Effects of crop residues for animal consumption and soil enhancement on the electricity generation potential of residues: A case study of Sawla-Tuna-Kalba district, Ghana

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Abstract: Many studies have estimated the potential of crop residues for energy generation globally and recognized its great potential, especially in rural areas where on-grid electricity is uneconomical. However, crop residues have other equally important uses as animal feed and as mulch for soil enhancement, especially in rural farming communities. Nevertheless, most of the known studies have neglected the estimation of the quantity of crop residues that will be required for feeding animals and also for the enhancement of soil through mulching in their energy potential estimation from crop residues. Neglecting these two important uses can lead to the over-exploitation of the residues for energy generation at the expense of conservation agriculture practices as well as depriving animals of quality feed which can lead to low crop yield and animal production, with the ability to cause hunger and poverty. This study has assessed the potential of electricity generation from agricultural residues in the Sawla-Tuna-Kalba district of Ghana using gasification technology, taking cognizance of the proportion of residues needed for animal consumption and soil enhancement. The results of the study indicate that out of the 207 646.22 t of residues that can be generated from maize, yam, cassava, millet, sorghum, and groundnut, 26 830.36 t (representing 13%) will be required by sheep, goats, and cows for consumption, and 13 936.17 t (representing 7%) will be required for mulching soils where the crops are planted. Also, it was found that a total of 592.17 MW·h of electricity can be generated from crop residues without animal consumption and soil enhancement needs, while 461.89 MW·h could be generated from the residues, considering animal feed and soil enhancement. This study has indicated that it is not enough to consider soil enhancement and animal feeding in agricultural biomass power generation through recovery factors without the exact quantification of residues required for these purposes since this can lead to a violation of conservation agricultural practice. Hence, it is concluded that the proper estimation of residues required for soil enhancement needs and animal feeding must be considered in the estimation of crop residues available for electricity generation following the method proposed in this study. It is further concluded from this study that, the proper utilization of crop residues serve as an important resource for meeting the electricity demand of the inhabitants in the study location without compromising on the residues that will be required for the consumption of all the animals in the location as well as for enhancement of the soil.

Keywords: animal feed, crop residue, electricity generation, soil enhancement
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1 Introduction

1.1 Global energy issues

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) on the impacts of climate change states that the world is at a moment where the prevention of climate breakdown and the achievement of climate goals must be tackled as 'now or never'[1]. Efforts toward the achievement of the Sustainable Development Goal (SDG)-7 (Affordable and clean energy) must not be at the expense of the SDG-13 (Climate action) achievement[2]. The growing global population and rapid industrialization have resulted in a high demand for energy worldwide, especially in developed countries. This has led to the generation of electricity using fossil fuels dominating the electricity mix of almost all countries in the world since the Industrial Revolution[3]. Fossils have not only dominated the energy generation mix of the world but also kept increasing in the percentage share of energy generation by source, except oil, as shown in Figure 1.

It is worrying to know the rapidly increasing spate of fossil fuels despite the several climate change mitigation programmes and investments by international organizations that aim at the achievement of a global transition from polluting fuels to clean and efficient ones due to the prime position fossils occupy in terms of

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Greenhouse Gas (GHG) emissions[4-6]. The prime cause of the over-reliance of the world on fossils for energy can be attributed to the cost-competitive nature of fossil fuels as compared to other fuel sources like renewables.

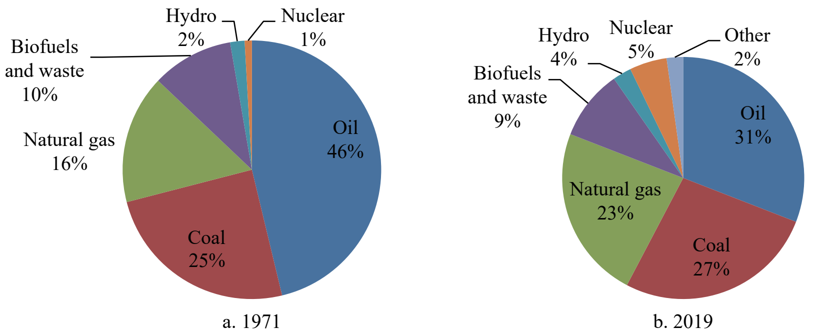


Figure 1 World total energy supply by source 1971 and 2019[4]

Fortunately, renewable energy sources are also becoming cost-competitive in recent years. The levelized cost of electricity (LCOE) generated from renewable sources in the period of 2010-2019 reduced significantly all over the world. This resulted in renewables becoming the least-cost alternative for universal electricity generation in 2020[7]. Solar photovoltaics (PV) experienced the largest cost reduction on the utility-scale, bringing down the price by up to 82%. About 7311 TWh of power was generated from renewables in 2019, representing 29% of total global electricity generation with the European Union (EU) contributing the largest share of 38% and the least contribution by Africa (21%)[6].

