	3398	637	149	767	432	10,273

Table 23 shows the energy potential of bioethanol production from fruit crop residues. Of a total estimated 2146 TJ/y, 1904 TJ/y is produced by mango pruning. The highest bioethanol potentials from fruit crops are located in Sikasso, with 1343 TJ/y, followed by Koulikoro, with 349 TJ/y, and Bamako, with 325 TJ/y. Other regions have lower or negligible values.

Table 23. Energy potential of bioethanol production from fruit crop waste per region in Mali.

Region	Energy Potential of Bioethanol Production from Fruit Crop Waste in TJ/y					
	Mango Pruning	Banana Leaves	Banana Stems	Banana Peels	Orange Pruning	Total
Bamako	315	1	8	1	1	325
Gao	0	0	0	0	0	0
Kayes	23	0	3	0	1	28
Kidal	0	0	0	0	0	0
Koulikoro	262	12	62	6	6	349
Mopti	25	0	2	0	0	28
Ségou	61	1	8	1	2	73
Sikasso	1218	14	74	7	29	1343
Tombouctou	1	0	0	0	0	1
Total	1904	29	157	15	40	2146

In Table 24, the bioethanol potential from other main crop residues is presented. Of the considered residues, cotton stalks have the highest potential, with 2356 TJ/y, in the entire country. As cotton cultivation primarily occurs in Sikasso, this region has the highest potential, with 1813 TJ/y. This is followed by Koulikoro, with 560 TJ/y, Kayes, with 343 TJ/y, and Ségou, with 305 TJ/y. Other regions have zero or low bioethanol potential from the considered crops.

Bioethanol production from crop residues is affected by the kind of feedstock used, as they have different DM and glucan content values. As seen before (Table 5), DM values are relatively homogeneous across different residues, except for banana waste, which has reduced bioethanol production potential. Regarding glucan content, the values range between 0.198 and 0.42 (Table 7). Therefore, residues with low glucan content, such as sweet potato waste or fruit tree pruning, halve their potential bioethanol production compared to other feedstock, such as sorghum straw or cotton stalks. This highlights the importance of the selection of feedstock for different bioenergy purposes, as their availability is not the only factor to consider.

Table 24. Energy potential of bioethanol production from other main crop waste per region in Mali.

Region	Energy Potential of Bioethanol Production from Other Main Crop Waste in TJ/y					
	Groundnut Stalks	Groundnut Husks	Sweet Potato Waste	Cotton Stalks	Sugarcane Bagasse	Total
Bamako	0	0	0	0	0	0
Gao	0	0	0	0	0	0
Kayes	124	53	1	165	0	343
Kidal	0	0	0	0	0	0
Koulikoro	87	38	11	424	0	560
Mopti	14	6	0	0	0	20
Ségou	34	15	0	236	20	305
Sikasso	53	23	206	1532	0	1813
Tombouctou	0	0	9	0	0	10
Total	313	135	227	2356	20	3051

When the different pathways to obtain biofuels from crop residues are compared, it is evident that adding biological and biochemical processes reduces the overall bioenergy potential derived from the feedstock. In this context, the total energy potential of briquettes is the largest, followed by biogas and bioethanol. However, it must be considered that this refers to the final energy potential, which differs from the useful energy used for cooking. Therefore, in the calculation of the bioenergy potential from crop residues, the efficiency of the cooking stoves was not considered. This is discussed later in the estimation of the bioenergy contribution to the cooking energy demand of the country (Section 3.4).

3.3. Cooking Energy Demand

In order to assess to what extent bioenergy potential can be applied in Malian households, it is essential to determine the cooking energy demand. In order to assess the same period as the bioenergy potential, the cooking energy demand was estimated for 2015. In this study, it has been calculated the annual weight consumption of cooking fuels (Table 25), the final energy demand of the fuels (Table 26), and the useful energy demand (Table 27).

The fuel demand per region (Table 25) depends on the population of that region and its urban/rural distribution. Urban areas show higher rates of charcoal consumption than rural areas. In some cases, like in Bamako, this leads to a higher consumption of charcoal than firewood. However, it is noticed in the country that there is more firewood directly consumed than charcoal. Table 25 shows that the annual demand for firewood in the country is around 2.8 million tons, while for charcoal, it is 1.1 million tons. Moreover, the demand is concentrated in the central and southern regions. Bamako has the maximum annual charcoal consumption, with almost 0.3 million tons.

