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Research article

Evaluation of a bioenergy resource of agricultural residues and municipal solid wastes in Benin

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Abstract: Benin is one of the West African countries with low access to energy. Abundant residues are generated from different activities in Benin, most of which are not yet considered for energy generation. In this study, we aim to evaluate the potential of bioenergy resources from agricultural residues and municipal solid waste (MSW) in Benin. Eleven (11) agricultural residues have been considered in the study and four of them with high bioenergy potential have been used in the Bioenergy and Food Security Rapid Appraisal (BEFS RA) tool to evaluate how much electricity could be generated from gasification and analyze the social and economic benefits that can be attained. We also introduce the residue-to-product approach and the NPV and IRR method to estimate the potential of agricultural residues and MSW and analyze the viability of generating electricity through the gasification process. Data for agricultural residues have been collected from Benin's Directorate of Agricultural Statistics governmental website and MSW data is estimated using World Bank data for 2012 and 2025. Our estimation shows that a total bioenergy potential of 142.63 PJ can be generated from agricultural residue and MSW in Benin produced in 2021. Agricultural residues are the highest contributor, contributing up to 98%. The bioenergy potential available for electricity generation is estimated at 85.6 PJ with maize the major contributor at 45%, followed by cotton and cassava residues at 17% and 13%, respectively. The BEFS RA simulation shows that 20,849; 83,395 and 208,488 kWh per year can be generated from the available feedstock based on using 10, 40, and 100 kW plants respectively. Moreover, the net present value and the internal rate of return of all power plants are positive, showing the importance of investing in power generation through gasification systems. It is also important that future bioenergy projects include maize, cotton, and cassava residue as a priority for bioenergy generation since their energy potential appears to be higher than for other crops.

Keywords: agricultural residue; biomass; bioenergy potential; municipal solid waste; BEFS rapid appraisal

Abbreviations: A: Area (m^2); BEFS RA: Bioenergy and food security rapid appraisal; DSA: Direction de la statistique agricole; ECOWAS: Economic Community of West African States; GDP: Gross domestic product; Gr: Population growth (%); IRR: Internal rate of return (%); LHV: Lower heating value (MJ/kg); MSW: Municipal solid waste; NGOs: Non-governmental organizations; NPV: Net present value ($); PAG: Programme d'Action du Gouvernement; RPR: Residue to product ratio (%); SAF: Surplus availability factor; SGDS-GN: Waste Management company of Grand Nokoue

1. Introduction

Access to energy is a strategic priority in all regions of the world, particularly in developing countries in Africa. Long-term energy supply and demand forecasting are of utmost importance in Africa and around the world due to the steady rise in energy requirements, lack of sufficient resources, high reliance on fossil fuels to meet these requirements, and global concerns about carbon-induced environmental issues [1]. Due to population growth, the world is facing a crisis of increasing waste and issues related to climate change [2,3]. Countries like China and the United States of America (USA) have abundant yearly Municipal Solid Waste (MSW) generation with more than 262 million tons of MSW generated in the USA in 2015 [4,5]. As of 2020, the total MSW generated by the Organization for Economic Cooperation and Development (OECD) countries is estimated to amount to 533.8 kg/capita [6]. It is also projected that, in 2025, a person will generate 0.5, 0.65, 1, and 2.1 kg a day in Ghana, Ethiopia, Cameroon, and South Africa, respectively [7]. There is an important potential for agricultural residue and municipal solid waste and technologies for waste management and energy production have become the focus of the international community [8–10]. Waste to energy systems and technology development is important to achieving sustainable development goals (SDGs) [11,12].

As the world becomes increasingly aware of the devastating effects of climate change, there is a growing need to reduce carbon emissions in various sectors [13]. To this end, researchers are exploring decarbonization pathways for transportation, industry, and power sectors, which are major contributors to greenhouse gas emissions [14]. One promising approach is the development of low-carbon emission systems which utilize waste energy recovery systems to reduce carbon footprint [15]. Agricultural residue and municipal solid waste are potential sources of waste energy that have been explored for various purposes. For example, in a study conducted in Tonga, researchers used agricultural residue and waste to generate cooling and electricity in small islands. The proposed system has the potential to supply up to 38% of the total electricity generation in the region, while reducing CO_2 emissions [16]. Other studies have also explored the use of agricultural residue for the production of biofuels and biodiesel, which are sustainable alternatives to fossil fuels [17,18]. By harnessing waste energy sources, governments could reduce reliance on fossil fuels and move towards a cleaner and more sustainable future.

Benin is one of the less developed west African countries endowed with abundant energy resources. Still now, the country does not have the infrastructure and modern systems to convert energy resources into power and transport them around the country [19]. A significant amount of Benin's energy comes from importation [20,21]. Mensah et al.,[19] stated that, electricity imports cost around USD 130 million per year in Benin, primarily from bordering countries like Nigeria, Ghana, and Ivory Coast. Agriculture is a significant source of revenue in rural areas of the country, providing jobs and a means of subsistence [22,23]. It also serves as a backbone in rural areas, employing 70% of the rural population and producing 40% of the country's gross domestic product [22]. According to [24], small-scale farmers use the traditional slash-and-burn agriculture practice to cultivate their land. Crop production is frequently hampered by a lack of inputs, recurring droughts, and low soil fertility. The livestock production system relies on grazing resources, which are mostly comprised of yearly forage on natural grassland and woodland lands. Agricultural practices are mainly rainfall-fed and characterized by small landholdings, and low inputs with maize, sorghum, rice, cassava, yams, and groundnut as major food crops and cashew, shea nut, and cotton as major cash crops. Major livestock includes sheep, goats, cattle, pigs, and poultry [23]. Crop residues, agro-industrial by-products, and other farm products are now used to make a significant volume of feed for animals. However, the relative contribution of these feeds changes according to location and season.

Furthermore, the country's management of municipal solid waste is a big problem with major environmental concerns [25]. In Benin, municipal solid waste management is the duty of town councils, which oversee the service and subcontract it to private operators and Non-Governmental Organizations (NGOs). Only a few cities have garbage transportation structures, including Cotonou, Porto Novo, Kandi, Ouidah, Lokossa, and Parakou. Only the cities of Cotonou and Porto-Novo have a manicured site in Ouèssè and Takon in terms of discharge. In other cities like Djougou, Bohicon, Parakou, and Malanville, there is no specific discharge place for a waste deposit. According to the World Bank [7], Benin, with a total urban population of 3,147,050 in 2012, generated 0.54 kg/capita/day, meaning approximately 197 kg/capita/year. The same source projected that the country would generate 274 kg per capita per year of MSW by 2025. This is showing that Municipal Solid Waste is increasing over time with the increase in population and, socio-economic development hence, action needs to be taken to find uses to MSW to mitigate climate-related issues and provide safe living conditions to the population.