1.2 Biomass power generation in Sub-Saharan Africa

The utilization of biomass power generation in Africa is gaining prominence in many scientific studies in recent years. This is attributable to the increasing rate of waste generation through agricultural, industrial, and domestic activities, due to the rapid population growth and industrialization of the continent[8,9]. When it comes to biomass power production, Sub-Saharan Africa (SSA) is counted among the regions with great potential for energy generation from biomass[10,11], which is projected to increase in the coming years due to the large area of unutilized arable land intended to be used for meeting the food demand of the continent due to its rapid population growth[12,13]. Even though, the study by Awaafo et al.[14] states crop production volumes alone without proper policies and frameworks will not translate into biopower generation in Africa, yet many studies have indicated the great potential of biomass in Africa for eco-friendly power generation, while providing green jobs for its population[15].

When it comes to electricity generation from biomass in Africa, countries like Mauritius, Ghana, Sudan, South Africa, Swaziland, and Zimbabwe are in the spotlight in SSA, with Mauritius taking the lead by meeting about 11.3% of its national electricity demand from bioenergy[16,17].

1.3 Ghana's energy situation and biomass potential

Ghana is counted among the countries that have made significant progress in terms of electricity access in the SSA region. In 2022, the electricity access rate of Ghana was pegged at 94.7%, 85.9%, and 74.0% for urban, national, and rural, respectively. In terms of the electricity generation mix, the case of Ghana is not different from the global scenario. The country has much of its electricity generation coming from oil and natural gas (NG) and about a third coming from hydro. The electricity mix of Ghana consists of 29.9% hydro, 69% thermal (fossil fuels), and 1.1% renewables as of 2020[18]. Table 1 presents the electricity generation by source in Ghana. The high dependence of Ghana on thermal power generation from fossils makes the country's power sector highly susceptible to price fluctuation from the international oil market[19].

Table 1 Electricity generation of Ghana by source in 2020[18]

Power plant	Generation type	Fuel type	Installed capacity/MW	Dependable capacity/MW
Akosombo	Hydro	Hydro	1020	900
Bui	Hydro	Hydro	400	360
Kpong	Hydro	Hydro	160	140
Sub total			1580	1400
Tapco	Thermal	Oil/NG	330	300
Tico	Thermal	Oil/NG	340	320
Sapp	Thermal	NG	560	520
Ttipp	Thermal	Oil/NG	110	100
Tt2pp	Thermal	Oil/NG	87	70
Cenit	Thermal	Oil/NG	110	100
Ktpp	Thermal	Oil	220	200
Ameri	Thermal	NG	250	230
Karpower	Thermal	Oil/NG	470	450
Aksa	Thermal	HFO	370	350
Cenpower	Thermal	Oil/DFO	360	340
Amandi	Thermal	Oil/NG	203	190
Early power	Thermal	NG/LPG	144	140
Sub total			3554	3310
VRA solar (Navrongo)	Renewables	Solar	2.500	2.000
Meinergy solar	Renewables	Solar	20.000	16.000
Bxc solar	Renewables	Solar	20.000	16.000
VRA solar (Lawra)	Renewables	Solar	6.500	4.500
Tsatsadu hydro	Renewables	Hydro (small)	0.045	0.045
Bui solar	Renewables	Solar	10.000	8.000
Safisana biogas	Renewables	Biogas	0.100	0.100
Sub total			59.145	46.645
Total (including embedded generation)			5288.100	4841.600
Total (excluding embedded generation)			5134.000	4710.000

Note: HFO=Heavy fuel oil and DFO=Diesel fuel oil.

Ghana is rich in renewable energy resources like solar, wind, biomass, and hydro[20]. All these resources are underutilized, except traditional biomass like firewood and charcoal which are used for cooking, but in unsustainable forms[21].

