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Bioenergy Potential Assessment of Crop Residue Biomass Resources in Africa Towards Circular Economy

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Abstract

Africa accounts for only about 4% of global greenhouse gas emissions, the lowest of any continent, yet it suffers disproportionately from the impacts of climate change. Additionally, the continent faces significant energy poverty, exacerbating its vulnerability. Due to the lack of electricity and clean cooking facilities, ~600 million and ~900 million of its population are deprived of these basic needs. Thus, this has significantly hindered both economic progress and human capital development. This study provided a comprehensive assessment of the energy potential associated with selected agricultural residues in Africa, focusing on promoting circular economy principles through bioenergy production. The study also examined the possible countries chosen based on their farming productions and bioenergy activities. The crop production data were acquired from the United Nations Food and Agricultural Organization Statistics database, while other necessary data were obtained from the literature and analyzed. Through a combination of empirical data analysis and modeling techniques, we estimate the energy potential of crop residues and highlight their role in promoting circular economy practices. Bioethanol production averaged 62.62 millions tonnes of oil equivalent (Mtoe), biomethane production was 83.05 Mtoe, and solid biofuel was 139.79 Mtoe. The findings of this study offer valuable information on the feasibility and viability of utilizing agricultural residues for bioenergy production, offering potential solutions to address energy challenges while fostering environmental sustainability in Africa. Biofuels may significantly cut greenhouse gas emissions. These reductions require careful crop selection management, processing, and delivery of biofuels to the point of use

Categories: Renewable Energy Systems, Bioprocess Engineering, Materials Engineering
Keywords: agricultural residue, bioenergy, energy potential, circular economy, crop residues, residual biomass, bioenergy barriers

Introduction

The global energy demands have experienced a significant increase due to economic progress, urbanization, and population expansion. According to data from 2009, global energy consumption was 482 exajoules and was increased to 584 exajoules by 2019 [1]. Energy access is a crucial factor in any nation's socioeconomic development and has presented significant global challenges, impacting all aspects of human existence [2]. Bioenergy development in Africa has presented a growing opportunity for youth employment. In South Africa, the sector created 26,246 jobs in 2016 [3]. A single 800-L biofuel plant in the country generates approximately 500 jobs. By 2030, projections revealed that the renewable energy sector could create 4.5 million jobs across Africa [3]. This includes opportunities for off-grid renewable energy entrepreneurs, distributors, installers, and technicians. Energy outlooks for Africa tend to favor increased reliance on fossil fuels, disregarding the potential of transitioning from traditional to modern bioenergy sources [4]. The literature [5] suggests that solid biofuels in Ghana have the potential to satisfy more than 50% of the national wood fuel demand. In addition, biomethane could cover 11.70% of liquified petroleum gas demand, while bioethanol-based electricity could fulfill approximately 91.2% of the national electricity demand, suggesting bioethanol's potential to support regional energy needs. Further studies [6] demonstrated the bioenergy capacity in Ghana's renewable power sector in alleviating energy poverty. According to the study, by 2050, ~18 TWh of electricity, equivalent to 16.9 % of Ghana's total demand, could be generated from bioenergy for grid balancing. This would also result in a decrease in electricity costs. This indicates the feasibility of a cost-effective, bioenergy-balanced renewable power system for Sub-Saharan Africa. Further studies revealed that the cost of energy generation from biomass gasification and combustion plants ranges from US$ 0.29/kWh to US$ 0.34/kWh [7], inferring that using crop residues for electricity could be a viable option for rural electrification, provided there is sufficient financial support. In Uganda, crop and animal residues offer an energy potential of 260 PJ annually, highlighting the significant potential of agricultural and forest residues as primary renewable energy sources for Uganda [8]. Converting lignocellulosic farming residues and animal waste into bioenergy is a promising waste management and renewable energy strategy [8]. It holds significant promise for promoting a circular economy in Africa. The increasing demand for renewable energy sources has increased interest in utilizing agricultural residues for bioenergy production [9]. These biofuels can be in liquid, solid, or gaseous forms. Some examples of the liquids are biomethanol, bioethanol, and bio-oil. The gaseous biofuels are biogas, syngas, and biohydrogen, while the solids are biochar, briquettes, and pellets. A study on the valorization of 15 African crops, including banana, barley, cassava, cocoa beans, maize, oats, rapeseed, rice, seed cotton, sugar beet, sugarcane, sunflower seed, sweet potatoes, triticale, and wheat, revealed that the continent could produce 31,303 Mm^3 of bio-methane and 1141 PJ of bio-energy annually. Combining bio-methane in combined heat and power systems can generate 109.7 TWh of electricity and 133 TWh of thermal energy annually, potentially supplying 16.3% of Africa's electricity needs [9]. In Zimbabwe, bio-waste availability for energy generation (agricultural residues, municipal solid waste (MSW), animal dung, and sewage sludge) produces 539 PJ annually from 49 gigatons of bio-waste.

Despite being underutilized, this energy source could potentially fulfill 42.3% of the country's energy demands, boosting industrial activities in Zimbabwe [1]. Segura-Rodríguez et al. [10] examined the potential of sustainable bioenergy in Mali, highlighting that crop residues, livestock waste, and MSW could reduce dependence on traditional fuels in urban areas where the demand for cooking energy exceeds the biomass availability. It was concluded that briquettes would offer a transitional fuel, biogas, from MSW to assist urban waste management. However, exploring alternative clean energy solutions such as renewable energy and electric cooking systems is imperative to ensure access to clean cooking. To improve access to power, it is necessary to increase the availability of electricity in rural areas by implementing both on-grid and off-grid solutions [11]. Gabisa et al. [12], studied bioenergy in eastern Africa. They discovered that Ethiopia has significant untapped biomass residues, which can be utilized sustainably without negatively impacting the socio-economic, the environment, and food security. The country's total bio-energy potential is estimated at 750 PJ per year, derived from forest residue (46.5 %), crop residue (34 %), livestock waste (18.8 %), and MSW (0.05 %). To maximize these potentials, the study suggested the establishment of an integrated bio-energy database, implementing research and development (R&D) activities, and identifying feasible bio-energy feedstock value chains. Furthermore, evaluating the bio-energy value chain across its complete life cycle is advisable. In Tanzania, research has shown that biomass residue production has the potential to generate renewable electricity from off-grid diesel generators using anaerobic digestion (AD) and gasification. In 2018, its biomass streams (agriculture, forestry, livestock, and urban waste) delivered an energy potential of 385 PJ, sufficient to produce 1.2 times the country's electricity output when coupled with diesel generators [13]. There is a need for extensive R&D in the area of biomass valorization of underutilized crop residues in Africa; for example, Tunisia is exploring olive oil, date palm, and almond value chains. Olive oil waste showed the highest bioenergy potential (82 %), yet only a tiny fraction is utilized. Date palm fruit and almond hulls also hold significant untapped potential [14]. In the case of Nigeria, bioenergy potential from agricultural residues and municipal waste was assessed, and it was found that the selected biomass had a greater biogas yield than cellulosic ethanol [15]. The agricultural residues have the potential to produce 14,766 ML/year of ethanol and 15,014 Mm^3 per year of biogas. Biogas offers versatile applications, including electricity generation, which can help to address Nigeria's power crisis and support Sustainable Development Goal 7. Appendix Table *7* shows the production capacity of the primary biomass produced in Africa from 2010 to 2022 [16].

The energy crisis significantly impacts developing nations, particularly African states, due to their heavy dependence on non-renewable energy sources and limited capacity to ensure a stable energy supply. However, they possess many untapped renewable energy resources, such as wind, solar, geothermal, biomass, and hydro [17]. Assessment of the present resources is essential to predict their future availability and guarantee a sustainable supply because there is a significant potential to harness energy from crop residues and residual biomass [4]. These crop residues offer a sustainable opportunity for generating off-grid energy in rural areas of Africa through various conversion methods. The current focus is on using agricultural residues such as rice husk, maize stover, and cassava peels as alternatives to firewood and charcoal, providing cleaner energy sources for cooking, industrial heat, and electricity generation in rural areas of Africa without access to electricity [11]. Biomass is more economically viable than other renewable energy sources, requiring less initial investment and having lower production expenses per unit [18]. Biomass energy can be harnessed through various conversion methods such as pyrolysis, liquefaction, microbial gasification, and supercritical fluid extraction. These processes are driven by biochemical activity, which converts cellulose into alcohol or oxygenated products by biochemical activity. The products include vapors, gases, tar, and carbon-rich solid residue. Pyrolysis generates radicals, while gasification yields primarily gases with limited char and ash. Valorization of valuable products can be categorized into three approaches [19]:

Fractionation and processing: The biomass is fractionated into its components, typically by removing lignin through pretreatment, making carbohydrates accessible for hydrolysis and fermentation [20-22]. This process yields bioethanol as the main product. Hydrolysate or fermentation effluents can also be used for biogas or biohydrogen production through AD or photo/dark fermentation [23]. Reductive catalytic fractionation, a sustainable approach, extracts lignin through solvolysis, depolymerization, and stabilization using redox catalysts. This method yields phenolic units and monolignol, further utilized for various value-added products [24].