The potential of bioenergy resources for energy generation has got interest in past recent years and most African countries are using bioenergy resources to meet their energy needs. In Cameroon, agricultural residues and MSW potential is estimated to amount 580 and 26 PJ, respectively, in 2020 [26]. Okello et al.,[27] conducted a study on evaluating the bioenergy potential of agricultural and forest residues in Uganda using the residue-to-product ratio (RPR) method to estimate the annual production of crop and forest residue. Their result showed that bioenergy resources could produce a total energy potential of 260 PJ per year in Uganda, with the highest contribution of about 57.7% coming from crop residues. Gabisa & Gheewala,[28] evaluated the potential of bioenergy production in Ethiopia using different available biomass residues. They estimated the total bioenergy potential available in the country at 750 PJ per year, with 34% and 0.05% coming from crop residue and Municipal Solid Waste, respectively. The maximum contribution of 46.5% came from forest residues. Furthermore, a biomass resource assessment and bioenergy generation study was carried out by Mboumboue & Njomo [29] in Cameroon in 2018. They found that biomass sources could produce 67.5 TWh per year in the country, which represents a high amount compared to the annual production of the country in 2010. In Nigeria, biomass resources estimation showed that about 2.33 EJ of energy could be generated from the available resources in the country [30]. Scarlat et al.,[31] evaluated the energy potential of MSW in urban areas in Africa and found that 1125 and 2199 PJ of energy could be generated from MSW based on data provided by the World Bank [7] for 2012 and 2025.

Recently, Adamon et al.,[32] evaluated the energy potential from three different residues which are maize stalks, millet stalks, and cotton stalks in Benin, and obtained 731 MW of energy. So far, those different studies showed the importance of bioenergy resources in helping the government to meet the energy needs of the population in African countries and how they can contribute to climate change mitigation and a safe living environment. However, none of those studies have introduced the technology and process of converting crop residue to useful energy in Benin. Even though Benin has a lot of potential for energy from agricultural and Municipal Solid Waste, there is a big roadblock to effective agricultural biomass and MSW promotion due to the lack of reliable data on the energy potential of those various biomass resources. The country still relies on traditional biomass and its electricity access is still low. The country's objective in terms of electricity is to achieve an electrification rate of 95 percent in urban areas and 65 percent in rural areas by 2025 [33]. To this end, it is necessary to investigate all available resources in the country. Therefore, biomass energy appears as an opportunity for the country to achieve its energy independence goal.

Despite the country's abundance of biomass resources, many actions need to be taken in the economy to improve people's living standards. Most of similar studies in the literature so far have failed to introduce the net present value (NPV) and internal rate of return (IRR) approach to analyse the financial viability of different production scales and compare feedstocks and plant capacity. In addition to applying surplus availability factor (SAF) and residues to product (RPR) method to estimate bioenergy potential, we use the NPV and IRR approach to analyze the viability of generating electricity through gasification process. The production of biofuels and biodiesel from waste is a promising field and has gotten a lot of interest and different approach has been developed for promising biodiesel production [34]. However, we did not focus on biogas and biofuel production as in most of available studies [35–38]. Here, we aim to evaluate the potential of bioenergy resources from agricultural residues and municipal solid waste in Benin and estimate the bioenergy potential of the country based on available residue. In addition, the lack of updated information leaves policymakers and researchers flying blind on the potential biomass resources in the country. We attempt to assist researchers, policymakers, and stakeholders in exploiting existing biomass resources, and authorities in the energy sector's attention to the bioenergy potential of the country to call for further investment in the sector.

Hence, the next section presents the method and material used in this study including the data collection method and mathematical formulas used to estimate the energy potential from different residues. The Bioenergy and Food Security Rapid Appraisal (BEFS RA) tool is used to show the feasibility of generating electricity through biomass gasification systems in rural areas without current electricity access. Section 3 presents the different results and discussions while the last section gives the concluding remarks and recommendations.

2. Methods and materials

2.1. Benin's location

Benin is a West African country that shares borders with Nigeria to the east and Niger to the north, Togo to the west, and Burkina Faso to the northwest. As shown in Figure 1, Benin is situated in the Atlantic Ocean's Gulf of Guinea, between 60°20' and 12°30' north latitude and 1° and 4° east latitude, with an altitude ranging from 0 to 600 meters [38]. On the country's coastline, the country stretches 700 kilometers from north to south and 125 kilometers from east to west. The total surface area of Benin is 112,622 km^2 with a current population estimated at 12,123,198 inhabitants [39]. The political capital of Benin is Porto-Novo, located in the south of the country, near the Atlantic coast but Cotonou is the most populous city in the country with approximately 780,000 inhabitants and is the city where most economical activities take place. The country has a Gross Domestic Product (GDP) of approximately 15.65 billion USD in 2020 as presented in Table 1.

Table 1. Benin's key indicators [39].

Key indicators (in 2020)	Amount
Population (million)	12.12
GDP (billion USD)	15.65
Growth rate (in %)	2.7
CO_2 emissions (M tonne CO_2)	6.7

Figure 1. Benin's geographical location on the world map: https://ontheworldmap.com/benin/ [40].

2.2. Source of data

Data for agricultural residues have been collected from the governmental site DSA ("Direction de la Statistique Agricole du Benin" in French), which provides yearly data for agricultural products [41] as presented in Table 2. Table 3 provides the areas for different years for each crop considered in this study. For the energy potential estimation of various agricultural residues, data for Residue-to-Product ratio (RPR), Surplus Availability Factor (SAF), and the Lower Heating Value (LHV) were collected from similar studies conducted in Benin, in West Africa, and different developing countries and are presented in Table 4. Municipal solid waste data were provided by the world bank for the years 2012 and 2025. Due to the lack of recent data for the whole country, we estimated MSW data for the year 2021 from the data for those two years by using an approximation method. Two similar studies have given approximate values for MSW in the city of Cotonou and Porto-Novo, respectively, for different years [42]. Major agricultural crop production in Benin are cotton, maize, cassava, yams, soybeans, palm oil, groundnuts, Potato, sweet potato, sorghum, rice, millet, and cashew nuts. These crops are the most available and easy to access by the population and for residue collection purposes [32].

Table 2. Agricultural crop production (Tonnes) per year in Benin [41].

Crop	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	Production (Tonnes)											
Maize	1065329	1012630	1165957	1174563	1345821	1354344	1286060	1376683	1514913	1543973	1580750	1611615
	1065329	1012630	1165957	1174563	1345821	1354344	1286060	1376683	1514913	1543973	15805750	1611615
Rice	112705	124986	133195	219101	206943	234145	204310	281428	361336	374706	406083	411578
Millet	27431	26929	24690	31023	22881	23668	21640	25182	25719	26218	26250	27294
Sorghum	131716	168088	133195	107969	114750	100249	129674	129665	154548	151065	160000	148236
Cassava	3787918	3444947	3645924	3295785	3695514	4066711	3420665	3892287	4078558	4324483	4525450	4161660
Yam	2373586	2624011	274862	2739088	3177265	3219993	260498	3041245	2885225	3353061	3365500	3150248
Sweet Potato	63901	77268	49016	69829	64860	65488	55405	58145	55881	59298	59400	56923
Potato	-	-	-	18017		171	86	1367	3365	3409	3534	2978
Groundnuts	132069	154403	131792	121510	134230	141698	134323	137214	156901	169277	170452	172641
Soybean	55259	59458	67153	72994	96944	99066	139909	156901	159852	178185	257000	253954
	55259	59458	67153	72994	96944	99066	139909	156901	159852	178185	257000	253954
Cotton	157968	136958	200000	240028	307353	393368	269212	451124	597986	677654	714714	731057

Table 3. Areas for different agricultural crop production [41].

