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Research article

Bioenergy potential of agricultural crop residues and municipal solid waste in Cameroon

Robinson J. Tanyi[1] and Muyiwa S Adaramola[2,*]

[1] Department of Mechanical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi Ghana

[2] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), P.O. Box 5003, NO-1432 Ås, Norway

* **Correspondence:** Email: samuelad@nmbu.no.

Abstract: Biomass has emerged as an important and promising energy source, particularly in developing countries, owing to continuous research for sustainable energy sources that do not interfere with food, water or land needs. This study introduces the surplus availability factor (SAF), minimum, average and maximum biogas production technique in the assessment of crop production data in 2020 to provide a more precise and current estimate of Cameroon's crop residue and municipal solid waste (MSW) bioenergy potential. Crop residues contributed roughly 96% while MSW contributed the remaining 4% of the total bioenergy potential of 606 PJ per year. The bioenergy potential was calculated using crop production statistics derived from the FAOSTAT database of the Food and Agriculture Organization, while the residue-to-product ratio (RPR) and surplus availability factors (SAF) were found from related studies. The study concludes that crop residues and MSW have significant energy potential capable of meeting the country's electricity, transport fuel and biogas demand while simultaneously mitigating climate change through the capture of about 1.6 billion kg of CO_2 through biogas recovery. It also highlights the lack of accurate and up-to-date data on the country's biomass potential and recommends ground data collection and geospatial mapping of areas with enormous potential for these resources to guide policymakers and investment plans.

Keywords: Sub-Saharan Africa; energy access; crop residues; surplus availability factor; waste generated per capita

1. Introduction

Agricultural crop residues and municipal solid waste (MSW) are highly neglected and underutilized energy sources, as they are generally regarded as waste in most parts of the world, especially in developing countries like Cameroon. Cameroon is a Central African nation with the third largest biomass potential in Sub-Saharan Africa [1], owing to its vast tropical rainforest in the Congo Basin (Figure 1*)*. This biomass potential is thought to equal about 6.3 billion tons [2]. Biomass and waste make up between 75–80% of the country's total energy supply, contributing about 290 PJ in 2020 [3]. When these wastes are collected and disposed of in landfills, they undergo decomposition usually anaerobically. In the process, they emit biogas (composition of carbon dioxide and methane) which, if properly captured and processed, can provide many times over the world's energy needs. The criticisms which have come with the clearing of land for the production of energy crops have encouraged research for biofuels from nonedible sources such as plant material, typically crop residues, and waste from other economic sectors [4]. Furthermore, the need to address major health and environmental concerns (such as indoor air pollution, deforestation, global warming, environmental pollution and climate change) associated with improper MSW management, widespread use of fossil fuels and cooking with traditional biomass necessitates the research of waste-to-energy ventures [5].

Cameroon's economy is dominated by the agricultural sector, which produces nearly 60 million tonnes of different crops annually [6]. This presents a huge market of agricultural residues from which bioenergy could be tapped to address the country's energy challenges. Crop residues can be categorized into primary and secondary residues, depending on whether they are primarily from the farm or industrial processing, respectively. Primary residues usually consist of shells, leaves and peelings that are left in fields or plowed back for organic manure or used as feed for animals. Meanwhile, secondary residues like bagasse and husks are derived during crop processing into more useful products [5]. Usually, the process residues have a higher residue recovery rate, of almost 100%, as compared to the lower residue recovery of field residues, where most are either used as animal feed or reused for cultivation [7]. Most of the crops used in this study are available throughout the year in Cameroon and as such can be regarded as renewable biomass feedstock. However, most residues are used for non-energy purposes, such as animal feed, reuse for cultivation and organic manure. The energy applications of these residues are usually done traditionally as cooking fuels, causing health and environmental concerns. Many business and public sector actors have taken steps to harness the energy potential of these crops' residues in order to reduce the use of fossil fuels, meet climate change targets and avoid the use of food crops for energy reasons. So far, most of these initiatives have been directed towards the production of cleaner cooking fuels (biogas and biochar) for the population in rural areas who mostly burn these residues directly for their energy needs. This does not only contribute to increasing the amount of greenhouse gas (GHG) in the atmosphere but also deteriorates the health of vulnerable women and children who stay more at home and are thereby more exposed.