Partial degradation and upgrading: The biomass undergoes partial degradation, such as pyrolysis, to produce bio-oil, which is further upgraded to improve the fuel properties [25,26].

Complete destruction into syngas: The biomass is completely decomposed into syngas (carbon monoxide and hydrogen gas) through gasification, which could serve as a precursor for hydrogen production or can be converted into fuels and organic chemicals via Fischer-Tropsch synthesis [27]. Catalytic biomass gasification has gained attention for its potential to improve gasification efficiency [28,29]. However, challenges such as methane and tar presence in syngas complicate the economic viability of biomass gasification. The produced gas can also be directly combusted for energy generation [30,31].

Many studies have presented the feasibility of using crop residues for biofuel production in Africa. However, these studies have been for specific countries. There is no published work on a consolidated feasibility for the continent where the majority of the countries are taken together, such an analysis is useful for bioenergy planning for the continent.

This study aims to evaluate the availability of crop biomass residue resources in African agricultural systems for bioenergy production and to determine if these residues can sustainably generate modern bioenergy. The objective is to quantify the total and recoverable crop residue biomass and assess the bioenergy potentials for biofuels (solid, liquid, and gaseous) production across Africa. The study considers residues from 30 crops widely cultivated across Africa. Standard procedures are applied, considering global and regional bioenergy sources and local variations. The study addresses data deficiencies in bioenergy resources, including feedstock availability and regional distribution. It establishes a baseline for estimating regional biomass residues and provides a foundation for future research on bioenergy utilization's social, environmental, economic, and technical aspects. The data and recommendations will assist bioenergy practitioners, analysts, academics, and policymakers formulate policies and strategies.

Materials And Methods

Data Sources and Preparation

The process involves assessing the biomass resource potential of selected agricultural residues excluding livestock wastes, and their bioenergy potential, focusing on briquette, biogas, and bioethanol. An in-depth analysis was conducted to examine the socio-technological and economic impact. The biomass residue estimations from the selected energy crops in Africa were based on detailed calculations using data from the public domain. The annual crop production data (Table *1*) for the study were obtained from the United Nations Food and Agricultural Organization Statistics (FAOSTAT) [16] database from 2010 to 2022. Twenty-five crops were selected based on three criteria: (1) extensive cultivation in African countries, (2) processing and field-based residues, and (3) data availability from these residues.

S/N	Crop Residues	No. of Countries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
1	Bananas	45	17.98	18.40	18.22	20.54	19.81	19.78	19.31	19.01	20.43	20.73	21.70	22.64	22.83	261.37
2	Barley	35	16.61	17.38	17.88	19.67	19.43	20.88	18.53	19.80	21.23	20.29	18.02	20.29	5.87	235.88
3	Beans	40	5.27	5.80	6.20	6.49	6.53	7.19	6.93	7.74	7.16	6.85	7.15	8.02	7.83	89.16
4	Cabbages	33	3.04	2.76	3.08	3.10	2.94	3.28	3.19	3.21	3.24	3.50	3.82	4.04	4.37	43.58
5	Cashew nuts	17	1.69	1.69	1.57	1.48	1.46	1.72	1.59	1.86	2.00	1.82	1.95	2.08	2.14	23.05
6	Cassava	42	143.87	151.86	155.84	160.14	163.45	167.12	174.28	178.54	196.94	190.83	194.24	201.45	208.63	2287.18
7	Coconuts	20	2.08	2.13	2.12	2.21	2.20	2.08	2.27	2.25	2.16	2.13	2.08	2.06	1.97	27.74
8	Cotton seed	41	2.07	2.36	2.72	2.58	2.67	2.43	2.55	2.73	2.98	3.02	2.82	2.95	0.00	31.87
9	Groundnuts	46	13.98	12.79	14.01	14.23	15.63	15.43	15.76	16.73	18.72	18.26	19.20	18.28	17.36	210.37
10	Lemons	31	1.05	1.11	1.12	1.15	1.26	1.34	1.33	1.51	1.55	1.58	1.84	1.84	1.98	18.67
11	Lettuce	18	0.35	0.32	0.33	0.35	0.39	0.47	0.45	0.46	0.44	0.51	0.60	0.58	0.60	5.85
12	Maize (corn)	53	69.01	68.75	74.16	73.48	82.07	75.60	75.39	92.38	85.07	85.81	96.01	102.08	94.58	1074.41
13	Millet	40	16.14	10.24	12.30	11.54	12.91	12.65	13.61	12.80	15.77	13.54	15.05	11.62	14.60	172.77
14	Oil palm	22	17.90	17.86	18.66	19.02	19.50	19.76	20.43	21.46	22.13	22.67	23.61	26.50	26.74	276.25
15	Oranges	39	7.49	8.02	8.59	8.92	9.26	9.39	8.86	9.53	9.59	9.96	10.59	10.17	10.75	121.12
16	Pepper	20	3.57	3.59	3.90	3.90	4.14	4.28	4.37	4.33	4.67	4.96	4.91	4.51	4.68	55.79
17	Potatoes	45	24.79	26.52	28.55	29.13	24.07	25.07	22.85	24.04	25.29	26.33	27.68	27.40	27.15	338.88
18	Rice	45	25.96	26.76	29.14	28.94	31.60	32.04	37.21	36.25	36.96	36.43	37.82	38.59	39.88	437.58
19	Sorghum	45	25.07	23.99	23.58	25.29	29.32	26.11	30.24	27.56	29.99	27.96	28.21	26.40	29.57	353.29
20	Soya beans	28	1.60	1.90	2.13	2.20	2.49	2.64	2.82	3.69	3.81	3.61	4.50	5.52	4.54	41.47
21	Sugar cane	43	87.40	89.35	90.91	97.88	95.16	92.58	91.93	92.55	96.42	96.81	96.98	96.23	97.63	1221.84
22	Sweet potatoes	46	16.86	18.04	18.79	21.02	25.25	24.69	26.17	28.49	26.34	27.50	28.17	28.60	29.53	319.43
23	Tomatoes	46	18.74	17.87	19.37	19.30	22.44	22.60	20.69	20.47	21.71	22.49	22.95	22.79	22.93	274.34
24	Wheat	35	21.34	25.32	24.65	28.06	25.43	29.08	23.33	26.53	29.16	26.53	25.37	30.68	27.31	342.81
25	Yams	28	54.47	50.90	50.98	54.52	63.50	64.06	69.84	71.18	77.11	75.99	79.81	84.72	86.58	883.66
	Total		598.34	605.71	628.81	655.12	682.92	682.30	693.95	725.09	760.87	750.09	775.05	800.06	790.06	9148.36

TABLE 1: Selected crop production in Africa (in million tonnes)

Data source: The United Nations Food and Agricultural Organization Statistics [16]

The residue potential of these crops can be determined by considering their gross potential, recoverable, economic, implementation, and sustainable biomass residue potentials [32,33]. This study focused on analyzing the gross and recoverable residue potentials (RRPs) to assess the potential for solid biofuel, biogas, and bioethanol production. Due to socioeconomic and environmental issues, some crop residues are not recoverable, while others are recoverable because of the significant residue-to-product ratio (RPR). The total agricultural yield determines the RRP, representing a fraction of the gross residue. The ratio of the crop production determines the gross residue potential (GRP). The RPR method [15] was deployed to estimate crop residue generation. RPR values for various crops and their corresponding calorific values were sourced from published literature. Table *2* presents the crop residues and their respective average RPR, recoverable fraction (RF), and lower heating values (LHV) for all the crop residues considered.

Regarding the specific location under investigation, it is crucial to provide RPR, RF (%), and LHV (MJ/kg) estimations. Unfortunately, such statistical data are often not accessible both locally and globally. Therefore, this study has addressed this by determining the average RPR, RF (%), and LHV (MJ/kg) of the selected crops in Africa. Table 2 displays the calculated average values for the RF and LHV. In addition, a new method was developed and used to assess the biomass energy potential of crop residues, aiming to accurately account for the wide range of diverse climatic and agricultural conditions. This study did not consider the socio-economic, sustainable, and socio-economic possibilities. Perhaps these factors may lower the overall predicted possibilities [15].