Crop	Year											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	Areas (ha)											
Maize	924,764	918,235	820,157	938,846	973,453	968,030	1,003,715	1,000,361	1,166,766	1,161,765	1,470,250	1,267,159
Rice	40,834	47,054	55,797	65,730	68,259	74,586	65,305	82,351	99,831	111,376	102,415	104,586
Millet	33,998	31,794	28,388	34,464	27,374	27,724	26,670	29,390	28,779	29,235	29,135	23,807
Sorghum	119,880	112,108	111,876	106,903	109,734	101,513	131,553	131,906	168,232	153,058	151,065	134,693
Cassava	256,615	285,765	209,813	247,754	279,513	296,641	284,033	297,978	338,032	321,885	319,299	346,382
Yam	167,919	201,195	182,204	200,393	210,795	214,054	202,605	205,658	235,325	252,096	235,331	228,998
Sweet potato	11,442	18,404	8,107	10,192	10,701	10,938	10,016	9,888	9,848	8,669	9,468	10,131
Potato	-	-	-	1,323	-	13	6	325	280	315	307	234
Groundnuts	147,798	175,432	136,701	140,014	153,763	163,009	158,009	159,414	199,527	164,943	174,628	172,783
Soybeans	58,225	68,114	74,651	79,714	95,107	97,783	152,138	153,162	185,251	141,687	192,412	203,572
Cotton	150,225	137,086	208,057	335,141	347,023	405,400	313,535	418,943	530,145	623,949	665,703	614,297

Table 4. Residue-to-Product ratio (RPR), Surplus Availability Factor (SAF), and the Lower Heating Value (LHV) for various crop residues in Benin [28,29,33,43].

Crop	Type of residue	RPR	Surplus availability Factor (SAF)	LHV (MJ/kg)
Maize	Stalk	2.5	0.8	17.4
	Cob	0.27	1	16.6
Rice	Straw	1.5	1	15.56
Millet	Stalk	3	0.8	17.8
Sorghum	Stalk	2.62	0.8	17
Cassava	Sterms and peels	0.4	0.8	13.1
Yam	Peels	0.2	0.35	10.61
Sweet Potato	Peels	0.4	0.8	16
Potato	leaves	0.76	0.8	16
Groundnuts	Trash and shell	2.1	0.92	11.2
Soybean	Straw	2.66	0.8	18
	Pods	1	0.8	18
Cotton	Stalk	2.1	0.91	17.1

2.3. Agricultural residues bioenergy potential estimation

Yams, corn, cassava, peanuts, rice, citrus, and cashew nuts as well as shea, almonds, African Locust beans (Parkia nuts), and peppers are among the principal crops in Benin. Most farmers in Benin usually cultivated one to two hectares, with 85% cultivating corn, 30% cassava, 31% yams, 30% sorghum, and 11% farming cotton, the country's main income crop. Borgou has the greatest agricultural plots, followed by Atacora, Collines, Alibori, Donga, Plateau, Ouémé, Atlantique, Mono, and Couffo, in that order [44].

The energy potential of agricultural residues estimation is based on crop residues amount available in the country. Crop residues are categorized into gross residues and surplus residues [28]. For the bioenergy potential, only the surplus residues are used. Therefore, we first calculated the amount of gross residue available before estimating the surplus.

The gross residue depends on the area covered by individual crops, the yield of the crop, and the residue-to-product ratio of the given crop. It is estimated using the Eq (1) given as follow:

$$R_{Gi} = \sum_{i=1}^{n} [RPR_i \times (A_i \times Y_i)] \quad (1)$$

where: R_{Gi} represents the gross residue potential of the i_{th} crop from n number of crops, RPR_i is the residue to product ratio of a given crop, A_i is the area used for the i_{th} and, Y_i is the yield of the i_{th} crop.

The surplus residue, which is available for energy production, is the gross residue minus other uses for which the residue can be used for. It is estimated using the Eq (2):

$$R_{Si} = \sum_{i=1}^{n} R_{Gi} \times SAF_i \quad (2)$$

where: R_{Si} represents the surplus residue potential of the i_{th} crop from n number of crops, SAF_i is the surplus availability factor or the surplus residue fraction of a given crop.

The bioenergy potential of the crop is estimated using the Eq (3):

$$E_i = \sum_{i=1}^{n} R_{Si} \times LHV_i \quad (3)$$

E_i is the bioenergy potential of the ith crop and, LHV_i is the Lower Heating Value of the ith crop.

2.4. Rural electrification through the bioenergy and food security rapid appraisal tool

The BEFS RA tool is used here to check how much electricity can be generated from the most dominant feedstocks in Benin for rural electrification. The Energy and End-Use option module of the BEFSRA is divided into five sub-modules, which are Intermediate or Final Products, Heating and Cooking, Rural Electrification, Heat and Power, and Transport. Each of the sub-modules includes a choice of components of analysis to assess the production of specific biofuels based on particular processing technologies as shown in Figure 2 [37]. The gasification component is used in the case study of this project since it helps to compare different biomass types (feedstock) and plant capacities to identify the most appropriate biomass sources based on several factors, including physical availability, and economic and social results.

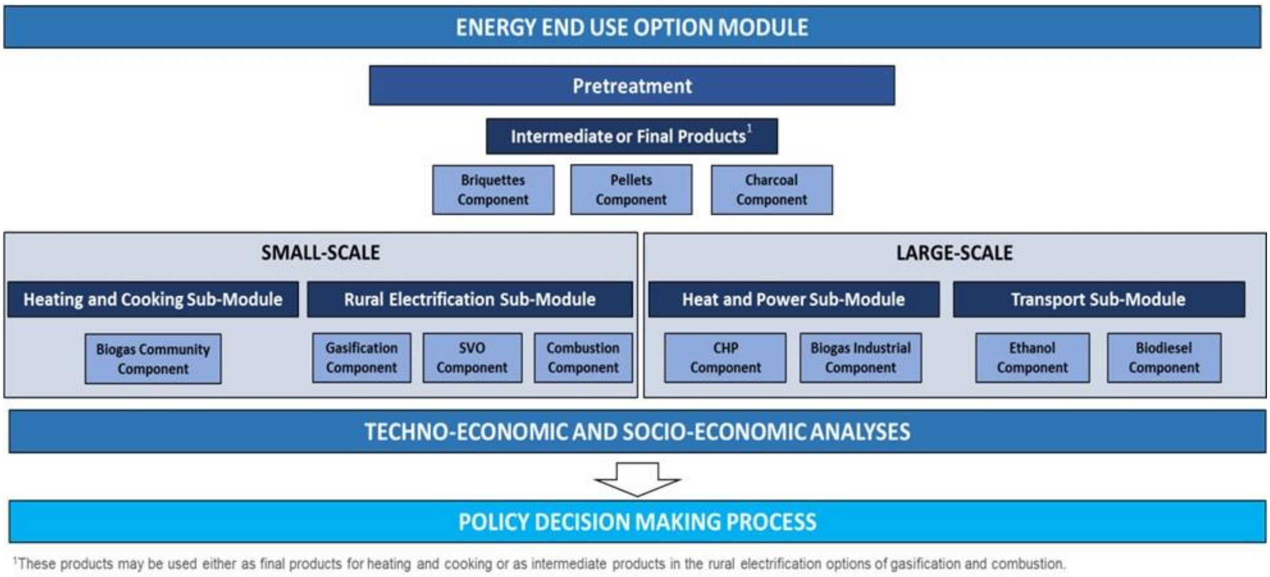

Figure 2. The structure of the energy end-use option module [45].