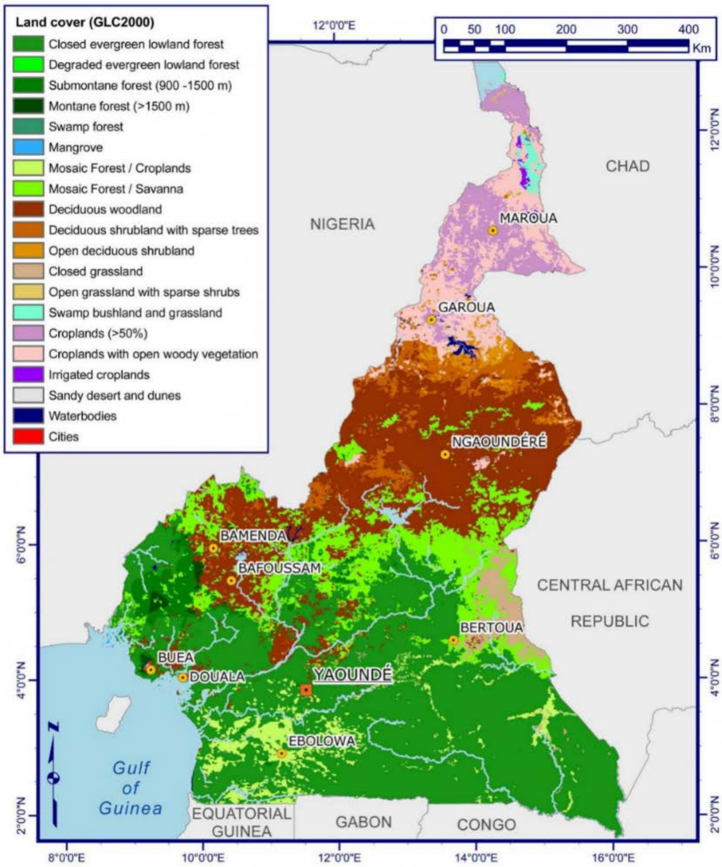

Figure 1. Vegetation cover in Cameroon (Source: https://www.wri.org/data/cameroon-vegetation-cover).

On the MSW management side, about 2.01 billion tonnes of waste is generated globally per annum, with at least 33% of it not managed in an environmentally friendly manner [8] These figures are relatively higher in developing countries like Cameroon, where most municipal waste is left uncollected and untreated due to irregular and insufficient waste collection and treatment facilities. Ref. [7] add that the component diversity of MSW, which is usually composed of organic waste, paper waste, plastic waste, glass, textiles, electrical appliances, etc., makes it difficult to manage. Moreover, the GHGs such as CO_2, N_2O and CH_4 emitted from improper waste management are responsible for about 5% of total GHGs in the atmosphere, while its leachate can cause significant environmental pollution in air and groundwater and gives rise to odor [9].

The drive for bioenergy in Cameroon can be attributed to many factors, including energy security, revenue additions from agricultural and forestry sectors, socio-economic benefits and the expensive cost of importation of refined oil [2]. Also, due to Cameroon's enormous biomass potential, many researchers have sought ways to exploit this enormous potential for energy purposes. As such, there are several published reviews, studies and technical works on techniques, prospects and economic feasibility of waste-to-energy using crop residues and MSW in Cameroon. Ref. [5] assessed the forest, crop, animal and MSW biomass resources in Cameroon, their bioenergy potential and potential contribution to the sustainable development of the country. They found out that the electricity production potential of these biomass sources for the year 2012 was about 67.5 $TWh.y^{-1}$ which amounted to more than twelve times Cameroon's total electricity production for the year 2010. Based on this, they concluded that biomass resources can significantly contribute to the country's energy supply. Ref. [2] also assessed the biomass resource potential in Cameroon from sustainably extracted agricultural and forest residues. They concluded that this potential could help spread electricity throughout the country, especially in farming communities where the residues are enormous. Ref. [10] examined the ground biomass assessment mapping in Cameroon's savanna ecosystem using ALOS PALSAR data and produced a biomass map of Cameroon, though they did not do an assessment of its bioenergy potential. Similar studies by [11] sought to evaluate the energy potential of crop residues (maize and sorghum stalk) for use in biomass power plants to produce electricity and thermal energy in the Northern region of Cameroon and the economic feasibility of it. Their techno-economic analysis of some 6 communities in this region gave an estimated total investment cost of about 874.5 million USD to produce a 270 MW installation, with levelized cost of electricity (LCOE) values between 6.81 USDcent/kWh to 12.9 USDcent/kWh. They however found that this project was only realizable with a Carbon bonus incentive of 5.16 USDcent/kWh for the biomass power plant, without which losses in the municipalities of Bouki and Tchollere were to the tune of 72.778 GWh/year and 137.331 GWh/year, respectively. They recommended that the biomass cost can be reduced by creating a biomass market for electricity generation and a biomass supply chain including the private company. Ref. [12] studied the potential of converting the lignocellulosic biomass wastes from banana plantations in Cameroon into bioethanol, biomethane and wood pellets. They found that about 4.5 million tons of fresh banana plant when bone-dried can produce approximately 93800, 92133, 447500 tons of bioethanol, biomethane and pellets, respectively.