S/N	Energy Crops	Crop Residues	Average RPR	Average RF %	Average LHV (MJ/kg)	References
1	Bananas	Leaves, stem, and peels	2.1	0.9	12.1	[10,34-36]
2	Barley	Straws	1.5	0.3	17.6	[12,35]
3	Beans	Straws	2.2	0.9	13.5	[8,36,37]
4	Cabbages	Foliage and stem	2.5	1.0	1.0	[19]
5	Cashew	Husks	2.1	0.2	14.9	[13]
6	Cassava	Stems and peels	0.9	0.6	13.2	[7,13,34,36,38]
7	Coconuts	Fronds, husks, and shells	0.7	1.0	14.2	[7,8,13,31,34]
8	Cotton seed	Stalk	2.1	0.8	17.2	[7,10,13,34,38]
9	Groundnuts	Trash and shells	1.5	0.8	15.4	[7,10,13,34-36,38]
10	Lemons	Pruning	0.3	0.8	1.0	[35]
11	Lettuce	Foliage	1.2	0.5	15.2	[35]
12	Maize (corn)	Stalk and cobs	1.1	0.7	15.9	[10,12,13,34-38]
13	Millet	Stalk and straws	2.0	0.7	15.5	[7,10,12,13,34-36,38]
14	Oil palm	Kernel shell, fiber, and fronds	0.3	1.0	14.3	[7,15,36]
15	Oranges	Peels	0.3	0.8	17.9	[10]
16	Pepper	Leaves	0.45	0.45	13.7	[39]
17	Potatoes	Leaves and peels	0.8	0.9	13.3	[10,13,34-38]
18	Rice	Straw and husks	1.1	0.7	14.3	[7,12,34,35,38]
19	Sorghum	Stalk and straws	2.0	0.8	13.4	[7,10,12,13,34-36,38]
20	Soya beans	Straw and pods	1.7	0.8	16.9	[12,13,34-36,38]
21	Sugar cane	Bagasse and leaves	0.2	0.8	15.4	[10,13,34,35]
22	Sweet potatoes	Leaves and peels	0.5	0.8	13.3	[12,34-36,38]
23	Tomatoes	Stem and leaves	0.2	0.5	13.7	[35]
24	Wheat	Straws and husks	0.8	0.3	14.9	[12,34-36]
25	Yams	Peels	0.3	0.7	10.6	[34-36,38]

TABLE 2: Average residue-to-product ratio (RPR), recoverable fraction (RF), and lower heating values (LHV) of selected crop residues widely considered for bioenergy production in Africa

Estimation of the Energy Potential and Feedstock from Biomass Wastes

Crop residue potential estimation involves assessing the quantity remaining after agricultural production or post-harvesting processing. Agricultural residues are generally categorized as primary or secondary. Primary residues consist of materials generated during harvesting and initial crop processing in the farm, which vary according to crop species and have been estimated to range from 19% to 75% [36]. Secondary residues are generated by agricultural processing at specific locations or factories to achieve further byproducts of post-harvest processing. The recoverable crop residue potential is the quantity of crop residue that remains after being utilized for purposes such as feeds, organic fertilizer, fuel, or animal bedding [39].

On the other hand, the gross crop residue potential represents the total quantity of crop residue produced. The recoverable portion can be employed for the production of bioenergy. Standard methods are used for the energy potential of recoverable residue biomass resources (Figure 1).

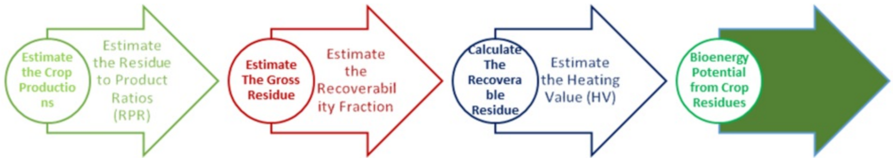

FIGURE 1: Process flow diagram for bioenergy potential determinations from crop residues

Gross residue potential (GRP) and recoverable residue potential (RRP): The GRP for each crop, sometimes called the theoretical residue potential [15], was calculated by multiplying the total specific crop available (Eq. 1) for a particular year by the RPR. RPR represents the weight of residue a crop generated relative to the quantity produced [15,40]. The crop residue potential was estimated using Eq. 2.

$$T_{cp(i)} = \sum_{k}^{i} A_{(i)} * Y_{(i)} \quad \text{.......} \quad (1)$$

$$GRP_{(j)} = T_c p_{(i)} * RPR_{(i)} \quad \text{.......} \quad (2)$$

where $T_{cp(i)}$ is the total specific crop available or crop output at j^{th} location from a set of "k" crops, while A_i, Y_i, and RPR_i are the harvested area, average crop yield, and RPR of crop i^{th} at j^{th} location, respectively, according to Ezealigo et al. [15], utilizing the GRP for bioenergy production was not feasible due to potential competition with other crop residue uses [35] and the need to rely on the recoverable residue fraction, known as the technical or RRP, as in Eq. 3 [35].

$$\mathrm{RRP}_j = \sum_{i=1}^{k} \mathrm{GRP}_{(i_j)} \times \mathrm{RF}_{(i_j)} \quad \text{.......} \quad (3)$$

where $GRP_{(ij)}$ is the residue potential at i^{th} location from a total k of crops, $RF_{(ij)}$ is the recoverability factor of the i^{th} crop at j^{th} location. The $RRP_{(j)}$ is the recoverable residue potential at location j^{th}. This accounts for surplus residue considering the competition from other uses and spatial constraints, as well as providing the number of excess residues available specifically for energy purposes. The RRP was used to estimate the energy potential of cellulosic bioethanol and biogas.

Solid biofuel potential: The bioenergy potential from dry crop residues in their natural state is determined according to Eq. 4. According to Tolessa [35], the estimated SBP is calculated by multiplying the total RRPs by their LHV (Eq. 4).

$$\mathrm{BEP}_{(C_j)} = \sum_{i=1}^{k} \mathrm{RRP}_{(i_j)} \times \mathrm{LHV}_{(i_j)} \quad \text{.......} \quad (4)$$

where $BEP_{(Cj)}$ is the bioenergy potential of 'k' crops at the j^{th} location,

$RRP_{(ij)}$ is the recoverable residue potential of the i^{th} crop at the j^{th} location, and

$LHV_{(ij)}$ is the lower heating value of the i^{th} crop at the j^{th} location.

Similarly, Tolessa [35] has shown that the estimated SBP can be derived by multiplying the total RRPs by their LHV (Eq. 4).

Bioethanol potential (BEP): The bioenergy potential and conversion of crop residues into cellulosic ethanol were determined by considering pre-treatment processes such as hydrolysis, enzymatic activities, and microbial fermentation. The estimation of cellulosic ethanol production from crop residues was determined using Eq. 5 [15].

$$Y_{\mathrm{BP}} = \mathrm{RRP} \times C_{\mathrm{glu}} \times y_{\mathrm{hyd}} \times y_{\mathrm{eth}} \times \eta_{\mathrm{pre}} \times \eta_{\mathrm{enz}} \quad \text{......} (5)$$

where Y_{BP} = cellulosic ethanol yield; RRP = recoverable residue potential; C_{glu} = glucan concentration; y_{hyd} = yield of enzymatically hydrolyzed glucan; y_{eth} = stoichiometric yield from glucose; η_{pre} = efficiency of pretreatment; η_{enz} = efficiency enzymatic cellulose conversion. To estimate the cellulosic ethanol production, it is assumed that the fermentation and distillation processes had a 100% efficiency, suggesting no loss was considered. The accepted values [15,32] for cellulosic ethanol production are shown in Table *3*. In the scenario where no pre-treatment was performed, enzymatic activity was believed to be minimal (30%), resulting in a cellulosic ethanol scale-up (η_{scale}) of 50%. In contrast, the pre-treatment scenario assumed an enzymatic efficiency of 90%, leading to a cellulosic ethanol yield of 80%. The bioenergy potential of cellulosic ethanol was estimated based on the LHV of 28.9 MJ/kg and an ethanol density of 0.789 kg/L [15].

Conditions	Buswell Glucan Yield (L CH_4/g)	Buswell Hemicellulose Yield (L CH_4/g)	y_{eth}	y_{hyd}	η_{pre} (%)	η_{enz} (%)	ρ_{Distil} (%)	P_{Ferm} (%)	η_{scale} (%)	Ethanol Density (kg/l)
Pre-treatment	0.414	0.423	0.51	1.11	-	30	100	100	50	0.789
No pre-treatment	0.414	0.423	0.51	1.11	80	90	100	100	80	0.789

TABLE 3: Assumptions used in the calculations

Biogas potential (BGP): Biogas was estimated using the technical residue potential derived from crop residues. The biomethane potential (BMP) was calculated using the Buswell BMP equivalent, representing the gross methane production estimate based on the experimental evaluation. The BMP quantifies the maximum methane volume generated per gram of volatile solid (VS) in a substrate, indicating its biodegradable fraction.