The Gasification Component is designed to assist in evaluating the potential to develop biomass gasification to supply electricity in rural areas without current access to electricity and where extension of the national grid is not feasible. It provides a technical foundation to perform an analysis of biomass gasification systems for the production of electricity at 10, 40, and 100 kW from an assortment of biomass sources. The results of the analysis can be used to identify the viability of electricity production from gasification in terms of feedstock availability, the financial viability of the different production scales, the optimum production capacity and feedstock combination, and the socio and economic benefits that can be attained for each production scheme [37]. The biomass Gasification System for Rural Electrification is presented in Figure 3. An application of the Energy End-Use option module has been used in Malawi for rural electrification options to help policy and decision-makers [46]. The tool is also suitable when evaluating the potential of biogas and biofuel systems [36,37]. Further detail on how to run the model, the assumptions made in the model, and the different formulas used are available in the user guide [45]. Four (04) agricultural residues with the highest bioenergy potential are considered in the case study namely maize cob, cotton stalk, cassava stalk, and sorghum straw. The data used for simulation are default values from the module's simulation user guide.

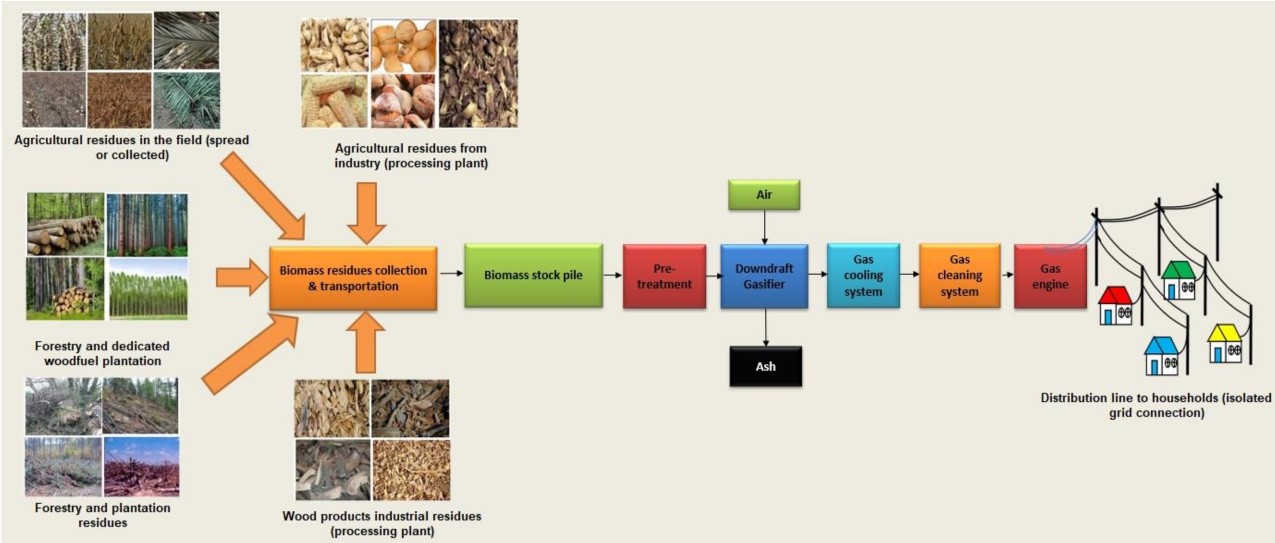

Figure 3. Biomass gasification system for rrural electricity [45].

2.5. Municipal solid waste bioenergy potential estimation

Municipal waste is defined as waste collected and treated by or for municipalities. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions, and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste. The definition excludes waste from municipal sewage networks and treatment and wastes from construction and demolition activities (Organisation for Economic Co-operation and Development [OECD]) [6]. In this study, the energy potential from municipal solid waste is calculated as follows (Eq 4):

$$MSW_{SEi} = 365 \sum_{i=1}^{n} [N \times Q \times Ɛ] \times [Q_{OR} \times LHV]_i \tag{4}$$

- MSW_{SEi} is the gross municipal solid waste energy potential per year,
- N is the total human population
- Q is the quantity of waste generated per capita per day,
- Q_{OR} is the fraction of the organic waste content,
- Ɛ is the collection efficiency and,
- LHV is the Lower Heating Value, taken as 12 MJ/kg [29].

Benin is in the category of Low Income (LI) from the classification of the world bank in 2012 [7] and the composition of MSW is given in Figure 4. The current MSW production can be estimated using the equation (Eq 5) as in [29]:

$$W_{2021} = W_{2012} \left(1 + \frac{Gr}{100}\right)^{n} \tag{5}$$

Gr = 2.7% representing Benin’s population growth as of 2021, W_{2021}, W_{2012} are the waste production (kg/capita/day) in 2021 and 2012, respectively and n is the number of years.

Waste is managed in Benin by the SGDS-GN in the Grand Nokoué cities (Cotonou, Abomey-Calavi, Porto-Novo, Ouidah, Sèmè Kpogji). They estimated that Grand Nokoué cities generate 450,000 t/year of MSW while Cotonou city alone produced 230,000 t/year [47]. Those different data were used to estimate the bioenergy from MSW for the country, for Grand Nokoué cities, and Cotonou as the economical capital and biggest city. At the Foun-Foun collection site in Porto-Novo, the first sorting and recovery facility for recyclable household waste was recently placed into operation. Only 30% of the 60,000 tonnes of rubbish produced annually in Benin's capital are transferred to landfills.

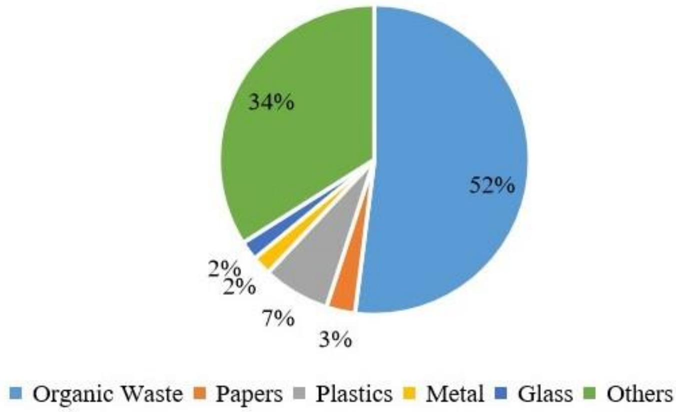

Figure 4. Composition of municipal solid waste in Benin [7].