Table 25. Annual consumption of fuels in weight per region in Mali.

Region	Annual Consumption of Firewood (kt/y)	Annual Consumption of Charcoal (kt/y)
Bamako	21	285
Gao	76	49
Kayes	406	147
Kidal	3	9
Koulikoro	587	146
Mopti	653	66
Ségou	395	197
Sikasso	620	158
Tombouctou	82	70
Total	2845	1127

Knowing the average energy content of firewood and charcoal, the final energy demand for cooking in the country was determined (Table 26). This demand was more than 81 PJ, which is in a realistic range when compared to energy demand reports for the same period [14]. If fuel sources are compared, firewood still has a higher demand, with almost 46 PJ/y, compared to 36 PJ from charcoal.

Table 26. Final energy cooking demand per region in Mali.

Region	Final Energy Demand from Firewood (TJ/y)	Final Energy Demand from Charcoal (TJ/y)	Total Final Energy Demand for Cooking (TJ/y)
Bamako	343	9072	9415
Gao	1223	1570	2792
Kayes	6494	4660	11,155
Kidal	53	292	346
Koulikoro	9398	4627	14,025
Mopti	10,451	2105	12,556
Ségou	6318	6269	12,586
Sikasso	9922	5035	14,957
Tombouctou	1313	2214	3528
Total	45,515	35,844	81,358

The useful energy demand was obtained from the final energy demand and the average efficiency of commonly used stoves in the country. This demand refers directly to the heat used for cooking and can be used directly to compare with the heat that can be produced by other fuels in different types of stoves. It was estimated that more than 5 PJ of this heat used for cooking was produced by firewood, while more than 4 PJ was produced by charcoal (Table 27).

Table 27. Useful energy demand for cooking per region in Mali.

Region	Useful Energy Demand from Firewood (TJ/y)	Useful Energy Demand from Charcoal (TJ/y)	Total Useful Energy Demand for Cooking (TJ/y)
Bamako	41	1089	1130
Gao	147	188	335
Kayes	779	559	1339
Kidal	6	35	41
Koulikoro	1128	555	1683
Mopti	1254	253	1507
Ségou	758	752	1510
Sikasso	1191	604	1795
Tombouctou	158	266	423
Total	5462	4301	9763

The differences between weight consumption and energy demand of the two fuels are related to their physical and combustion characteristics, as well as to the stoves commonly used for cooking. Firewood users require a larger quantity or weight of fuel to cover the same energy requirements than when using charcoal, making the contrast in the useful energy demand smaller than in the fuel consumption. In this sense, the adaptability of charcoal to more efficient stoves, its requirements of less space, and the possibility to buy it in different-sized bags have helped to increase its demand in the last decades, making it the predominant fuel in urban areas [76].

3.4. Bioenergy Contribution to the Cooking Energy Demand

In order to compare the cooking energy demand of the country with its bioenergy potential, it is necessary to estimate the useful energy potential from bioenergy sources. This is shown in Table 28, differentiating between bioenergy fuels and considered feedstock. This useful energy potential was calculated considering that briquettes are used in ICSs, biogas is used in biogas stoves, and bioethanol is used in an ethanol stove. The highest potential is given by biogas, exhibiting a potential production of more than 64 PJ/y nationwide, with 46 PJ derived from livestock waste and 18 PJ from crop waste. If crop waste is used for briquette production, its potential reaches almost 25 PJ, while for bioethanol, it amounts to 8.5 PJ/y.

Table 28. Useful bioenergy potential per region in Mali.