Several assumptions were made to calculate the energy potential of biogas: It is assumed that each cubic meter (m^3) of biomethane would yield 10 kWh at standard temperature and pressure (STP). The methane conversion process has an energy potential of 0.278 gigawatt-hours per year (GWh/yr). To convert this energy from terajoules (TJ) to million tonnes of oil equivalent (Mtoe), a conversion factor of 24 is considered [15].

$$\gamma_{\mathrm{BMP\ Buswell}} = (\gamma_{\mathrm{Buswell,glu}} \times C_{\mathrm{glu}}) + (\gamma_{\mathrm{Buswell,hem}} \times C_{\mathrm{hem}}) \quad \text{......} (6)$$

The maximum BGP estimate is determined (Eq. 7)

$$\gamma_{\mathrm{Biogas}} = \mathrm{RRP} \times \gamma_{\mathrm{BMP\ Buswell}} \times \eta_{\mathrm{scale}} \quad \text{......} (7)$$

where $Y_{BMP\ Buswell}$ = estimated biodegradable fraction in specific crop residue (feedstock) for biogas production using Buswell formula; $Y_{Buswell.glu}$ = estimated glucan in specific residue using Buswell formula; $Y_{Buswell.hem}$ = estimated hemicellulose using Buswell formula; C_{glu} = concentration of glucan; C_{hem} = concentration of hemicellulose. Y_{Biogas} = biogas yield; ηscale = average efficiency for continuous biogas production.

Case Studies

The bioenergy potentials of 15 selected countries (Algeria, Morocco, Egypt, Nigeria, Ivory Coast, Ghana, Sudan, Democratic Republic of Congo, Ethiopia, Kenya, Mozambique, South Africa, Namibia, Angola, and Central African Republic) from the five regions of Africa (Figure *2*) were analyzed based on the country's significant agricultural activities, available data, and potentials for using biomass for energy purposes. These estimates were also based on the 25 selected crops and production year (2010-2022).

FIGURE 2: Map showing the 15 selected countries based on regions and agricultural activities

Results

Crop Production and Residues Potentials

An assessment was conducted to determine Africa's capacity to produce bioenergy from various feedstock sources. This was done by evaluating the total production of the 25 selected crops by multiplying the crop yields by the harvested areas according to data obtained from FAOSTAT [16]. The average ratios of residue to product (RPR) were calculated for these locations. The crop residues considered were the leaves, stems, foliage, fronds, straws, stalks, cobs, pods, shells, peels, and husks from the harvesting and processing activities. These values were used to determine the energy capacity of the crop residues and, consequently, the biomethane and cellulosic ethanol yields. To guarantee a sustainable supply of biomass feedstocks for bioenergy production, estimating the quantity of recoverable crop residues is essential.

Figure *3* shows the residues projections for 2023, 2024, and 2025. It showed cassava will grow to 223.56, 218.48, and 223.43 Mt for 2023, 2024, and 2025, respectively. Barley had a decrease in 2024 (8.39 Mt) and 2025 (13.78 Mt) when compared to 2023 (15.64 Mt) projections. Maize and sugarcane also recorded low production rates in 2023, 2024, and 2025 at an average 0.2% growth rate. This could be inferred due to climate change impacts and political or tribal unrest in regions known for high production of these agricultural products.

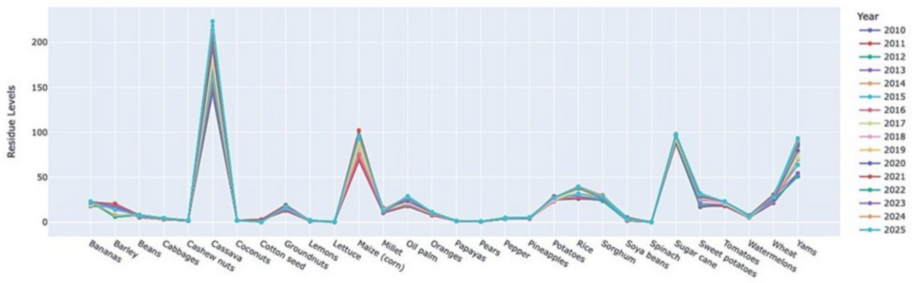

FIGURE 3: The crop residues projections

Table 4 shows that the crop production has increased steadily from 598.34 Mt in 2010 to a peak of 800.06 Mt in 2021. Correspondingly, the gross residue potential grew from 525.18 Mt in 2010 to 691.45 Mt in 2021. These potentials can be utilized for solid biofuel productions such as briquettes and pellets and the generation of biogas, bioethanol, or a combination. The solid biofuel potential increased from 120.57 Mtoe/year to 157.72 Mtoe/year. Appendix Tables 8-10 show that Nigeria and Egypt have the highest potential for solid biofuel production with consistent growth and high averages. Ivory Coast, Ghana, Ethiopia, and Democratic Republic of Congo (DRC) also showed steady growth in crop production over the years, while Central African Republic (CAR) and Namibia revealed relatively low and stable production values. By region, North Africa's output is heavily reliant on Egypt. Nigeria and Ghana in Western Africa showed robust growth, and moderate growth was seen for Sudan and CAR in Central and North Eastern Africa region. Ethiopia dominates in the Eastern and South Eastern regions, while the Republic of South Africa drives Southern Africa's production.

Year	Crop Production	Gross Residue Potential	Solid Biofuel		Biomethane		Bioethanol	
	Mt	Mt	Mt/year (Recoverable)	Mtoe/year	Mm^3 CH_4/year	Mtoe/year	ML/year	Mtoe/year
2010	598.34	525.18	360.60	120.57	8,247.85	71.20	98,629.02	53.97
2011	605.71	525.94	358.32	119.73	8,206.50	70.85	99,005.77	54.18
2012	628.81	548.73	374.86	125.53	8,630.62	74.51	104,468.69	57.17
2013	655.12	568.90	388.21	129.70	8,855.89	76.45	107,039.08	58.58
2014	682.92	594.22	407.42	136.59	9,399.33	81.15	111,652.32	61.10
2015	682.30	592.06	402.38	134.48	9,159.33	79.07	109,003.99	59.65
2016	693.95	605.35	414.95	138.55	9,415.88	81.29	110,695.16	60.58
2017	725.09	631.86	431.63	144.90	10,068.41	86.92	119,274.26	65.27
2018	760.87	665.68	452.48	151.61	10,382.47	89.63	122,196.63	66.87
2019	750.09	649.63	443.43	148.38	10,207.92	88.13	120,870.21	66.15
2020	775.05	673.49	462.94	154.93	10,759.77	92.89	127,586.13	69.82
2021	800.06	691.45	471.97	157.72	11,055.35	95.44	131,263.33	71.83
2022	790.06	672.49	467.37	154.59	10,691.13	92.30	125,522.48	68.69
Average	703.72	611.15	418.20	139.79	9,621.57	83.06	114,400.54	62.61

TABLE 4: Total annual crop yield and bioenergy equivalent for 2010 to 2022

Mt: million tonnes, Mtoe: million tonnes of oil equivalent, Mm^3 CH_4/year: million cubic meters of methane per year, ML/year: million liters per year

Cellulosic Ethanol and Biomethane Production

The estimated average cellulosic ethanol production (Table 5) for the investigative period is 114,400 ML per annum (62.62 Mtoe/year). With the highest production recorded in 2021. The average biomethane production is 9,621 Mm^3 CH_4/year (83.06 Mtoe/year). However, residues from cassava, maize, and cereal crops recorded a significant quantity of solid biofuel, biomethane, and bioethanol potentials. Table 5 shows that the biomethane production grew from 8,247.85 Mm^3 CH_4/year in 2010 to 11,055.35 Mm^3 CH_4/year in 2021, while its energy equivalent increased from 71.20 Mtoe/year to 95.44 Mtoe/year. The bioethanol production also increased from 98,629.02 ML/year in 2010 to 131,263.33 ML/year in 2021, while the energy equivalent increased from 53.97 Mtoe/year to 71.83 Mtoe/year during the same period. These increasing trends show a growing capacity for bioenergy production and support for energy security in Africa and could reduce fossil fuel dependencies. Table 5 shows that bananas (543.07 Mt/year), cassava (2141.72 Mt/year), maize (1139.46 Mt/year), and sorghum (693.05 Mt/year) had the highest gross residue potentials. The biomethane potential showed the highest values with maize (corn), cassava, sorghum, and banana at 569,865.59, 254,661.19, 112,668.76, and 90,845.18 Mm^3 CH_4, respectively. Maize (corn) (284,251.24 ML/year), cassava (151,172.27 ML/year), sorghum (71,142.32 ML/year), and bananas (54,402.80 ML/year) had the highest bioethanol production potential. These infer that cassava and maize are promising crops for bioenergy production across all categories (solid biofuel, biomethane, and bioethanol). However, the sorghum and bananas indicated significant potential, particularly in terms of biomethane and bioethanol production. Other crops such as groundnuts, potatoes, and rice revealed substantial contributions, especially for solid biofuel and biomethane, while crops with lower residue and energy potential include lemons, lettuce, and tomatoes. Appendix Table 11 shows that Southern Africa consistently leads in biomethane production, followed by Northern Africa and Western Africa. Central/North Eastern Africa and Eastern/South East Africa generally have lower production levels. Nigeria stands out as a significant contributor to biomethane production, showing substantial growth over the years. On average, Southern Africa has the highest biomethane production at 7.48 Mtoe, followed by Western Africa (6.33 Mtoe) and Northern Africa (0.66 Mtoe). The percentage change from 2010 to 2022 varies across regions, with notable increases in some areas such as Southern Africa (9%) and Nigeria (15%).