3. Results and discussions

3.1. Potential of agricultural crop residue

Table 5 presents the bioenergy potential from different agricultural crop residues in Benin from 2010 to 2021. That includes the bioenergy potential for eleven (11) different crops mainly maize, rice, millet, sorghum, cassava, yam, sweet potato, potato, groundnuts, soybean, and cotton. As shown in Table 5, the maximum production is obtained for the year 2020 with a maximum value of 140.79 PJ while the minimum bioenergy potential is 77.57 PJ obtained in 2011. The energy potential increases slightly from 2011 to 2015 at 104.17 PJ, decreases up to 94.73 PJ in 2016, and shows a considerable increase from 2016 to 2021. These changes could be due to different factors such as weather-related issues, insects that can affect crop production from year to year, and changes in cultivation area and proportion of different crops for the different years. In fact, in Benin, the year 2016 was a transition year, where a different government was installed and most of the action that year was devoted to the election campaign explaining the less production in the year 2016. When the new government was inaugurated, its PAG (Programme d'Action du Gouvernement in French) had a main focus on agricultural development, which is remarkable by the increase in crop production over the first five years from 2016 to 2021[48].

Table 5. Bioenergy production from agricultural crop residues over the ten past years.

	Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Crop	Type of residue	Energy (PJ)											
Maize	Stalk	37.07	35.24	40.58	40.87	46.83	47.13	44.75	47.91	52.72	53.73	55.01	56.08
	Cob	4.77	4.54	5.23	5.26	6.03	6.07	5.76	6.17	6.79	6.92	7.08	7.22
Rice	Straw	2.63	2.92	3.11	5.11	4.83	5.46	4.77	6.57	8.43	8.75	9.48	9.61
Millet	Stalk	1.17	1.15	1.05	1.33	0.98	1.01	0.92	1.08	1.10	1.12	1.12	1.17
Sorghum	Stalk	4.69	5.99	4.75	3.85	4.09	3.57	4.62	4.62	5.51	5.38	5.70	5.28
Cassava	Sterms and peels	15.88	14.44	15.28	13.82	15.49	17.05	14.34	16.32	17.10	18.13	18.97	17.45
Yam	Peels	1.76	1.95	0.20	2.03	2.36	2.39	0.19	2.26	2.14	2.49	2.50	2.34
Sweet Potato	Peels	0.33	0.40	0.25	0.36	0.33	0.34	0.28	0.30	0.29	0.30	0.30	0.29
Potato	leaves	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.01	0.03	0.03	0.03	0.03
Groundnuts	Trash and shell	2.86	3.34	2.85	2.63	2.90	3.07	2.91	2.97	3.40	3.66	3.69	3.74
Soybean	Straw	2.12	2.28	2.57	2.80	3.71	3.79	5.36	6.01	6.12	6.83	9.84	9.73
	Pods	0.80	0.86	0.97	1.05	1.40	1.43	2.01	2.26	2.30	2.57	3.70	3.66
Cotton	Stalk	5.16	4.48	6.54	7.84	10.04	12.85	8.80	14.74	19.54	22.14	23.36	23.89
	Total	79.25	77.57	83.38	87.13	99.00	104.17	94.73	111.21	125.47	132.05	140.79	140.48

Figure 5 shows the proportion of bioenergy potential contribution from different crop residues for the year 2021 (in %). Since it is not possible to collect all the residue generated in the country, a recovery rate of 60% is applied [49]. Therefore, for the year 2021, the most recent, the bioenergy potential from agricultural crop residue is estimated to be 84.28 PJ which is equivalent to yearly power production of 2,672.5 MW. Maize appears to be the highest contributor at 45% representing 1,202.6 MW followed by cotton at 17% (454.33 MW). Cassava is the third contributor at 12.42% equivalent to 332 MW, followed by soybean and rice generating, 254.7 and 182.8 MW, respectively. There is a huge difference between the bioenergy potential from crop residue of 2,672.5 MW estimated in this study and that of 731 MW estimated by [32]. This can be explained by the number of crop residues considered since this study considers eleven (11) crop residues against 3 by Adamon et al.,[32]. Also, they used a recovery rate of 30% and 60% for maize residues and millet residues, respectively, while we applied a recovery rate of 60% for all residues [49]. The interest of Benin's government in the CIF/SREP program for biomass energy of 125 MW by 2030, is good but could be increased for the country since our estimation shows that the country's bioenergy potential from crop residues alone is 21 times higher than that the government target. Furthermore, the estimated of 23.41 TWh/year is almost 70 times higher than the total production of all electric energy-producing facilities of 0.335 TWh in 2020 [19], showing that bioenergy can significantly contribute to meeting the future energy need of the country and help to fill the gap between the in-country production of electricity and the electricity importation from neighboring countries.

Figure 6 presents the cultivated area and energy potential in Benin in 2021 while Figure 7 shows the different variations in area cultivation in the country over the last ten years. Both figures show the predominance of maize in terms of cultivation making it more accessible to the population followed by cotton and cassava, respectively. Maize is the most cultivated crop in Benin and appears as the major staple food in the country [50] that's why it appears as the most contributing crop residue. Moreover, Benin, as of 2019/2020, becomes the leading cotton producer in West Africa's franc zone due to the modernization of the cotton supply chain by the government through huge investment [51]. In Benin, agricultural crop residues are burned as a pest control measure on farms, while other residues are utilized as wood fuel alternatives. In the country, effective quantification and assessment of agricultural crop wastes and their energy potential have gotten little attention. It is therefore important that future bioenergy projects include maize, cotton, and cassava residue as a priority for bioenergy generation since their energy potential appears to be higher than for other crops (Figures 6 and 7).

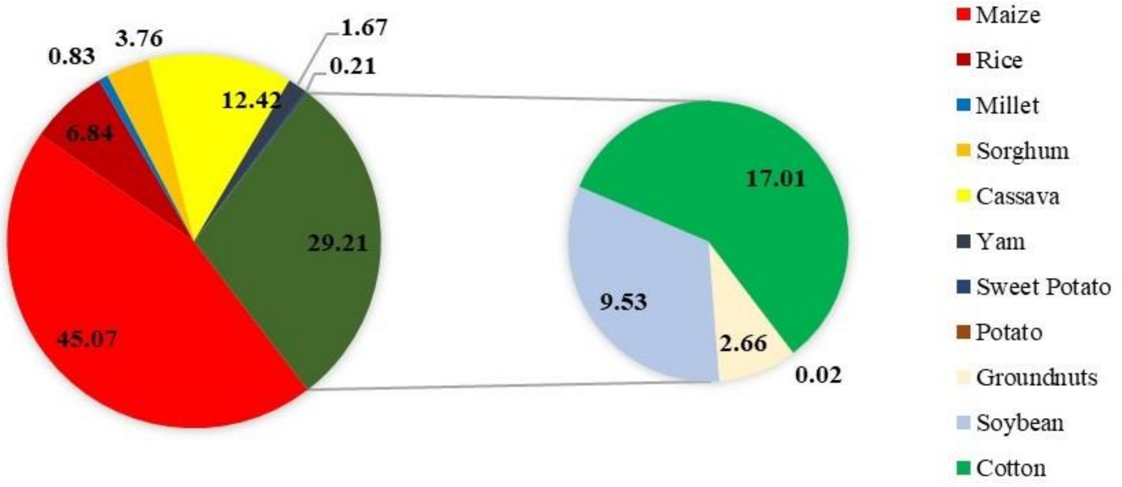

Figure 5. Potential bioenergy contribution from different crop residues in 2021.