Most studies on MSW in Cameroon dwell mostly on the composition, sources, management and environmental impacts with little or no assessment of its energy potential. Other studies like [13] provide a broad description of the energy potential of MSW for African cities, including Cameroon. This study showed that Cameroon's MSW in 2012 had a potential of about 290 million Nm^3 and is expected to almost double in 2025 to about 524 million Nm^3. In terms of potential energy recovery from waste incineration and landfill gas, recovery values were approximately 31,034 TJ/year and 7799 TJ/year, respectively, from the total waste generated in 2012. Correspondingly, this translates to 1724 GWh and 758 GWh of electricity potential.

Nonetheless, from the reviewed literature, there is limited data and an information gap on the energy potential of the country's crop residues and MSW, and this served as the impetus for this study. There is very little country-specific data on the moisture content, residue-to-product (RPR) and surplus availability factor (SAF) of crop residues. Most of the values utilized in this study are derived from similar studies in countries with identical weather patterns as Cameroon. Also, the geographical scope of many studies is limited to specific cities and does not give a comprehensive review of the energy potential of these resources nationally. Research around MSW is usually focused on its composition, generation, collection and disposal, with little or no characterization of its energy potential. There is also no GIS mapping of MSW hotspots and regions with high crop production to ease identification for further research or development. Most importantly, most studies do not depict a realistic picture of the total energy potential of crop residues, as they do not consider the surplus availability factor (SAF) of each crop residue. This introduces inaccuracies in the energy potential assessment, as it is assumed all residues are used for energy generation purposes while some are used for animal feeding and organic manure. The lack of updated information leaves policymakers flying blind and could deter investors who may be unable to conduct feasibility studies due to limited or outdated data.

This study aims to bridge some of these gaps by

1. providing a more accurate and recent assessment of the energy potential of crop residues and MSW in Cameroon through the introduction of the SAF as used in similar studies by [14,15];
2. introducing the minimum, average and maximum biogas production methodology used by [16,17] to observe uncertainties in results;
3. assessing the electricity generation potential of these sources, the amount of CO_2 emissions saved with their use and the quantity of biofuels that could be produced from crop residues.

The bioenergy assessment in this study is however limited to data collected from recommendable sites and related literature. No ground data collection for crop residues and MSW was done. Also, the most up-to-date data consulted was for 2020, as it was the most recent in the FAOSTAT database available at the time of this study.

2. Methods and materials

The statistics of human population and annual crop production of different kinds of crops for 2021 were obtained from the Food and Agricultural Organization statistics database [6]. To estimate the number of residues generated from each crop, the residue-to-product ratio (RPR) of each crop was used. The RPR values of several crops, as well as their respective heating values, were found in various published studies. Similarly, the heating values of biomass residues and MSW-derived biogas were sought from published documents.

2.1. Determining the bioenergy potential of agricultural crop residues

Procedures and methods for estimating bioenergy from agricultural residues were adapted from [18,19]. The crop residues can be primary residues generated during crop harvesting and primary processing in farms or secondary residues generated during secondary processing in industries [14]. The amount of residue recovered from these crops is unknown, but for this study, it is assumed at 100% to enable the determination of the maximum energy potential of crop residues generated in Cameroon. The crop residues can be further divided into gross residue and surplus residue, which is the part of the gross residue used for energy production. The gross residue as given in formula (1) is a function of the area covered by the crop, the crop yield and the residue-to-product (RPR) ratio of the crops.

$$R_{g(l)} = \sum_{i=1}^{n} A(il) * Y(il) * RPR(il) \quad (1)$$

where $R_{g(l)}$ is the gross residue potential at the lth location from n number of crops in t y^{-1}, $A_{(il)}$ is the area of the area ith crop at the lth location in ha, $Y_{(il)}$ is the yield of the ith crop at the lth location in t ha^{-1}, and RPR$_{(il)}$ is the residue to product ratio of the ith crop at the lth location. The value of total crops produced ($A_{(il)} * Y_{(il)}$) was sourced from the FAOSTAT 2022 database [6], while the RPR values given in Table 1 were obtained from already published studies conducted in other countries, such as Ghana, Uganda, Zambia and China.