Crops	Residues	Crop Production	Gross Residue Potential	Solid Biofuel		Biomethane		Bioethanol	
		Mt	Mt	Mt/year (Recoverable)	Mtoe/year	Mm^3 CH_4/year	Mtoe/year	ML/year	Mtoe/year
Bananas	Leaves, stem, and peels	261.37	543.07	481.00	139.40	90845.18	78.43	54402.80	47.82
Barley	Straws	235.88	359.71	106.12	44.70	22048.37	19.03	14972.61	13.16
Beans	Straws	89.16	195.27	166.63	54.15	29957.21	25.86	16418.68	14.43
Cabbages	Foliage and stem	43.58	108.95	103.50	2.48	7553.36	6.52	6790.07	5.97
Cashew	Husks	23.05	48.41	8.23	2.94	1300.61	1.12	820.22	0.72
Cassava	Stems and peels	2287.18	2141.72	1181.69	373.62	254661.19	219.85	151172.27	132.89
Coconuts	Fronds, husks, and shells	27.74	18.31	18.31	6.24	6308.20	5.45	2425.65	2.13
Cotton seed	Stalk	31.87	65.86	55.10	22.75	17530.77	15.13	16478.97	14.49
Groundnuts	Trash and shells	210.37	306.45	249.98	92.13	76174.21	65.76	58604.26	51.52
Lemons	Peels	18.67	5.60	4.48	0.11	704.65	0.61	522.28	0.46
Lettuce	Foliage	5.85	7.02	3.51	1.28	882.32	0.76	366.73	0.32
Maize (corn)	Stalk and cobs	1074.41	1139.46	833.08	318.28	569865.59	491.97	284251.24	249.88
Millet	Stalk and straws	172.77	336.90	240.55	89.62	34862.03	30.10	20809.08	18.29
Oil palm	Kernel shell, fiber, and fronds	276.25	72.93	72.93	25.00	39564.76	34.16	21475.85	18.88
Oranges	Peels	121.12	35.73	28.58	12.25	1887.51	1.63	846.59	0.74
Pepper	Leaves	55.79	55.79	55.79	32.14	9275.33	8.01	628.00	0.55
Potatoes	Leaves and peels	338.88	263.48	223.96	71.50	52955.37	45.72	42492.84	37.35
Rice	Straws	437.58	467.77	317.38	108.55	50288.16	43.41	36356.40	31.96
Sorghum	Stalk and straws	353.29	693.05	582.16	186.83	112668.76	97.27	71142.32	62.54
Soya beans	Straw and pods	41.47	69.01	57.96	23.48	8885.23	7.67	6151.45	5.41
Sugar cane	Bagasse and leaves	1221.84	293.24	234.59	86.96	52513.36	45.34	30177.22	26.53
Sweet potatoes	Leaves and peels	319.43	159.72	127.77	40.80	14691.86	12.68	8135.93	7.15
Tomatoes	Stem and leaves	274.34	54.87	27.43	9.02	4404.76	3.80	2587.66	2.27
Wheat	Straws and husks	342.81	259.68	76.61	27.44	14661.12	12.66	8622.52	7.58
Yams	Peels	883.66	243.01	179.22	45.61	34764.50	30.01	16725.54	14.70
Average		365.93	317.80	217.46	72.69	60370.18	52.12	34935.09	30.71

TABLE 5: Bioenergy potential by crops residues

Mt: million tonnes, Mtoe: million tonnes of oil equivalent, Mm^3 CH_4/year: million cubic meters of methane per year, ML/year: million liters per year

Figure *4* reveals that Nigeria, South Africa, and Ethiopia dominate bioethanol production in Western Africa, Southern Africa, and Central/North Eastern Africa with substantial growth from 2010 to 2022. Furthermore, all 15 countries contributed more than 50% of Africa's bioenergy potential for the period under investigation. Southern Africa consistently has the highest bioethanol production among the regions (Appendix Table *12*). These data reflect a promising shift towards renewable energy, particularly in biomethane production, across various African regions, with notable differences in growth rates and production levels between countries.

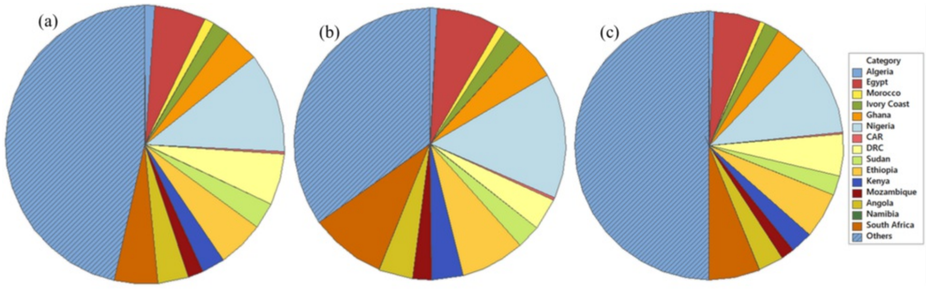

FIGURE 4: Potential distribution of (a) solid biofuel, (b) biomethane, and (c) bioethanol

Figure *5a* shows that Nigeria, Ghana, and DRC witnessed significant and continuous increases in crop production compared to other countries. Namibia and CAR are the lowest, with no substantial increase. The residue production from the crops are potential feedstock for biofuel production and, therefore, significant in the bioenergy value chain. The production profiles for solid biofuel potential (Figure *5b*), biomethane potential (Figure *5c*), and bioethanol potential (Figure*5d*) for the various countries were evaluated. Figure 8d also shows clear and distinct variations in bioethanol production potential in South Africa, which is now leading in Africa.

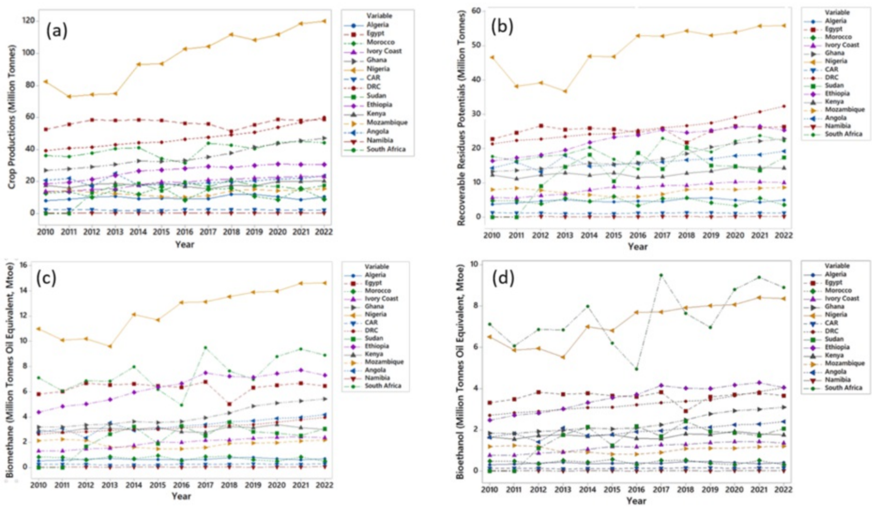

FIGURE 5: Profiles of (a) crop productions by countries, (b) recoverable residues potential (solid biofuel potential) by countries, (c) biomethane potential by countries, and (d) bioethanol potentials by countries

Discussion

The results showed that Africa has enormous energy potential in the form of biomass-generated energy that could address rural energy poverty, mainly in rural areas, when scaled up. The 15 selected countries by region, out of the 55 African countries, made significant contributions of over 50% towards their energy potentials. This implies that developing bioenergy at regional levels can effectively contribute to economic growth in the respective regions. Although Africa contributes about 4% of global emissions, it disproportionately experiences negative impacts such as drought, desert encroachment, flooding, diseases, and inter-tribal crises due to the migration of herders. These factors significantly affect agricultural production and hinder the development of bioenergy. On the other side, there are insecurities and insurgencies. Therefore, there is a need to strengthen the security architecture continentally, thereby strengthening the agricultural sector, not just for food security but also to extract energy value addition, including biomass residue collection, processing, transportation, logistics, storage, and financing.