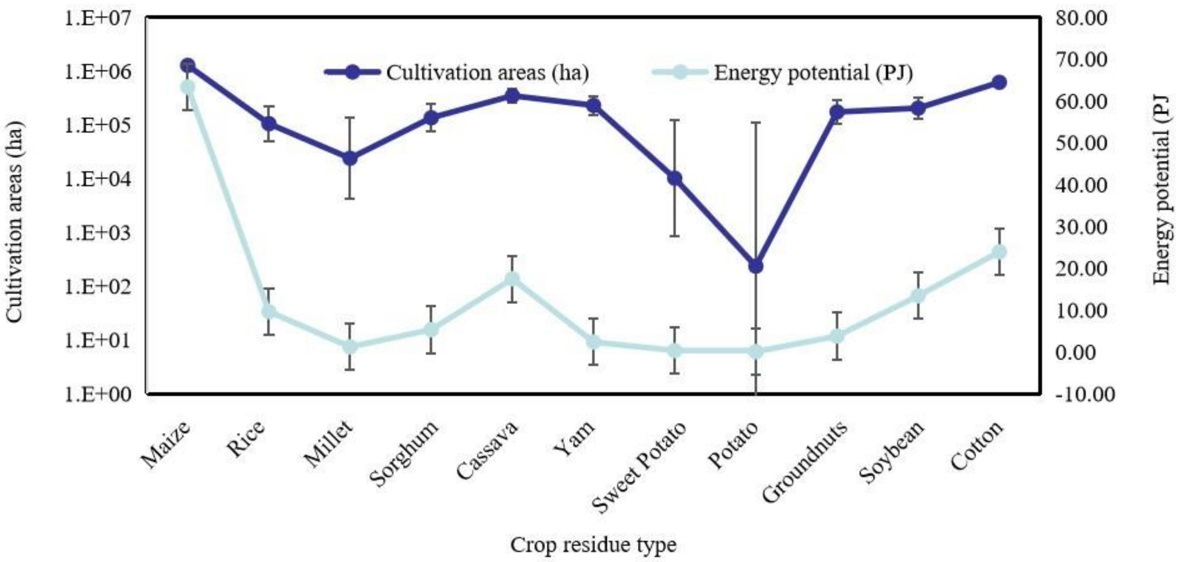

Figure 6. Cultivated areas (ha) and energy potential (PJ) of major crops in Benin.

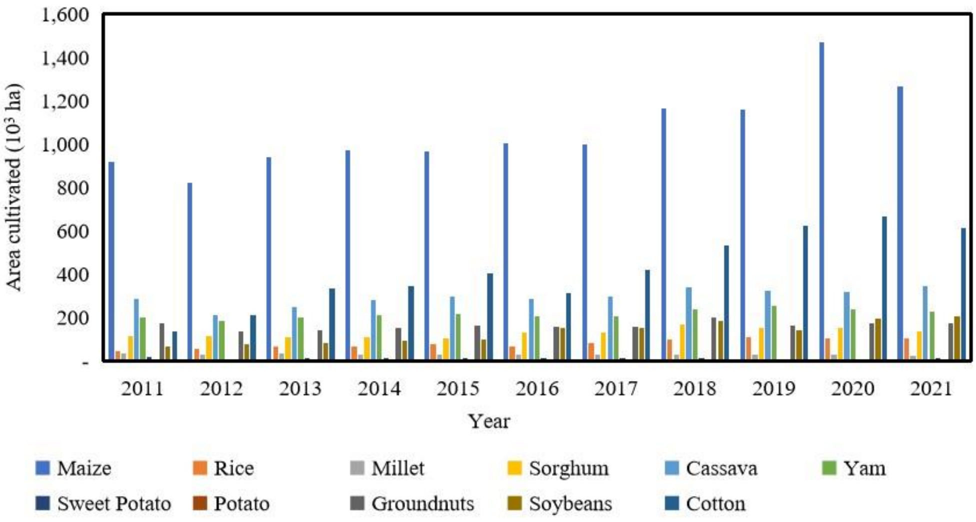

Figure 7. Trends in the cultivation area of different crops over the last decade in Benin.

3.2. Bioenergy potential of municipal solid waste

The total bioenergy potential from MSW in Benin is estimated to be 2.15 PJ/year in 2021. An organic matter content of 52% is used for the energy potential calculation. Organic matter is a very important parameter for bioenergy estimation and varies from country to country based on income level [7]. There is no source evaluating waste generated in Benin for different cities so far, here, a global waste generation rate of 0.668 kg/capita/day is estimated for the whole country in 2021. In Ghana and Cameroon, one person produces on average 0.6 kg of MSW per day [30,52] while in Etiopia and Zimbabwe that value is 0.5 kg/capita per person on average [29,53].

As shown in Figure 8, an increase in urban population increases directly the amount of waste generated and the bioenergy potential. The waste generated has more than doubled from 2012 to 2021 and it is projected that by 2025, the country will generate 2 Mt equivalent to 2.9 PJ bioenergy production. However, the waste collection rate is low in Benin at just 23%, which is not good for the country compared to other countries like Ghana where the collection rate is about 85% [7]. This low collection efficiency could be explained by the lack of waste management strategies with low resource availability for waste deposition in a specific for efficient collection. Different effort is been made to increase the collection rate so far in the country but they are only concentrated in major cities like Cotonou, Abomey-Calavi, and Porto-Novo, which are the so-called Grand Nokoué cities. They generated 33.6% of the country’s waste in 2021 equivalent to a bioenergy production of 0.7 PJ. Cotonou alone accounted for 15.64% generation equivalent to 0.33 PJ of Bioenergy production as shown in Figure 9. The MSW potential estimated is smaller than estimated by [30,52] in cameroon and Ghana because, the collection rate is higher in those countries than in Benin republic with more waste production per year.

In Benin, the inhabitants of the councils of Cotonou, Sèmè-Podji, Porto-Novo, Ouidah, and Abomey-Calavi will henceforth pay fees for the collection of their household waste from January 2023, an operation that has been free until now. The announcement was made by the Société de gestion des déchets et de la salubrité urbaine du Grand Nokoué (SGDS-GN) and may have impact on the collection rate.

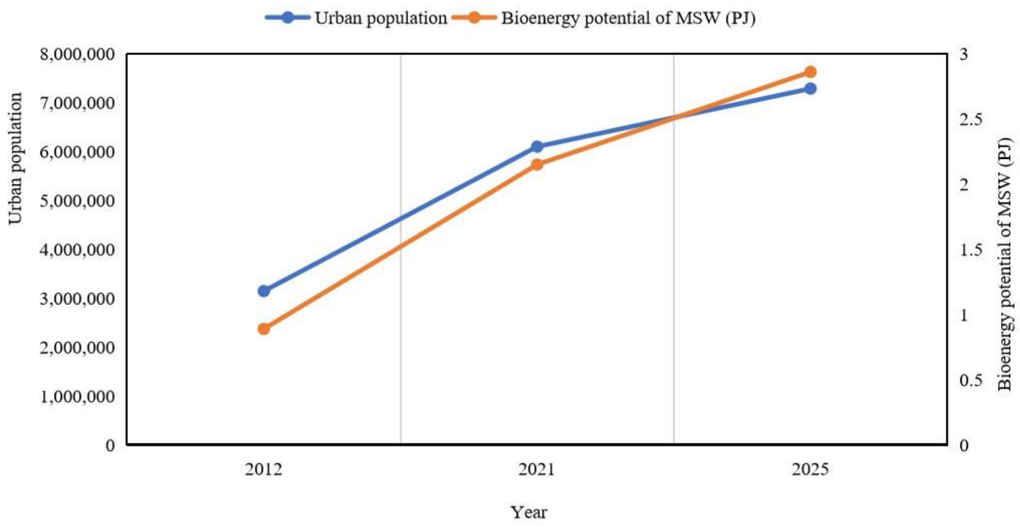

Figure 8. Urban population versus MSW energy potential for different year.