Table 1. The RPR, SAF and LHV for studied crops.

Crop	Residue Type	RPR	SAF	LHV (MJ/kg)	Sources
Maize	Stalk	2	0.8	16.3	a,b,j
	Cob	0.273	1	16.63	
	Husk	0.2	1	15.56	
Rice	Straw	1.757	0.684	8.83	b,d,e
	Husk	0.23	0.83	12.9	c,e,f
Sorghum	Straw	1.25	0.8	12.38	a,b
	Husk	1.4	1	13	c,j
Millet	Straw	1.4	1	13	c,j
	Stalk	1.75	0.8	15.51	a,b,f
Wheat	Straw	1.2	0.29	15.6	b,j
	Husk	0.23	0.29	12.9	b,f
Cassava	Stalk	0.062	0.407	16.99	a,d,e
	Peelings	3	0.2	10.61	a,i
Cocoyam	Peelings	0.2	0.8	10.61	i,j
Sweet potato	Peelings	0.6	0.8	10.61	b,j
Yam	Peelings	0.2	0.8	10.61	i,j
Potatoes	Peelings	0.75	0.8	10.61	i,j
Groundnuts	Shells/husks	0.477	1	15.56	a,i,c
	Straw	2.3	1	17.58	a
Palm oil	Fiber	0.147	1	19.94	a,i
	Shells	0.049	1	21.1	a,i
	Fronds	2.604	1	7.97	i
	Empty bunches	0.428	1	19.41	a,i
	Male bunches	0.233	1	14.86	i,j
Coconuts	Shell	0.6	1	10.61	i,j
	Husk	1.03	1	18.6	i,j
	Coir dust	0.62	1	13.4	j
Beans	Straw	2.5	1	12.38	j
Soybean	Straw	2.66	0.8	18	b,f
	pods	1	0.8	18	a,b,f
Banana	leaves	0.35	1	11.37	g
	stem	5.6	1	11.66	a,j
	peels	0.25	1	17	h,j
Plantain	leaves	0.35	0.8	12.12	g,i
	stem	3.91	0.8	10.9	g,i
	peels	0.25	1	12.56	a,h
Sugar Cane	baggase	0.25	1	6.43	b,c
	tops/leaves	0.32	0.8	15.8	b,c
Coffee	husk	1	1	12.8	b,c
Cocoa	pods/husks	1	1	15.48	j
Cotton	stalk	2.1	1	15.9	c,i

Data sources:

a = Ref. [20]; b = Ref. [15]; c = Ref. [14]; d = Ref. [21] ; e = Ref. [22]; f = Ref. [23] ; g = Ref. [24] ; h = Ref. [25] ; i = Ref. [4] ; j = Ref. [5]

It should be noted that some parts of the generated gross residue from crops were used for other purposes like feeding livestock or for soil amendment. The unused part is the surplus, and this surplus (referred to as surplus residue potential (SRP)) is considered to be available for bioenergy purposes. The SRP is estimated using the surplus availability factor (SAF) or recoverability factor of the crop residues. The SAF is defined as the ratio of residues available for energy purposes compared to the total residue amount. The SAF values used in this study were taken from similar published work (such as Ref. [15]), and where SAF for a particular crop (or crop residue) is not available, a SAF value of 1 was assumed. The surplus residue potential at location *l* is estimated using formula (2) according to Ref. [18].

$$R_{sl} = \sum_{i=1}^{n} (Rg(il) * SAF(il)) \quad (2)$$

where *Rsl* is the surplus residue potential at location *l* in tonnes per year, and SAF is the surplus availability factor or surplus residue fraction of the *i*th crop at *l*th location.

The bioenergy crop residue potential is then calculated from the available surplus residue using Eq (3).

$$E_l = \sum_{i=1}^{n} (R(sl) * LHV(il)) \quad (3)$$

where E_l is the estimated bioenergy potential at the *l*th location in PJ y^{-1}, and $LHV_{(il)}$ is the lower heating value of the *i*th crop at *l*th location in MJ kg^{-1}. The lower heating values were obtained in similar studies in Ghana and Nigeria with similar climate patterns as Cameroon. Though the moisture content of the residues was not directly used in computing the bioenergy potential, it should be known as it varies with location, harvest and storage periods and substantially affects the heating value of the crop [26].