Rural areas in Africa have a higher incidence of poverty, primarily because most of the population is involved in semi-mechanized agriculture. However, providing education on residue collection and processing for bioenergy generation is crucial for improving the farmers' livelihood. Moreover, these activities would necessitate substantial reductions in infrastructure investments for road networks, transportation systems, irrigation and water supply, and power supply. Effective policies and robust R&D are essential value chain components. They can process these residues by gasification for synthesis gas (syngas), pyrolysis for biochar and bio-oils, fermentation for liquid biofuel, briquetting, or pelletization for solid biofuels.

Bioenergy is a versatile and adaptable solution that can facilitate Africa's climate neutrality by 2050 by creating employment opportunities and fostering economic growth. Its impact on income, employment, and food security has recently attracted broad discussions. The production of bioenergy can yield both positive and negative environmental consequences, and these can vary based on factors such as the type of biomass utilized, the geographical locations of some useful land, and the methods of management employed [41]. By reducing reliance on fossil fuels, biofuels contribute to GHG emission reductions and environmental pollutant mitigations. They also enhance the local economy by creating employment opportunities. Moreover, the bioeconomy plays a crucial role in waste management, utilizing various waste streams such as agricultural residue, MSW, and industrial waste to produce biofuels and other high-value products. This addresses waste disposal challenges and creates new employment opportunities across the biofuel production and processing sectors. While the bioeconomy may have some adverse effects, its benefits for environmental sustainability and human welfare are substantial and can be effectively managed for long-term sustainability [42].

Africa has progressively developed in food and bioenergy crop cultivation since the 2000s, which poses challenges toward its transition to a bioeconomy [43]. In Europe, each additional Mtoe of biomass for energy could impact €359 million in terms of GDP and 7,376 full-time equivalent employment creation while mitigating ~2.4 $MtCO_2eq$ emissions due to the transition from fossil energy[44]. Various innovative technologies and tools have emerged in Africa to produce and distribute renewable bioenergy. These technologies promote the sustainable use of locally available resources without disrupting food and water supply [45]. Researchers have identified three primary challenges in rural bioenergy for Africa: the use of unsustainable bioenergy feedstock resulting in deforestation, inefficient domestic energy production systems, and the absence of mechanisms to guarantee the sustainability of improved bioenergy solutions, mainly through R&D [46]. South Africa has witnessed the implementation of waste-to-energy systems in rural and underserved municipalities, notably micro-biodigesters, and these have been instrumental in advancing sustainable development goals by enhancing livelihood [47]. The South African government has implemented various measures to encourage the commercial production of biofuels, such as exempting biofuels from existing fuel levies. Prospective biodiesel producers were granted a 50% exemption from fuel levies, while prospective bioethanol producers received a 100% exemption [48]. In Zambia, Sunbird Bioenergy has set up a biorefinery in Luapula that uses cassava as a feedstock to produce 120 million liters of bioethanol per annum [46]. This production delivers 20% of Zambia's petroleum consumption, reducing its import bill by $100 m [46].

Future Perspectives: Overcoming the Barriers to Bioenergy Production in Africa

Africa faces several barriers that hinder bioenergy solutions' development and widespread adoption[49]. The continent can unlock its bioenergy potential by addressing these challenges and contributing to energy security, economic development, and environmental sustainability [50]. Collaboration among governments, industries, academia, and communities is essential to realize the full benefits of bioenergy and drive the continent towards a sustainable energy future [51]. Overcoming these challenges requires a robust approach integrating technological advancements, monetary incentives, social engagement, institutional capacity, and supportive policies. In Zambia for instance, the barriers to biogas technology adoption were identified by non-beneficiaries and private sector representatives to be due to institutional, situational, technical, and dispositional factors [52]. The study recommended the Zambian government to strengthen institutional infrastructure, focus on renewable energy policies, foster public-private partnerships, encourage R&D, stabilize the market, improve coordination, and boost public awareness to enhance clean energy provision. Table *6* shows, but is not limited to, the mitigations and solutions to the barriers.

Barriers to Bioenergy Production		Mitigation Measures/Solutions
Categories	Barriers	
Financial Barriers	High initial capital outlay required. Limited access to loans and financial support. Long payback periods for household-level biogas digesters.	Reliable information dissemination on bioenergy technology with local authorities, politicians, and the public. Financial institutions should provide loans for bioenergy projects. Subsidies for pilot and demonstration projects to enhance adoption. Offer partnerships with private companies for biogas technology production. Promote community-level biogas digesters to reduce payback periods through shared resources and labor.
Technological Barriers	Lack of knowledge and technical skills. Inadequate design adaptation to local needs. Dependence on imported materials and prefabricated systems. Limited follow-up services post-installation.	Knowledge transfer among bioenergy projects and between research institutions and practitioners. Provide training for skilled labor, owners, operators, and technicians in biogas technology. Support research to optimize production and improve technology. Train and employ technicians for post-installation services and encourage user engagement. Provide operation and maintenance manuals in local languages.
Socio-Cultural Barriers	Lack of awareness and understanding of bioenergy technology. Social perception and resistance to new technology.	Conduct educational and awareness programs through pamphlets, community meetings, and media. Encourage penning of livestock for effective dung collection.
Institutional Barriers	Inadequate institutional support and frameworks. Insufficient government commitment to renewable energy.	Introduce policies, legislation, and financial subsidies to support biofuel adoption. Establish national frameworks to support bioenergy system implementation. Promote government commitment to renewable energy programs and sources.
Policy and Regulatory Barriers and Solutions	Complicated or insufficient regulatory frameworks that create obstacles for biogas projects.	Streamline regulations to make it easier to start and maintain biogas projects. Implement coherent and consistent policies to support the development of bioenergy energy.
Environmental and Sustainability Considerations	Limited availability of raw materials for biodiesel production. The conflict between using agricultural resources for food versus fuel production.	Develop sustainable agricultural practices and diversify feedstock sources. Implement policies to balance agricultural resources between food and fuel production.

TABLE 6: Barriers and solutions to bioenergy production

[53-55]

Achieving Circular Economy in Africa Through Bioenergy

Utilizing crop residues for biofuel production aligns with circular economy principles, promoting sustainability. The principles and models of circular economy aim to minimize waste and make the most of resources. It can also optimize energy transition [51]. In Africa, where waste management and energy access are significant challenges, leveraging bioenergy can drive both environmental and socio-economic benefits, fostering a more sustainable and circular economy [56]. Key components in achieving the circular economy are shown in Figure *6*. Africa's vast agricultural lands generate substantial biomass residues, which can be harnessed for bioenergy production. Key sources include forest residues, crop residues, animal manure, and organic MSW. Transforming these resources into energy can reduce reliance on fossil fuels, decrease GHG emissions, and enhance energy security. Achieving a circular economy in Africa through bioenergy is both a viable and necessary endeavor. By transforming waste into valuable energy, Africa can address its energy and waste management challenges, drive economic growth, and promote environmental sustainability. Collaboration among governments, the private sector, academia, and communities is essential to harness the full potential of bioenergy and realize a sustainable future for the continent [53]. There should be a continent-wide investment portfolio on bioenergy to drive African Union, regional bodies, Afrexim Bank, and the African Development Bank, as well as donor agencies such as the U.S. Agency for International Development, International Development Research Centre, and Deutsche Gesellschaft für Internationale Zusammenarbeit.

FIGURE 6: Key components of achieving circular economy through bioenergy

Conclusions

This study evaluated the potential role of solid biofuel, biogas, and bioethanol from 25 energy crops to meet the energy demand of Africa and 15 selected countries within the continent for 13 years. The feedstock considered was limited to crop residues, while forestry, animal dung, and MSW were excluded. The result demonstrated that the residues can sustainably generate modern energy for Africa. For the time frame analyzed, African bioethanol production averaged 62.62 Mtoe, 83.05 Mtoe of biomethane, and 139.79 Mtoe of solid biofuel annually. Maize (corn) exhibited the highest bioenergy potential among the crops, followed by cassava and sorghum. Three countries were regionally selected based on their agricultural and bioenergy activities and evaluated for their bioenergy potentials. The result showed that South Africa and Nigeria have the most potential, while Namibia and the CAR demonstrate the lowest potential. The quantity of bioenergy produced depends on crop production, recoverable residue-to-product ratio, the lower heating value of the crops, and biochemical compositions such as starch, cellulose, hemicellulose, and lignin. Biofuel production has the potential to transform Africa's agriculture, industrial, and rural sectors by increasing energy self-sufficiency and sustainability. However, these require overcoming challenges such as a lack of agricultural expansion, deteriorated soils, inadequate infrastructure, corruption, and land tenure challenges, which are crucial for achieving sustainable development in Africa. Furthermore, to comprehensively understand the challenges that prevent the widespread implementation of bioenergy in Africa, it is necessary to carry out socio-economics, technology, environment, and risk assessments. This study has implications for Africa's socioeconomic and sustainable development. Our findings are relevant as they show underutilized crop residues' potential for sustainable development and potential benefits in areas where bioenergy is often considered unsuccessful.