Region	Useful Energy Potential from Bioenergy Sources (TJ/y)				
	Crop Waste Briquettes	Crop Waste Biogas	Livestock Waste Biogas	MSW Biogas	Crop Waste Ethanol
Bamako	1005	458	257	188	179
Gao	125	102	5541	20	50
Kayes	1705	1549	4668	56	744
Kidal	0	0	3887	3	0
Koulikoro	5170	3627	5654	83	1697
Mopti	2655	1961	10,020	41	1087
Ségou	3967	3096	4550	56	1598
Sikasso	9836	6831	5479	87	2957
Tombouctou	464	398	5840	16	198
Total	24,927	18,023	45,898	551	8508

Once the useful cooking energy demand and the useful bioenergy potential are determined, a comparison can be made to assess to what extent these energy sources can be used. The potential contribution of briquettes from crop waste to the cooking energy demand per region is shown in Figure 2. In central and southern regions, where agriculture in rural areas predominates, there is a high briquette potential in comparison to the energy demand. In the regions of Sikasso, Koulikoro, Ségou, Mopti, and Kayes, the energy potential from briquettes would exceed the cooking energy demand in a range from around 8 PJ in Sikasso to 0.4 PJ/y in Kayes. Sikasso stands out due to its high availability of crop residues. In Bamako and the northern regions, the situation is different. Northern regions present both low energy demand and briquette potential. Only Tombouctou has sufficient briquette potential to cover the cooking energy demand, with an excess of only 41 TJ/y. In the case of Kidal and Gao, the useful energy demand for cooking is higher, with values of 41 and 210 TJ/y, respectively. Despite Bamako having considerable briquette potential from fruit crops, the cooking energy demand surpasses it, resulting in a deficit of around 124 TJ/y.

When the sum of biogas potential from crop residues, livestock waste, and MSW is considered, it was noticed that all regions except Bamako could cover their cooking energy demand (Figure 3). In this case, even regions in the north have enough waste from animals such as camels, donkeys, sheep and goats to produce bioenergy. The excess of biogas potential in all these regions varies in a range from 3.8 PJ in Kidal to 10.6 PJ in Sikasso. These excesses are produced by the availability of livestock waste. Crop residues cannot cover the cooking energy demand in Kidal, Gao, and Tombouctou, and their potential is limited in Kayes or Mopti (Tables 27 and 28). Moreover, MSW is not enough to cover the cooking energy demand in any part of the country, being even negligible in rural areas (Table 28). Regarding Bamako, in consideration of all available biomass resources, biogas could not cover the whole cooking energy demand of the region, causing a deficit of 226 TJ/y.

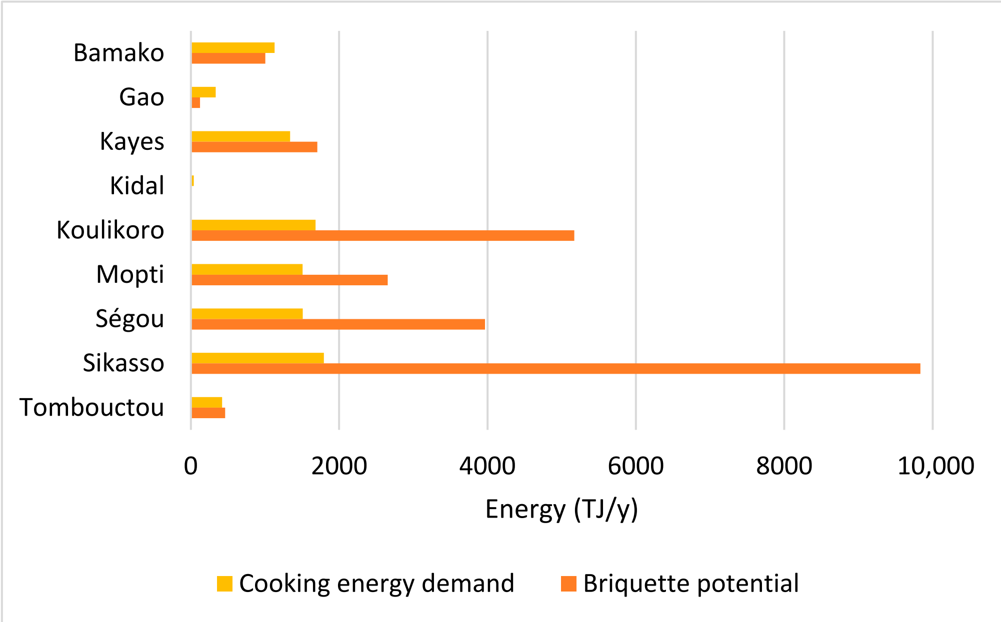

Figure 2. Potential contribution of briquettes to cooking energy demand.