The energy potential of crop residues can be realized through their heat, electricity and biofuels production potential. In this study, the electricity potential and the bioethanol and biodiesel potential were analyzed using methodologies proposed and used by [2,27]in their studies. The average moisture content of 22.7% for all crop residues was used in calculating the total bone-dry mass, which was subsequently used in the calculation of the bioethanol and biodiesel production potential. In the bioethanol production, a low conversion factor of 110 litres per bone dry tonne was applied, and 300 liters per bone dry tonne was utilized for high limit biochemical enzymatic hydrolysis and fermentation ethanol. Meanwhile, for Fischer Tropsch biodiesel production, a lower conversion factor of 75 liters per bone dry tonne was used, and 200 liters per bone dry tonne was utilized as the higher conversion factor.

2.2. Bioenergy potential of Municipal Solid Wastes (MSW)

Municipal Solid Waste includes waste generated from households, commerce, trade, small businesses, office buildings and institutions (such as schools, hospitals and government buildings). It also includes bulky waste (e.g., old furniture, mattresses) and wastes from selected municipal services, e.g., waste from park and garden maintenance, waste from street cleaning services (street sweepings, the content of litter containers, market cleansing waste), if managed as waste. These sources exclude waste from municipal sewage network and treatment, municipal construction and demolition waste [28]. The economic status, season, food habit, age and gender of household members all affect the per capita generation from house to house [5]. Usually, larger per capita MSW generation amounts are seen in countries with higher socio-economic indicators like Gross Domestic Product (GDP) per capita, Gross National Income (GNI) and Human Development Index (HDI) [29]. According to [5], MSW in Cameroon can broadly be classified into three main groups (see Figure (2)), which are as follows:

- The directly and rapidly biodegradable fraction (69.50%) consists of organic matter, paper/cardboard and herbs.
- The combustible and slowly biodegradable fraction (5.20%) includes solid organic matter such as wood chips, leather and plastics.
- The inert and non-valorizable fraction (5.80%) is composed of pebbles, stones, ceramics, sand and metals.

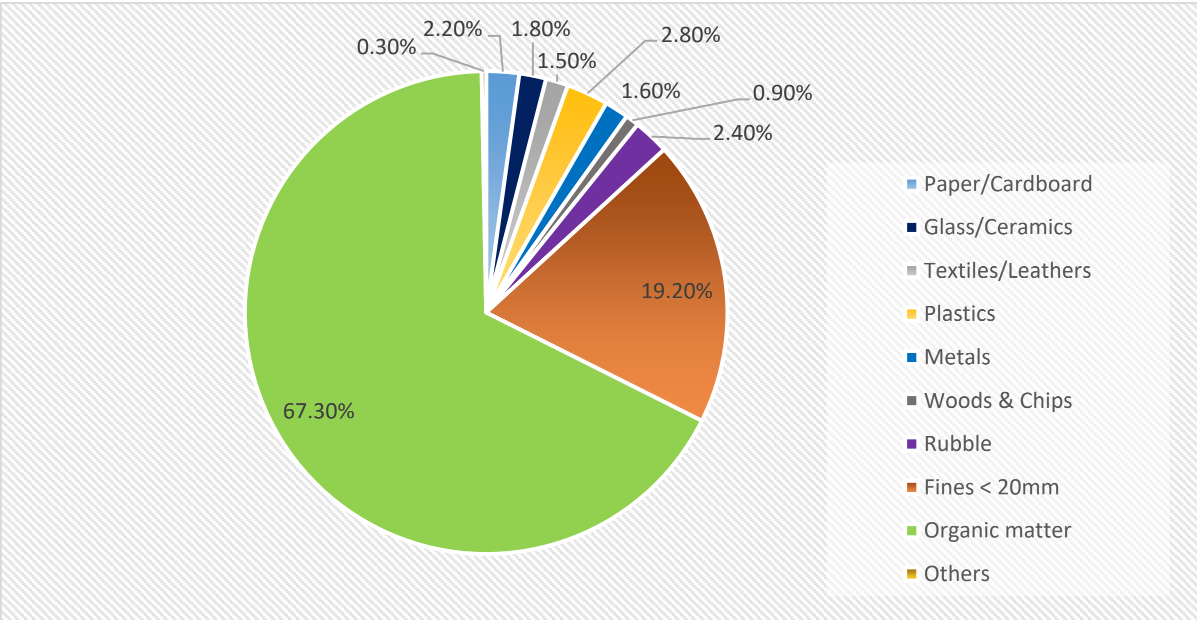

Figure 2. Average composition of MSW in Cameroon (Source: Ref. [5]).