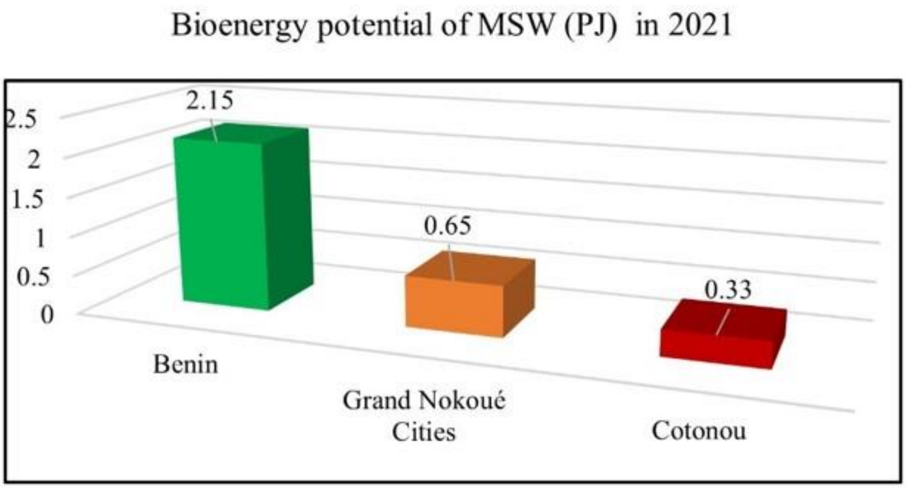

Figure 9. Bioenergy potential from MSW in Benin in 2021.

MSW plays a pivotal role not only for energy generation but also in the dynamics of a community, influencing aspects ranging from public health to economic sustainability. Effective waste management is a cornerstone for preventing the spread of diseases and maintaining public health. Proper disposal practices mitigate the risks associated with disease vectors such as rodents and insects. In region such as Italy, social network analysis has been used to demonstrate the potential of environmental justice movements in overcoming repression and criminalization [54]. Furthermore, the environmental impact of waste, particularly in landfills, raises concerns about soil and water quality. Uncontrolled disposal can contribute to soil degradation, and the leachate from landfills may pollute groundwater, affecting both human health and the overall ecosystem. Additionally, the decomposition of organic waste in landfills produces methane, a potent greenhouse gas [28]. Implementing responsible waste management strategies, such as recycling and waste-to-energy technologies, becomes crucial to minimize environmental harm and reduce greenhouse gas emissions. For developing countries in SSA, particularly for Benin, bioenergy policy and effective waste management practices are needed for fostering a sustainable, healthy, and thriving community.

3.3. Total bioenergy potential from agricultural residue and MSW in Benin

Overall, Benin has a total bioenergy potential of 142.63 PJ/year in 2021. Bioenergy potential from agricultural residue represents more than 98% of this total production in the year in consideration. 60% of this total amount is recoverable and maize and cotton residues are the most contributors.

3.4. Rural electrification through BEFS rapid appraisal tool results

To see how much electricity can be generated to supply rural areas in Benin, four (04) feedstocks with the maximum bioenergy potential have been considered for simulation in the BEFS Rapid Appraisal tool in the gasification component.

3.4.1. Power generation and distribution

The results of the simulations show that the total power generation was estimated as 20,849 kWh/year for the 10 kW plant and as 83,395, 208,488 kWh/year, respectively, for the 40 and 100 kW plant. The total feedstock available was sufficient to supply the three production capacities. Considering feedstock availability, 6,990 potential plants of 10 kW capacity, which requires 182 hectares of area of feedstock can be developed from maize cob. The cotton stalk is the second feedstock considered for power generation. A maximum of 352 potential plants are available for the 100 kW plant and considering the available feedstock, up to 290 households need can be made. Using cassava stalk as feedstock for the gasification process will require 185 ha of area with 1873 potential plants available for the 100 kW plant installation. Sorghum stalk on other hand requires 51 plants of 100 kW with 2,619 ha of area for plant processing as presented in Figure 10.

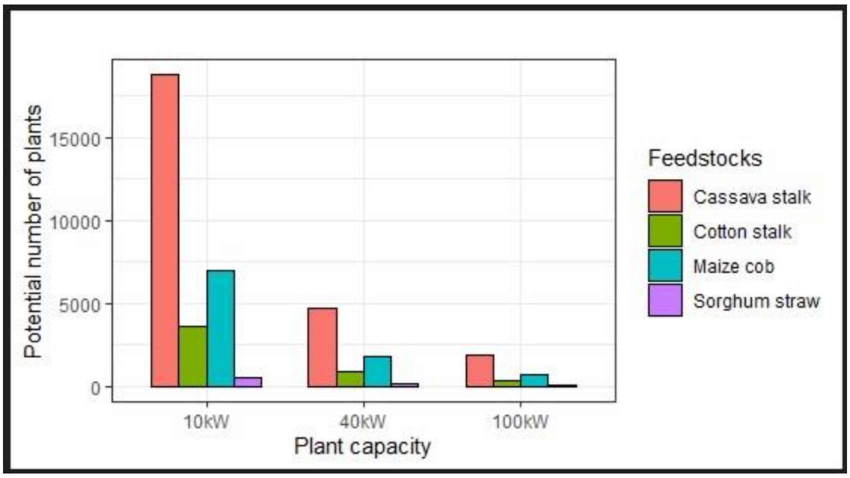

Figure 10. Potential number of plants for different feedstocks.

3.4.2. Socio-economic and financial analysis

Overall, maize cob and cassava stalk have the highest number of job creation in the country for power plant processing. A total number of 27,960 and 56,196 jobs can be created for all 10 kW plant installations. The energy generated from cassava stalk alone can supply up to 540,000 households and that from maize cob could supply up to 200,000 households in the country. The total investment cost for a 10 kW plant is $62,939 for all feedstocks. It is noticed that the Net Present Value (NPV) and the Internal Rate of Return (IRR) for all plant capacities are positive as presented in Table 6. Therefore it can be deduced that all feedstock can generate power through gasification process with 10, 40, and 100 kW, respectively, and that the project is interesting to attract investment for the country. Furthermore, Table 6 shows that plants of 40 and 100 kW are more performant compared with that of 10 kW and that the 100 kW gasification plant performed much better when comparing their NPV and IRR using the same feedstock type. The results are similar to what [45,55] have found in Zambia and Malawi, respectively.

Table 6. Net present values and internal rate of return for different plant capacity and different feedstock.