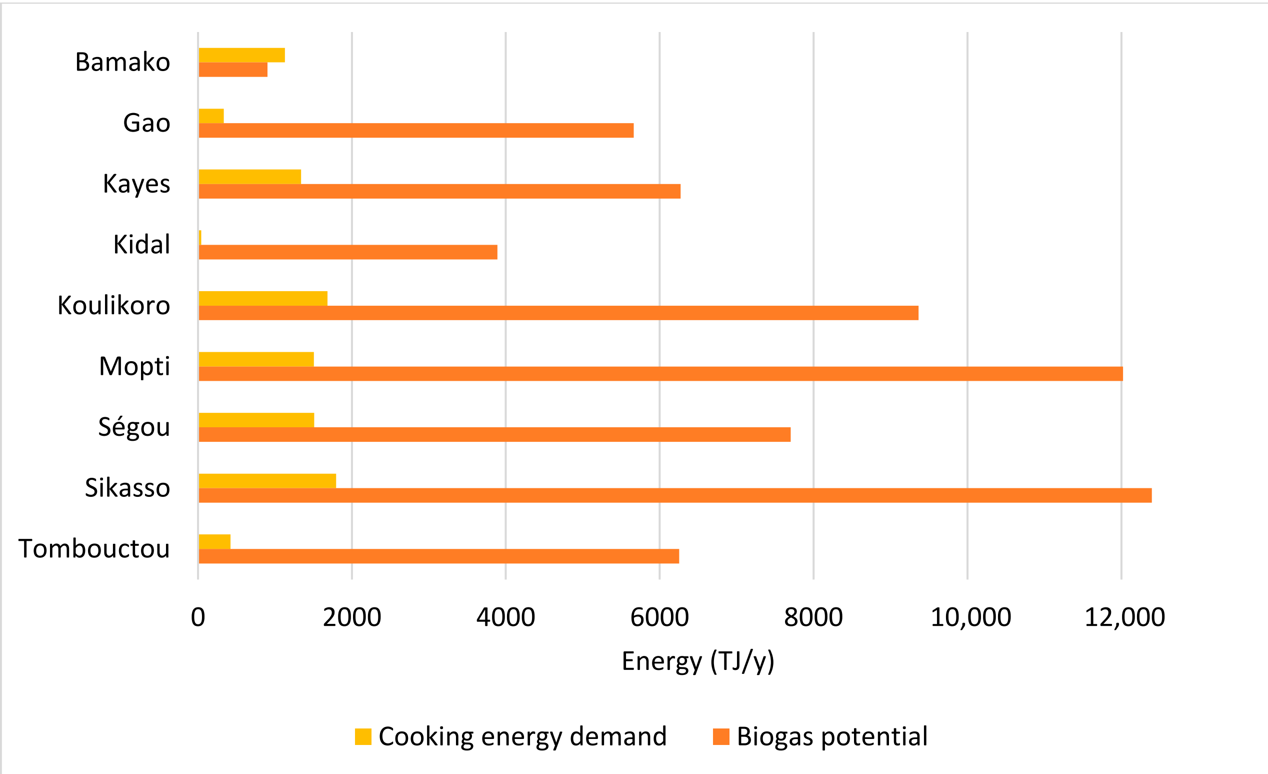

Figure 3. Potential contribution of biogas to cooking energy demand.

For the potential contribution of bioethanol from crop residues to the cooking energy demand, it is shown that almost all regions would have a limited contribution from this fuel (Figure 4). Only in Sikasso, where there is a significant potential for crop waste production, would there be an excess bioethanol potential of 1.2 PJ/y. In Ségou and Koulikoro, bioethanol would cover the whole demand, with a low excess of 88 and 14 TJ/y, respectively. In the remaining regions, there is a deficit when compared to the cooking energy demand. In the northern regions, the deficit is comparatively low, as the demand for energy is lower. However, in the case of Kayes, Mopti, and, especially, Bamako, bioethanol potential availability is far below the energy demand. Only in the case of Bamako, there is almost 1 PJ/y of cooking energy demand that would not be covered by the entire bioethanol potential of the region.