As per the 2020 World Bank World Development Indicators, Cameroon's total population stood at 26545864 people with an urban population of 57.56%. The country's per capita MSW generation as of 2018 stood at 0.42 kg/person/day [30]. According to Cameroon's main waste collection company, HYSACAM, it collects about 5000 tons of waste per day for over 15 million people [31]. This is about 45.5% of the estimated 11000 tons generated daily throughout the country as per the daily generation rate of 0.42 kg/day*person. Assuming that the national per capita waste generation level remained fairly the same between 2018 and 2020 and using 18.47 MJ/kg as LHV of MSW, the energy potential of MSW generated in Cameroon for 2020 can be calculated using Eq (4):

$$MSW_{SE(i)} = 365\ [(N*Q*\mathcal{E}) * (Q_{OR}*LHV)] \tag{4}$$

where $MSW_{SE(i)}$ is the gross municipal solid waste solid energy potential in MJ/year, N is the total population, Q is the quantity of waste generated per capita per day for a household, Q_{OR} is the fraction of the rapidly and slowly degradable organic waste content, $\mathcal{E}$ is the waste collection efficiency, *LHV* is the lower heating value of the MSW, and product $N * Q * \mathcal{E}$ is the quantity of organic waste collected.

The energy potential of landfills can be exploited through the capture of the biogas produced for cooking fuels, combustion engines and electricity generation. It is important to predict the rate and volume of biogas production for the feasibility of energy generation projects [17]. As such, the amount of waste collected and its level of biodegradability are very important. As seen in Figure 2, the rapidly degradable (organic matter and paper/cardboard) and slowly degradable (textiles/leathers, plastics, wood and chips) portions of Cameroon's MSW are 69.5% and 5.2%, respectively.

To calculate the methane production potential and rate in this study, it is assumed that the landfills are engineered for biogas recovery. The Ref. [17] methodology was used with slight modifications, while the Ref. [16] approach (which estimates the potential for 3 scenarios: minimum, average and maximum) was applied to account for result uncertainty. The minimum, maximum and average biogas production factors (Table 2) were generated from [32] for moderate and rapidly degradable organic waste.

Table 2. Suggested values for methane production potential*.

MSW type	CH4 production factor (m^3/t of waste)		
	Minimum value	Average value	Maximum value
Relatively inert	5	15	25
Moderately degradable	140	170	200
Highly degradable	225	262.5	300

*Source: Ref. (17,32].

For the landfill collection efficiency, the arithmetic mean of 55.5% used by [17] was considered. The gross methane production was computed using Eq (5) below:

$$Q_{CH4} = \frac{fL * fLF * MMSW * \mathcal{E}gas}{1000} \quad (5)$$

where Q_{CH4} is the methane production potential as m^3 per year, f_L is the biogas production factor (m^3/tonne) of MSW, f_{LF} is the fraction of MSW sent to landfills, $\mathcal{E}_{gas}$ is the landfill gas collection efficiency, M_{MSW} is the organic fraction (rapidly degradable and moderately degradable), and 1000 = factor for unit adjustment.

The energy potential of the generated methane can be calculated using Eq (6):

$$E_{CH4} = Q_{CH4} * LHV_{CH4} \quad (6)$$

where LHV_{CH4} is the lower heating value of methane = 35.5 MJ/m^3 [33].

The captured methane can be purified for various energy uses like electricity production, which can be calculated using the following equation [33]:

$$E_{M(i)} = \frac{M_{T(i)} * P_{eff} * LHV_{CH4} * CF}{3.6 \times 10^6} \quad (7)$$

where $E_{M(i)}$ is the annual electrical energy production potential (GWh/year), $M_{T(i)}$ is the total methane to be produced annually in the landfills (m^3/year), P_{eff} is the efficiency of the internal combustion engines (typically 35% for such systems [33], LHV_{CH4} is the lower heating value for methane, 35.5 MJ/m^3, CF capacity factor of the plant is 0.8 [17], and 3.6×10^6 is the factor unit conversion.

Given the need to meet carbon emission reduction targets, it will be of interest to many countries and investors to know how much carbon dioxide emissions are avoided using any renewable energy source. Avoidable equivalent CO_2 refers to the amount of methane that could have been released into the atmosphere in CO_2 equivalents, if the gas had not been captured [33]. This amount can be calculated for methane using its global warming potential (GWP) with respect to CO_2. Methane being 25 times more potent than CO_2 as a greenhouse gas implies the ratio can be given as 25 $kgCO_2/kgCH_4$ [34] was used and with a density of 0.716 kg/m^3 [35], the mass of methane can be computed.