	Net present value (USD $1000)			Internal rate of return (%)		
	10 kW	40 kW	100 kW	10 kW	40 kW	100 kW
Maize cob	78	562	1669	27	50	88
Cotton stalk	95	628	1836	31	54	96
Cassava stalk	93	621	1816	31	54	95
Sorghum straw	67	515	1549	25	46	82

3.5. Energy policy and current status in Benin

Benin is one of the most biomass-dependent countries in West Africa. Biomass is used in the country for cooking, heating, or charcoal production [56]. The energy sector in Benin is characterized by low per capita power consumption, significant reliance on external sources, a predominance of biomass fuels, and limited access to modern energy sources by the people (petroleum products and electricity). Electricity usage per capita is very low, and the country's energy supply is entirely derived from outside sources, exposing it to external shocks over which it has no control [57]. There is no overall strategy for bioenergy in Benin, so it is necessary to treat each sub-sector separately, and therefore mainly that of biomass energy and biofuels [58]. Biomass is considered a renewable energy source but if it is not well managed, its utilization can also lead to significant greenhouse gas emissions with great social and economic impact [28]. It is therefore very important to carefully analyze the impact associated with the use of biomass as an energy source, the losses, and the effect on the environment as well as socio-economic impacts [59].

The government of Benin is making a lot of efforts to create a better environment for bioenergy production for investors and different producers in the sector. Some of the objectives are to replace at least 10% of gasoline and diesel imports for road transport with the national production of bioethanol and biodiesel; replace 15% of household wood-energy demand (firewood or charcoal) with the national production of bioethanol; develop the export of biofuels to satisfy at least 2% of demand European [58]. To achieve these objectives, the former Ministry of Energy, Petroleum and Mining Research, water and the development of renewable energies (MERPMEDER) has adopted a strategy for the promotion of biofuel sectors in Benin, adopted by the Government in 2016, including, the development of national biofuel production capacities; development of national biofuel storage and distribution capacities; promotion of biofuel exports. Even though considerable effort has been made, there is a lot to do to improve bioenergy utilization and in-country energy production and to provide a safe and clean environment to Benin citizens.

3.6. Interest and benefits of bioenergy in Benin

The development and improvement of bioenergy projects is a key condition in the overall development of a country in terms of social, economic, environmental, and technological aspects.

Biomass is an energy source that can be exploited in various ways, such as Domestic and industrial heating, cooling, drying, and cooking, for electricity generation and as an alternative fuel in vehicles. As a renewable energy resource, it helps in reduction of greenhouse gas emissions. Its technologies can improve hygienic conditions through good practice of waste management. In the social and economic aspects, biomass can create employment and wealth in the country, reduce the poverty rate, and consists of a market expansion, especially for rural farmers. It can also be a source of skill acquisition and rural infrastructure development. Biomass energy technologies are mature, simple, and easy to install on small scale at any place. It is important in the process of cooking stove improvement and biogas production. However, there is a lot of room for improvement, replication, and scaling up the technology, and access to suitable financing for the project developer is challenging.

The conversion of these residues into useful energy stands as a promising avenue for electricity generation and biofuel production, contributing to both energy sustainability and waste management [60]. However, the challenge lies in striking a balance between utilizing agricultural residues for energy purposes and preserving soil fertility, as these residues also play a crucial role in maintaining crop productivity [61]. Investments in infrastructure and technology are pivotal to efficiently transform agricultural residues into viable energy sources. Furthermore, municipal waste presents another avenue for sustainable energy generation in Benin. Proper waste management practices can turn municipal solid waste into valuable energy through methods like anaerobic digestion, incineration, or gasification. Such waste-to-energy projects not only offer an alternative to traditional landfill disposal but also contribute to the country's energy needs. However, effective waste management systems are essential to ensure a clean and reliable feedstock for energy generation. Additionally, the economic viability of these initiatives depends on factors such as technology costs, existing infrastructure, and the regulatory environment [62]. To fully capitalize on these prospects, a supportive policy framework and continued efforts toward sustainable waste management are crucial for the successful integration of agriculture residue and municipal waste into Benin's energy landscape.

4. Conclusions

In this study, we aim to assess different agricultural residues and municipal solid waste (MSW) in Benin and evaluate their bioenergy potential. Various agricultural residues were considered for a period of a decade from 2010 to 2021 to analyse trends. As there was no specific data for the whole country for municipal solid waste for 2021, the amount of MSW was estimated from literature. The supply availability factor and residue-to-product approach was employed to evaluate the bioenergy potentil of different waste. The results were discussed with similar studies conducted in sub-Saharan Africa and in developing countries across the world. To help policy and decision makers in choosing the good electricity generation process, the BEFS Rapid Appraisal tool was used on four agricultural residues with maximum bioenergy potential to show the feasibility and the socio-economic benefits of electricity generation through gasification systems in rural area in Benin. We conclude that:

- A total bioenergy potential of 142.63 PJ can be generated from agricultural residue and municipal solid waste in Benin in 2021. Agricultural residues are predominant, contributing for more than 98% of the total bioenergy potential while only 2% comes from MSW. Within the agricultural residue categories, maize appeared to be the highest contributor, with more than 45% contributions, followed by cotton residue and cassava residue contributing with 17% and 13%, respectively.
- From the BEFS Rapid appraisal simulation, it is found that 20,849 kWh/year can be generated from 10 kW plant using maize cob, cotton stalk or cassava stalk as feedstock. The plants of 40

and 100 kW can generate 83,395 and 208,488 kWh/year, respectively for the same feedstock. The total investment cost is USD 62,939, USD 194,831, and USD 293,177 for 10, 40, and 100 kW plants.

- In addition, 27,960 and 56,196 jobs could be created from a 10 kW plant using maize cob and cassava stalk, respectively. Also, the net present value and the internal rate of return of all plants are positive for all feedstocks and therefore, power generation through gasification is attractive for investment and decision makers in the country should seriously consider bioenergy resource as one way to enhance the country's energy independence.
- One of the biggest challenges noticed during this study is the non-existence of database especially for municipal solid waste in the country. There is a need to increase the rate of MSW collection in the country and there should be a database at regional and national level in various sector with regular update and accessible for researchers. The bioenergy technology development is very low and more attention need to be concentrated in appropriate training and investment in bioenergy project development.

We omitted some biomass resources available in Benin republic. Further research could analyze the bioenergy potential of other biomass resources such as animal and forest waste. An environmental assessment and potential contribution to reducing global warming from electricity generation through gasification from biomass resources could further be analyzed. The results from this study is important to identify the viability of electricity production from gasification in terms of feedstock availability, the financial viability of the different production scales, the optimum production capacity and feedstock combination, and the socio and economic benefits that can be attained. This will also help to attract decision-makers and authorities in the energy sector's attention on the bioenergy potential of the country to call for further investment in the sector. Enhancing the cost-effectiveness of private-public participation in bioenergy technologies is achievable through state support and robust infrastructure development. Additionally, dedicating funding to capacity-building initiatives can significantly stimulate the expansion of waste-to-energy. This study plays a crucial role in waste valorization and policy development in Benin and serves as a valuable reference for other developing countries aspiring to implement biomass conversion technologies.

Use of AI tools declaration

The authors declare they that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Muyiwa S Adaramola is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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