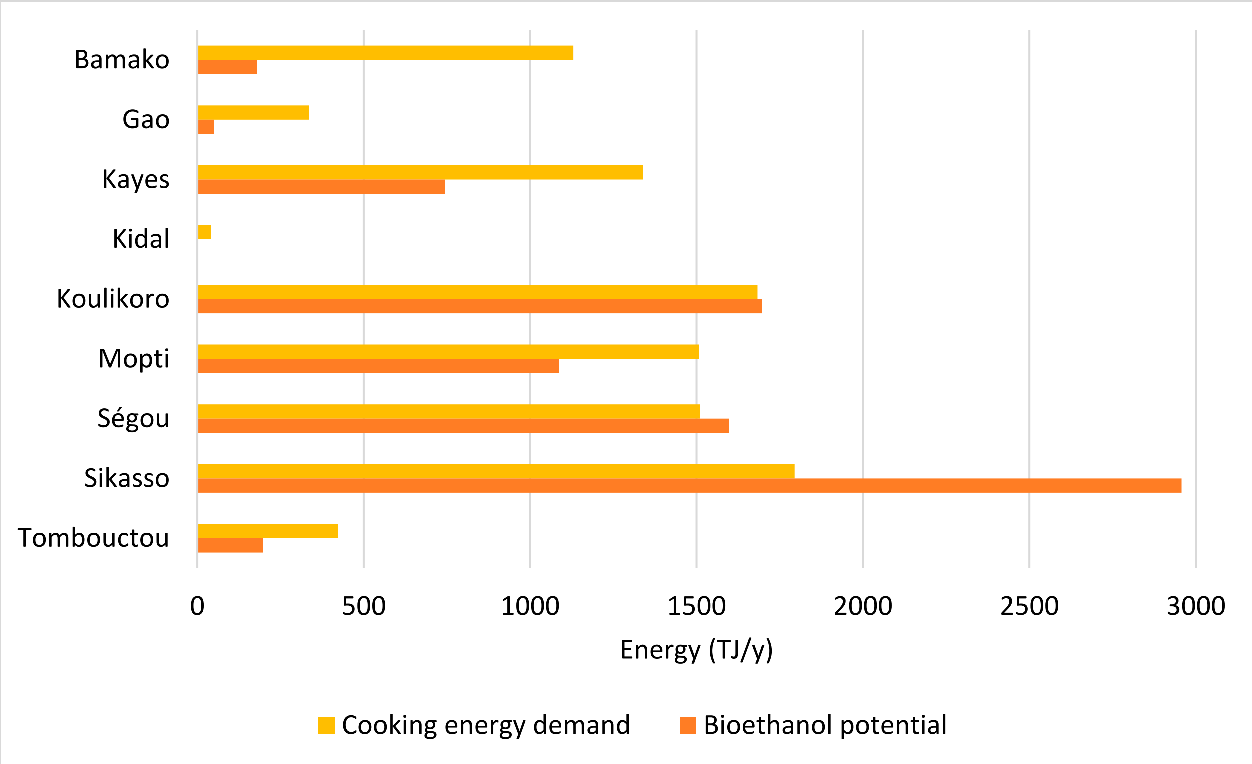

Figure 4. Potential contribution of bioethanol to cooking energy demand.

When comparing the bioenergy potential of the whole country with the cooking energy demand, it is possible to obtain a rough estimate of how much biomass can contribute to a clean cooking transition in Malian kitchens. For bioethanol, its total potential in the country could cover 87% of the total cooking energy demand in Mali. For the biogas produced from MSW, the share is only 6%. In the case of biogas produced from crop waste, there is the potential to generate 1.85 times the energy required for cooking, while with livestock waste, this potential is 4.70 times the cooking energy demand. Regarding briquettes made from crop residues, it is possible to produce up to 2.55 times the cooking energy demand of the country.