3. Results and discussion

3.1. Energy potential of agricultural crop residues in Cameroon

Table 3 shows the estimated quantities of selected crop residues produced in Cameroon in 2020 and their corresponding energy potentials. The selected crops are the country's main subsistence and cash crops in terms of production quantities and can be generally found throughout the country. Also, the availability of data for these crops made them suitable for this study. From this table, it can be seen that the annual estimated bioenergy potential of agricultural residues available for energy purposes is about 580 PJ/y. Furthermore, this table shows that the crop residues with the highest energy potential are plantains, palm oil, maize, sorghum and cassava with estimated energy potentials of 183 PJ/y, 80 PJ/y, 71 PJ/y, 37 PJ/y and 32 PJ/y, respectively. The high energy contents of these crops can be attributed to their high production quantities, residue-to-product ratios and heating values of their residues.

Table 3. Energy potential of agricultural crop residues.

Crop	Surplus Residue (tonnes)	Energy Potential (PJ/year)
Maize	4335188.20	70.540
Rice	457502.19	4.300
Sorghum	2916904.80	37.170
Millet	273264.30	3.900
Wheat	181.22	0.002
Cassava	3037592.47	33.010
Cocoyam	290439.36	3.080
Sweet potato	249483.84	2.650
Yam	113212.16	1.200
Potatoes	212642.40	2.260
Groundnuts	1388500.00	23.930
Palm oil	8532832.46	89.970
Coconuts	8687.25	0.130
Beans	1066192.50	13.200
Soybean	70842.96	1.280
Banana	7500450.00	88.940

Continued on next page

Crop	Surplus Residue (tonnes)	Energy Potential (PJ/year)
Plantain	16556360.40	183.890
Sugar Cane	632022.34	7.060
Coffee	36207.00	0.460
Cocoa	290000.00	4.490
Cotton	516600.00	8.210
Total	48485105.853	579.672

3.2. Energy potential of MSW resources in Cameroon.

Deducing from Eq (4), approximately 4.07 million tonnes of MSW were generated in Cameroon in 2020 with about 1.85 million tonnes collected. The energy potential of the collected waste amounts to about 25.5 PJ. On the other hand, the methane production potential of MSW collected and landfilled computed from Eq (5) gives an average yield of about 88.64 million m^3 of methane per year, corresponding to 3.15 PJ worth of energy for just over 45% of MSW collected *(*see Table 4). This is a significant amount of energy potential which could be used to feed the country's demand for clean electricity, heating or cooking energy sources.

Table 4. Methane and energy potential of MSW in Cameroon.

MSW type	Biogas production potential (million m^3/t/y)			Energy Potential (PJ/y)		
	Minimum value	Average value	Maximum value	Minimum value	Average value	Maximum value
Moderately degradable	3.0	4.10	4.82	0.12	0.15	0.17
Highly degradable	70.0	84.54	96.61	2.57	3.0	3.43
Total	73.0	88.64	101.43	2.69	3.15	3.6

Deducing from Eq (7) the methane generated from landfills in Cameroon has an electricity generation potential of 0.24 GWh/year, which could add significantly to the country's electricity generation potential from biofuels, which stood at 41.0 GWh in 2019 [3].

Using the proposed methodology above to determine the amount of avoided carbon dioxide emissions, it can be estimated that the captured methane in Cameroon's landfills can save up to about 1.6 billion kgs of CO_2 from entering the atmosphere, hence mitigating its global warming and consequent climate change effects.

3.3. General discussions

From the calculations, the total annual energy potential of both crop residues and collected MSW is about 606 PJ y^{-1}. The approximately 580 PJ energy potential of crop residues is significantly greater than the 251.3 TJ energy potential in 2012 of Ref. [5]. This can be attributed to the increase in crop productivity of the selected crops over the years, which stood at about 18 million tons in 2012 compared to 57 million tons in 2020 [6]. Furthermore, the energy potential of major food and cash crops like maize, sorghum, rice, millet, wheat, sugarcane, cocoa, coconut and coffee considered in [2] gives a significantly lower energy potential of about 2.46 PJ as compared to the 128 PJ in this study.

This significant difference is also due to increased productivity over time and because their analysis was based on the energy potential of the bone-dry residue.