Appendices

S/N	Biomass	African Producers
1	Bananas	Angola (46.624 Mt), Kenya (19.92 Mt), Egypt (15.92 Mt), Democratic Republic of Congo (10.43 Mt), Sudan (9.80 Mt), Ethiopia (7.59 Mt), Mozambique (6.5 Mt), South Africa (5.17 Mt)
2	Barley	Ethiopia (26.59 Mt), Morocco (25.06 Mt), Algeria (16.69 Mt), South Africa (4.37 Mt), Egypt (1.36 Mt)
3	Beans	Kenya (8.798 Mt), Ethiopia (8.25 Mt), Angola (4.2 Mt), Mozambique (3.64 Mt), Democratic Republic of Congo (3.16 Mt)
4	Cassava	Nigeria (717.65 Mt), Democratic Republic Congo (248.65 Mt), Angola (134.59 Mt), Mozambique (66.36 Mt), Ivory Coast (59.29 Mt), Central African Republic (16.50 Mt)
5	Groundnuts	Nigeria (53.92 Mt), Sudan (24.24 Mt), Ghana (7.06 Mt), Democratic Republic Congo (5.89 Mt), Central African Republic (5.52 Mt)
6	Wheat	Egypt (115.56 Mt), Morocco (68.88 Mt), Ethiopia (59.64 Mt), Algeria (38.35 Mt), South Africa (23.73 Mt), Kenya (4.14 Mt)
7	Maize (corn)	South Africa (171.61 Mt), Nigeria (136.80 Mt), Ethiopia (111.73 Mt), Egypt (98.02 Mt), Tanzania (76.58 Mt), Malawi (45.04 Mt)
8	Millet	Niger (44.22 Mt), Nigeria (24.88 Mt), Mali (22.22 Mt), Sudan (13.8 Mt), Ethiopia (12.58 Mt), Burkina Faso (12.52 Mt), Senegal (10.19 Mt)
9	Potatoes	Egypt (64.9 Mt), Algeria (57.84 Mt), South Africa (30.96 Mt), Kenya (26.22 Mt), Morocco (23.40 Mt), Tanzania (16.19 Mt), Rwanda (16.19 Mt)
10	Rice	Nigeria (98.86 Mt), Egypt (64.97 Mt), Madagascar (53.46 Mt), Tanzania (38.69 Mt), Mali (31.74 Mt), Guinea (27.91 Mt), Ivory Coast (22.98 Mt)
11	Sorghum	Nigeria (85.94 Mt), Ethiopia (58.37 Mt), Sudan (47.31 Mt), Burkina Faso (22.77 Mt), Niger (21.30 Mt), Mali (18.5 Mt), Malawi (26.78 Mt)
12	Sugar cane	South Africa (227.16 Mt), Egypt (204.66 Mt), Kenya (82.11 Mt), Eswatini (72.28 Mt), Uganda (63.4 Mt), Sudan (62.58 Mt), Zambia (57.97 Mt), Zimbabwe (45.02 Mt)
13	Oil Palm	Nigeria (120.62 Mt), Ghana (31.03 Mt), Ivory Coast (27.08 Mt), Democratic Republic Congo (23.52 Mt), Guinea (11.08 Mt), Benin (7.7 Mt), Togo (6.41 Mt)
14	Yam	Nigeria (610.39 Mt), Ghana (102.24 Mt), Ivory Coast (86.91 Mt), Benin (39.16 Mt), Togo (10.79 Mt), Cameroon (7.2 Mt), Central African Republic (5.76 Mt)
15	Soya Beans	South Africa (13.79 Mt), Nigeria (10.12 Mt), Zambia (3.52 Mt), Benin (2.17 Mt), Ghana (2.13 Mt), Malawi (2.01 Mt)

TABLE 7: Africa’s production capacity (Mt – million tonnes) of the main biomasses (2010–2022)

[16]

Year	Crop Productions (Million Tonnes)														
	Northern Africa			Western Africa			Central/North Eastern Africa			Eastern/South East Africa			Southern Africa		
	Algeria	Egypt	Morocco	Ivory Coast	Ghana	Nigeria	CAR	DRC	Sudan	Ethiopia	Kenya	Mozambique	Angola	Namibia	South Africa
2010	8.11	52.68	12.76	13.81	26.88	82.28	2.38	39.30	0.00	18.53	17.45	13.35	20.58	0.15	36.32
2011	9.00	55.63	13.54	13.90	27.84	73.16	2.27	40.73	0.00	19.37	16.12	14.54	22.08	0.15	35.58
2012	10.23	58.60	10.07	15.02	28.90	74.38	2.33	41.59	12.91	21.20	18.26	13.26	17.03	0.19	37.83
2013	10.76	58.19	14.93	15.54	30.74	74.92	1.80	43.02	17.17	23.74	18.72	12.32	24.89	0.11	40.49
2014	9.21	58.41	11.86	17.98	32.84	93.28	1.91	44.31	18.75	26.56	17.45	11.71	17.53	0.14	41.04
2015	9.41	58.21	16.73	19.86	32.40	93.54	1.90	44.52	14.11	27.16	19.08	10.38	17.89	0.15	34.46
2016	9.24	56.24	8.33	19.53	33.20	102.89	2.38	46.48	19.37	28.24	17.06	10.30	18.64	0.11	31.48
2017	9.24	56.14	15.05	21.06	35.30	104.40	2.39	47.65	16.74	29.45	15.31	11.19	19.01	0.17	44.08
2018	11.97	51.35	15.76	21.43	37.76	111.75	2.47	49.07	21.01	28.70	17.51	14.22	19.82	0.18	42.55
2019	11.99	55.44	10.81	22.33	41.43	108.30	2.54	50.62	17.15	30.04	17.13	14.98	20.34	0.09	40.57
2020	10.41	58.78	8.52	22.67	43.49	111.83	2.11	53.96	16.90	30.86	20.13	14.07	21.53	0.20	44.36
2021	8.53	58.08	15.58	23.08	45.62	118.57	2.16	57.09	15.07	30.46	20.10	14.85	22.03	0.19	45.09
2022	10.38	58.70	8.99	23.23	47.00	120.10	2.20	60.13	17.51	30.48	20.38	15.54	23.35	0.21	44.22
Average	9.88	56.65	12.53	19.19	35.65	97.65	2.22	47.57	14.36	26.52	18.05	13.13	20.36	0.16	39.85

TABLE 8: Crop productions of selected countries by regions

CAR: Central African Republic, DRC: Democratic Republic of Congo

Year	Recoverable Residues Potentials (Million Tonnes)														
	Northern Africa			Western Africa			Central/North Eastern Africa			Eastern/South East Africa			Southern Africa		
	Algeria	Egypt	Morocco	Ivory Coast	Ghana	Nigeria	CAR	DRC	Sudan	Ethiopia	Kenya	Mozambique	Angola	Namibia	South Africa
2010	3.73	22.82	4.82	5.68	13.37	46.61	1.31	21.35	0.00	16.35	12.34	8.00	14.32	0.14	17.75
2011	4.15	24.62	4.82	5.59	13.61	38.13	1.25	22.34	0.00	17.26	11.22	8.45	16.08	0.14	16.34
2012	4.70	26.60	3.84	6.34	14.14	39.20	1.27	22.75	9.06	18.14	12.31	7.80	13.23	0.19	17.68
2013	5.09	25.54	5.48	6.73	14.74	36.67	0.98	23.50	14.70	19.49	12.95	7.03	18.00	0.10	18.21
2014	4.54	25.93	4.56	7.93	15.81	46.93	1.02	24.23	18.19	21.78	12.17	6.48	14.83	0.14	20.30
2015	4.53	25.59	5.97	8.83	15.51	46.75	1.02	24.30	10.46	23.32	12.91	5.88	15.23	0.14	16.91
2016	4.65	24.73	3.39	8.61	15.84	52.85	1.27	25.34	18.76	23.93	11.65	6.02	15.69	0.09	13.99
2017	4.56	25.81	5.41	9.31	16.94	52.75	1.27	26.00	14.01	25.42	11.81	6.74	16.07	0.17	22.98
2018	5.45	21.80	5.59	9.31	18.50	54.28	1.33	26.69	20.14	24.66	12.81	8.08	16.67	0.20	20.64
2019	5.56	25.14	4.14	9.92	20.45	53.00	1.36	27.42	15.07	25.20	13.46	8.22	17.01	0.08	19.05
2020	4.97	26.51	3.41	10.25	21.53	53.89	1.16	29.05	14.88	26.29	14.61	7.99	17.88	0.21	22.16
2021	4.36	26.15	5.53	10.23	22.16	55.77	1.19	30.71	13.65	26.46	14.40	8.41	18.19	0.18	23.80
2022	4.94	26.37	3.58	10.06	22.92	55.79	1.21	32.38	17.41	25.34	14.33	8.64	19.21	0.18	22.25
Average	4.71	25.20	4.66	8.37	17.35	48.66	1.20	25.85	12.79	22.59	12.84	7.52	16.34	0.15	19.39