In the presented results, crop production, livestock, and population were based on governmental statistical data from 2015 [27]. The lack of more recent data on biomass adds uncertainty to an extrapolation of these data. Moreover, the expected increase in biomass resources is not considered significant compared to population growth [77]. Using population distribution data from 2022 [78], it was calculated how the estimated biomass potential could meet the demand of an increased population. The differences considering the population in 2015 and 2022 were not very significant for the final results. In this sense, the extrapolation showed that crop waste ethanol would cover up to 71% of the total cooking energy demand in the country, while MSW biogas only covers around 5%. Biogas from crop waste could generate 1.51 times the cooking energy demand; biogas from livestock waste could produce 3.86 times this demand; and crop waste briquettes could produce up to 2.09 times. In both cases, considering the populations of 2015 and 2022, the differences between regions are similar, showing the same patterns.

Although there is plenty of bioenergy potential from biomass residues to cover the entire cooking energy demand of Mali, its regional distribution is unequal. This is especially true at the rural and urban divide, where urban areas have higher cooking energy demand while the availability of biomass is lower. Bamako is the main example of this, as none of the bioenergy fuels considered can cover the full cooking energy demand of the region. This would lead to a dependence on other regions to import fuels, which is costly and, in some cases, not even feasible. Moreover, demographic and consumption patterns should also be considered to estimate the future trends of bioenergy potential and energy demand, as this would have repercussions on the potential contribution of biomass.

3.5. Future Prospects for Clean Cooking Transition

The current study analyzed the potential production of bioenergy per region in Mali to evaluate its capacity to cover the residential cooking energy demand. Northern regions, like Kidal, Gao, and Tombouctou, have lower population, being more distributed in rural areas. This leads to a relatively low energy demand (Table 27). Although this low demand could be easier to cover, their location in a hot desert zone makes agriculture almost non-existent (Figure 1), reducing the availability of biomass. However, a positive point is that these regions have great potential for producing biogas from livestock waste (Table 20). Considering that rural areas in the north of Mali lack roads and grid infrastructure [79], the use of self-produced biogas seems like a prominent pathway in their cooking transition. Nevertheless, one of the main challenges in facilitating this transition is the availability of water supply for biogas production [80]. One way to increase the supply of water for biogas production could be to use domestic wastewater [81]. This would require not only feedstock availability and financial support for building biogas infrastructure but also raising awareness and education regarding the use of waste to produce energy [82].

In southern and central regions, like Sikasso, Kayes, Koulikoro, Ségou, and Mopti, there is better access to water supply, although rapid urbanization has put more pressure on urban areas [79]. Moreover, the diversification of bioenergy fuels is more favorable, as there is more bioenergy potential from crop residues. Therefore, rural areas in these regions could benefit not only from biogas from livestock waste but also from energy products coming from crop residues. Biogas from crop waste is an interesting option, as it is a well-known clean technology in the country, although briquettes could have an important role in the transition to clean cooking fuels in the country due to their easier adaptation to current stoves and locally manufactured ICSs. In this sense, the Malian government has foreseen ICS as a technology to improve the energy efficiency of domestic kitchens over the next decade, although it is not considered a modern cooking technology for the long term, unlike stoves that use biogas, bioethanol, or electricity [83].

In order to promote bioenergy fuels for cooking in the coming decades, it is important to estimate their potential contribution to the energy demand. This requires an analysis of population growth and urbanization rates. During the last two decades, Mali has experienced significant population growth, with an average annual growth rate of over 3% [11]. This growth is expected to continue, causing a significant increase in the future energy demand of the country. Moreover, Mali is also experiencing a high urbanization rate that will continue in the following years, increasing the pressure on infrastructure and resource demand in cities [12]. Another point to consider is that the country has been facing armed conflicts in recent years, especially in the northern regions. This has led to the internal displacement of more than 300,000 people. Although most migrations happen within the same region, there is a clear pattern of people moving to southern areas of the country [84]. This would increase energy demand in these regions. In order to cover the expected increase in cooking energy demand, more energy resources will be needed, and this includes biomass.

The International Fund for Agricultural Development (FIDA) has forecasted the evolution of agricultural activities in Mali [77]. An increase in population will lead to an increase in food consumption and, thus, agricultural production. In general, it is expected that there will be a major increase in fruit, vegetable, and legume production over cereals and livestock. Moreover, the consumption of traditional cereals like sorghum and millet could be limited by an increase in rice consumption. A study by the FIDA [77] shows that the expected growth in key biomass resources for bioenergy potential, such as livestock waste or cereal residues, will be lower than population growth. Therefore, it seems very likely that the potential contribution of bioenergy to cooking energy demand could decrease within the next decades. To what extent that contribution could decrease was not quantified in the present study, but it could be part of future research. However, when the results from this study are analyzed, it seems that rural areas still have a huge bioenergy potential in comparison to their demand, while urban areas like Bamako could struggle to cover their cooking energy demand with biomass residues. Therefore, alternatives to bioenergy would be needed to achieve a clean cooking transition across the country, with a special focus on urban areas.