From Table 5, about 37 million tons of bone-dry crop residues were available for biofuel or electricity production in 2020. These residues had the potential of producing between 4.13–11.23 billion liters of bioethanol which could be used to offset gasoline consumption in Cameroon. Using the estimation methodology used by [2], this quantity of bioethanol is more than 5 times Cameroon's total gasoline consumption of 8.74 thousand barrels per day in 2018 [36]. Alternatively, it could also yield between 2.81 to 7.51 billion liters per year of biodiesel which could be used in reducing the demand for petroleum diesel consumption. On the electricity generation side, crop residues could generate between 24.35 and 64.92 TWh of electricity, which is 3.67 to 9.83 times the entire country's electricity consumption, of 6.6 TWh in 2019 [3].

Table 5. Electricity, bioethanol and biodiesel production potential from crop residues.

Average Moisture Content (%)	Surplus residue (Bone-dry tons)	Total Energy Potential (GJ)	Electricity potential (GJ *0.28* Efficiency)		Bioethanol potential		Biodiesel potential	
			15% efficiency TWh (Low)	40% efficiency TWh (High)	(Low) liters	(High) liters	(Low) liters	(High) liters
22.6	37.53E+06	579.66E+06	24.35	64.92	4.13E+09	11.23E+09	2.81E+09	7.51E+09

At an annual population growth rate of 2.6% [37], Cameroon could have a population of around 33 million people by 2030, with a 62 percent urbanization rate [38]. Economic expansion and rapid urbanization are expected to follow this population increase marked by increased energy demand for biomass and an equivalent increase in MSW generation. The 1.6 billion kgs of CO_2 that could potentially be captured in landfills through biogas recovery shows that uncontrolled disposal sites can be a major source of Greenhouse Gases (GHG) in Cameroon. The Ref. [39] report predicts that about 8–10% of global anthropogenic GHG emissions by 2025 will come from the waste sector, particularly food waste. This may present a major challenge to governments if this growth is not matched with adequate planning of energy security projects and proper waste management. In contrast, this presents a huge market for resource recovery and cheap energy generation. The development and integration of renewable energy from crop residues and MSW can provide sustainable solutions to the energy demands which could double in the next decade. Energy from these sources will not only satisfy energy needs but also help in clearing the streets from unwanted garbage and contribute to the waste management efforts of the government and, in general, foster its transition into a circular economy. Also, energy generation from crop residues and MSW takes away the question of food-vs-fuel that usually comes with the generation of bioenergy using edible food crops. The crop residues of plantain, palm oil, maize, sorghum and cassava are the most energy-intensive crops in Cameroon and should be priority crops for energy generation investments.

Despite all these advantages, there are challenges to the wide-scale development of bioenergy technology in Cameroon. Ref. [5] raise concern over the sustainability of supply, environmental impacts and difficulties with the collection, transportation and storage. In addition, most of these wastes are not sorted at the source, and there is a social stigma around MSW waste collection and sorting. Not up to half of MSW generated is collected and landfilled, with the rest being emptied into waterways and streams. There is also a lack of spatial geographical information system (GIS) data on the crop production level per region of Cameroon, and this makes it challenging to situate areas for potential research and investment. If proper waste-to-energy techniques are set up, the integration of biomass energy in the country's energy mix will be accelerated.

4. Conclusions

In this study, the energy potentials of agricultural residues and MSW in Cameroon are calculated and estimated at roughly 580 PJ and 26 PJ, respectively, in 2020. This is an enormous amount of energy potential which is not sufficiently utilized and, in most cases, utilized traditionally and unsustainably. These crop and MSW resources could be harnessed to provide electricity for off-grid communities and also used to replace fossil-based transportation fuels and cooking gas through bioethanol and biodiesel production.

However, there are not sufficient policies to create the demand or promote technological development for modern biofuels in order to reduce the country's dependence on expensive fossil fuel options. This has slowed the integration of alternative energy sources and consequently its climate change mitigation and adaptation efforts. These policies cannot be put in place without the availability of sufficient and accurate data on national energy demand and supply potential. In that light, there is a need for ground research and geospatial analysis of the country's crop residue potential and waste generation hotspots so that concrete policies and plans can be drawn from realistic estimates and not guesstimates. Furthermore, Cameroon's waste management needs to be improved holistically, with biogas recovery at landfill sites developed, with sorting at source encouraged, and waste collection coverage expanded to vulnerable and remote communities. There is also a lack of accurate and updated data on the quantity of landfilled waste and the per capita waste generation in various cities and nationally.

In all, biomass and MSW are key resources which, if developed sustainably, will enable the country to be energy secure and self-sufficient, while achieving its emission reduction targets without compromising on its socio-economic development goals and fight against poverty.

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Conflict of interest

The authors declare no conflict of interest.

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