TABLE 9: Recoverable residues potentials of the selected energy crops by countries (regions)

CAR: Central African Republic, DRC: Democratic Republic of Congo

Year	Solid Biofuel Potentials (Million Tonnes Oil Equivalent)														
	Northern Africa			Western Africa			Central/North Eastern Africa			Eastern/South East Africa			Southern Africa		
	Algeria	Egypt	Morocco	Ivory Coast	Ghana	Nigeria	CAR	DRC	Sudan	Ethiopia	Kenya	Mozambique	Angola	Namibia	South Africa
2010	1.26	7.49	1.68	1.84	4.38	15.66	0.41	6.87	0.00	5.42	3.55	2.70	4.27	0.05	6.44
2011	1.38	8.14	1.72	1.81	4.44	12.74	0.39	7.19	0.00	5.74	3.38	2.86	4.79	0.05	5.91
2012	1.56	8.68	1.26	2.07	4.62	13.11	0.40	7.32	3.02	6.04	3.79	2.66	3.86	0.06	6.43
2013	1.68	8.53	1.89	2.20	4.79	12.14	0.30	7.57	4.92	6.53	3.80	2.34	5.43	0.03	6.62
2014	1.47	8.68	1.55	2.58	5.13	15.60	0.32	7.81	6.05	7.32	3.67	2.18	4.40	0.05	7.40
2015	1.49	8.51	2.11	2.87	5.03	15.49	0.32	7.83	3.47	7.81	3.83	1.96	4.53	0.05	6.12
2016	1.49	8.27	1.13	2.79	5.14	17.55	0.40	8.17	6.24	8.05	3.37	2.02	4.74	0.03	5.03
2017	1.48	8.66	1.89	3.03	5.51	17.53	0.40	8.38	4.67	8.64	3.39	2.25	4.84	0.06	8.44
2018	1.82	7.22	1.97	3.04	6.02	17.95	0.41	8.60	6.83	8.29	3.82	2.69	5.05	0.07	7.54
2019	1.83	8.36	1.40	3.22	6.67	17.61	0.43	8.84	5.09	8.50	3.88	2.75	5.15	0.02	6.90
2020	1.61	8.87	1.11	3.32	7.02	17.90	0.37	9.36	5.08	8.86	4.19	2.67	5.42	0.07	8.10
2021	1.35	8.77	1.91	3.32	7.20	18.48	0.38	9.89	4.57	8.88	3.98	2.82	5.54	0.06	8.71
2022	1.60	8.80	1.16	3.23	7.45	18.43	0.38	10.42	5.82	8.50	3.76	2.89	5.85	0.06	8.08
Average	1.54	8.38	1.60	2.72	5.65	16.17	0.38	8.33	4.29	7.58	3.72	2.52	4.91	0.05	7.06
	1%	6%	1%	2%	4%	12%	0%	6%	3%	5%	3%	2%	4%	0%	5%

TABLE 10: Solid biofuel potentials by countries (regions)

CAR: Central African Republic, DRC: Democratic Republic of Congo

Year	Biomethane (Million Tonnes Oil Equivalent)														
	Northern Africa			Western Africa			Central/North Eastern Africa			Eastern/South East Africa			Southern Africa		
	Algeria	Egypt	Morocco	Ivory Coast	Ghana	Nigeria	CAR	DRC	Sudan	Ethiopia	Kenya	Mozambique	Angola	Namibia	South Africa
2010	0.53	5.81	0.82	1.33	3.20	10.99	0.26	2.64	0.00	4.38	2.94	2.12	2.75	0.037	7.11
2011	0.59	6.03	0.81	1.33	3.20	10.08	0.25	2.77	0.00	4.84	2.80	2.23	3.10	0.036	6.06
2012	0.67	6.68	0.58	1.48	3.38	10.19	0.25	2.84	1.67	5.03	3.10	2.16	2.35	0.055	6.87
2013	0.72	6.53	0.86	1.54	3.44	9.61	0.19	2.93	2.64	5.38	3.11	1.62	3.54	0.027	6.85
2014	0.63	6.63	0.70	1.76	3.65	12.12	0.21	3.01	3.23	5.94	3.01	1.62	2.94	0.037	7.98
2015	0.63	6.47	0.94	2.03	3.57	11.68	0.21	3.03	1.89	6.36	3.18	1.48	3.07	0.037	6.20
2016	0.65	6.35	0.53	1.99	3.65	13.07	0.26	3.15	3.30	6.66	2.83	1.48	3.28	0.026	4.95
2017	0.64	6.78	0.85	2.16	3.94	13.13	0.26	3.24	2.52	7.48	2.79	1.60	3.40	0.046	9.50
2018	0.78	5.04	0.88	2.18	4.33	13.53	0.27	3.31	3.59	7.21	3.24	1.91	3.63	0.045	7.64
2019	0.79	6.33	0.62	2.33	4.87	13.88	0.28	3.39	2.82	7.14	3.16	1.95	3.71	0.025	6.97
2020	0.70	6.52	0.50	2.41	5.12	13.97	0.27	3.58	2.72	7.44	3.40	1.96	3.90	0.048	8.80
2021	0.61	6.67	0.84	2.42	5.27	14.59	0.27	3.77	2.53	7.71	3.17	2.09	3.97	0.051	9.39
2022	0.70	6.45	0.51	2.36	5.42	14.62	0.28	3.96	3.09	7.31	3.03	2.17	4.18	0.058	8.90
Average	0.66	6.33	0.73	1.95	4.08	12.42	0.25	3.20	2.31	6.38	3.06	1.87	3.37	0.041	7.48
	1%	8%	1%	2%	5%	15%	0%	4%	3%	8%	4%	2%	4%	0%	9%

TABLE 11: Biomethane biofuel potentials by countries (regions)

CAR: Central African Republic, DRC: Democratic Republic of Congo

Year	Bioethanol (Million Tonnes Oil Equivalent)														
	Northern Africa			Western Africa			Central/North Eastern Africa			Eastern/ South East Africa			Southern Africa		
	Algeria	Egypt	Morocco	Ivory Coast	Ghana	Nigeria	CAR	DRC	Sudan	Ethiopia	Kenya	Mozambique	Angola	Namibia	South Africa
2010	0.32	3.32	0.49	0.77	1.84	6.51	0.15	2.70	0.00	2.47	1.65	1.19	1.63	0.020	3.74
2011	0.35	3.48	0.48	0.77	1.83	5.86	0.15	2.82	0.00	2.71	1.55	1.25	1.83	0.020	3.22
2012	0.40	3.83	0.35	0.88	1.93	5.95	0.15	2.89	1.11	2.81	1.72	1.20	1.42	0.030	3.62
2013	0.43	3.72	0.52	0.92	1.97	5.53	0.11	2.99	1.76	3.01	1.75	0.92	2.09	0.015	3.63
2014	0.37	3.77	0.43	1.06	2.09	7.00	0.12	3.08	2.14	3.32	1.68	0.92	1.72	0.020	4.21
2015	0.38	3.66	0.57	1.20	2.05	6.81	0.12	3.09	1.25	3.56	1.77	0.83	1.78	0.020	3.30
2016	0.39	3.60	0.32	1.17	2.09	7.69	0.15	3.22	2.18	3.71	1.58	0.83	1.90	0.014	2.64
2017	0.38	3.83	0.52	1.28	2.25	7.71	0.15	3.31	1.68	4.14	1.56	0.91	1.96	0.025	4.99
2018	0.46	2.91	0.54	1.30	2.48	7.91	0.16	3.38	2.41	4.01	1.80	1.09	2.09	0.025	4.08
2019	0.47	3.60	0.38	1.38	2.78	8.01	0.16	3.46	1.93	3.99	1.77	1.11	2.13	0.013	3.71
2020	0.41	3.71	0.31	1.43	2.92	8.07	0.15	3.66	1.86	4.16	1.92	1.11	2.24	0.027	4.65
2021	0.36	3.79	0.52	1.44	3.00	8.40	0.16	3.85	1.72	4.28	1.81	1.18	2.28	0.028	4.97
2022	0.41	3.66	0.31	1.36	3.09	8.36	0.16	4.04	2.06	4.05	1.75	1.21	2.40	0.031	4.68
Average	0.39	3.61	0.44	1.15	2.33	7.22	0.14	3.27	1.55	3.56	1.72	1.06	1.96	0.022	3.96
	0.63%	5.76%	0.70%	1.84%	3.73%	11.53%	0.23%	5.22%	2.47%	5.68%	2.74%	1.69%	3.13%	0.04%	6.32%

TABLE 12: Biomethanol potentials by countries (regions)

CAR: Central African Republic, DRC: Democratic Republic of Congo

Additional Information

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All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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