The case of the Bamako region is the main example of bioenergy potential and cooking energy demand in urban areas of the country. None of the biofuels considered can cover the whole demand of the region, as there is a huge population and low availability of biomass resources. Therefore, to cover the whole demand with bioenergy would require the transport of fuels or feedstock from other places, adding more steps and costs to the supply chain. Future trends of population and biomass availability [77] show that these areas, and especially Bamako, would have an increase in MSW and fruit crop waste. However, the potential contribution of MSW to the cooking energy demand in Bamako is only 17%, so it is far from covering the total demand. For fruit crop waste, even if its production exceeds demand, its effect on biogas generation or bioethanol production is reduced, having a stronger effect on the production of briquettes. Although this could be a transition option to phase out charcoal and firewood, a long-term clean cooking transition requires the adoption of modern cooking solutions, and the use of briquettes would not be contemplated by the Malian government's goals [83].

One of the modern cooking solutions promoted in Mali and other countries in the Global South to reduce firewood consumption is liquefied petroleum gas (LPG). In Mali, the state subsidized LPG between 1989 and 2012 to increase its consumption, especially in the Bamako region [76]. However, the dependency on fossil fuel prices and imports and the emission of GHGs caused by LPG have diminished the interest of governments and international agencies in its use for clean cooking. In contrast, locally produced biofuels based on residues can be considered carbon neutral. This is also the case for other cooking alternatives, such as electric stoves with electricity generated from renewable resources. Therefore, given the current climate crisis, special attention to renewable energy sources like sustainable biomass is required to achieve a clean cooking transition.

Considering the distribution of bioenergy potential and the state of technology, biogas could play an important role in achieving clean cooking access in the rural areas of Mali, as it can be produced locally and has less dependence on grid or road infrastructure. In urban areas like Bamako, the availability of feedstock and the comparable high energy demand would be the main constraints. In cities, biogas from available waste, including MSW, could be a good approach to tackle the problems of waste management. However, other sources of energy would be required to achieve universal clean cooking access. With urban areas in Mali having a 97% electrification rate [15], transitioning to electric stoves could be a long-term solution, as observed in many countries. However, in order to achieve a fully clean transition, a major deployment of renewable energy would be required, reducing the dependence on fossil fuels. As Mali has high solar radiation potential, the promotion of solar energy could also be a turning point for increased electrification in rural areas and for the emergence of alternative options for cooking, such as solar electric cooking. However, proper policy and investment tools are required to unlock the potential of this technology for electricity generation across the country. Therefore, there is a further need for research into electric cooking with renewable energy, especially solar electric cooking.

4. Conclusions

In this study, it was shown that bioenergy from crop residues, livestock waste, and MSW can significantly contribute to the cooking energy demand in Mali. A transition from traditional cooking fuels, like firewood or charcoal, to bioenergy products, such as briquettes, biogas, and bioethanol, would have positive effects on the health of the population and the environment. To carry out this transition, it is important to determine the quantity of sustainable biomass in the country at the regional level. Livestock waste is produced in significant quantities throughout the country, while crop residues are concentrated in the southern and central regions. This study has shown that biogas from livestock waste seems to be a promising energy source for cooking in rural areas of Mali, especially in the North, where the demand is relatively low and other biomass resources are scarce. However, the analysis of the Bamako region indicates that urban areas are facing high and increasing cooking energy demands that surpass the availability of sustainable biomass resources. Briquettes can be used as a transition cooking fuel. Biogas from MSW is an encouraging option to deal with waste management in urban areas. However, other clean alternatives should be considered to fulfill universal clean cooking energy access in the country. In this regard, the deployment of renewable energy and the use of electric cooking systems could be a long-term solution to achieve this goal.

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