In 2019, Ghana developed the Renewable Energy Master Plan (REMP), intending to provide an investment-focused framework for the promotion and development of renewable energy resources for economic growth, improved social life, and minimizing the adverse effects of climate change[22]. Before the development of the REMP, there was the Renewable Energy Act (ACT 832, 2011), which was amended in 2020 to Renewable Energy ACT 1045, 2020[23,24]. The target of the ACT is to achieve a 10% renewable energy share in the electricity generation mix of Ghana by 2020, but this was missed and it has been extended to 2030. Nevertheless, this resulted in increasing renewables (excluding large hydro) in the electricity generation mix from 0.2% in 2013 to 1.1% in 2020[18]. The low penetration of renewable energy generation in the energy mix of Africa, including Ghana can be attributed to the following factors: 1) high initial investment cost, 2) inadequate funds for ensuring continuity and affordability of renewables through subsidies, and 3) poor market awareness creation and the lack of technical know-how in terms of renewables operations and maintenance[25,26].

Among the several renewable energy sources available for usage in Ghana, biomass is considered one of the best options for expanding electricity access, especially in rural areas while reducing GHG emissions[8,20,27]. However, that references[13,28] argued that bioenergy cannot be considered carbon neutral, due to the fossil fuel usage during land preparation, transportation of biomass, and also the clearing of land for planting, which results in carbon emissions. Nevertheless, bioenergy has the potential to reduce carbon emissions by up to 80% when used for electricity generation as compared to fossils[29]. Many studies have been carried out on the potential contribution of agro-waste for power generation worldwide, especially in developing countries like Ghana[8,10,27,30,31].

The studies conducted in Ghana on this subject include the study by Doe et al.[32] who estimated that about 91.2% of the total electricity demand of Ghana can be met through bioethanol-based electricity generation using crop residues. In the study, regions like the Eastern, Bono, Ahafo, Bono East, Northern, Upper East, and Upper West have the potential to generate electricity in the range of 2 to 6 times higher than their current electricity demand.

Arranz-Piera et al.[33] stated that a cluster of 22 to 54 of 10 hm^2 farmlands is required to economically feed a 1000 kWe plant with crop residues using combined heat and power (CHP) plants, while 13 to 30 cluster farms of the same size can feed a 600 kWe CHP plant.

Odoi-Yorke et al.[20] estimated the total potential of agricultural residues in Ghana to be about 35 t, of which 29 t are available for energy generation. They found that the approximate energy potential of crop residues for energy generation is about 401 PJ/a.

Osei et al.[34] reviewed crop residue utilization for thermochemical energy generation in Ghana. They found Northern, Brong Ahafo (now divided into Bono, Bono East, and Ahafo), and Eastern regions to be the leading regions in terms of agricultural residues yield with major crop wastes such as rice husk, cassava peels, and oil palm residues. Also, Jekayinfa et al.[35] identified 14 biomass energy installations that use thermochemical conversion technologies in Ghana with a combined capacity of 10.7 MW.

The findings of all the studies reviewed stated that Ghana has a high potential for energy generation from agricultural biomass. Crop biomass can be obtained from either the residues of crops[35,36] or the planting of energy crops[28,37]. However many studies have considered agricultural residues as the preferred choice for energy generation rather than energy crop plantation due to the possibility energy crops competing with food crops for land and water resources which could lead to land grabbing, food shortage, and food price increase[14,38,39,40].

There is another school of thought that the increasing awareness creation on the potential of agricultural biomass for energy generation can lead to the over-exploitation of agricultural residues for energy generation at the detriment of soil enhancement and animal feeding[28,41,42]. This can result in soil nutrient depletion and the reduction in animal production since residues usually have their indirect use for these two purposes in Ghana[43,44].

To examine this, Gojiya et al.[42] studied the comparison between the use of agricultural residues for power generation and soil enhancement. However, they didn't analyze the potential electricity that could be generated after considering soil needs. Rather, the study considered the cost comparison between the use of biomass for electricity and for soil fertilization. The study concluded that the use of crops like cotton stalk and groundnut shell residues, which have very high nitrogen content for power generation, is not economical in comparison to their use for soil fertilization, while rice and wheat residues proved more cost-effective for power generation than soil enhancement.

Sarkar et al.[43] provided a comprehensive review of crop residue management, taking into consideration the use of residues for energy generation, soil enhancement, and environmental sustainability. Also, the focus of a study by Govaerts et al.[44] was on the impact of residue use on crops and soil health for improved farm yield and environmental friendliness, rather than the assessment of the energy and soil improvement potential collectively.

There is no known study so far that considers the quantity of residues needed for feeding animals and as well as soil enhancement in their estimation of the potential of crop residues for energy generation, which can lead to the violation of conservation agriculture (CA) practices. CA is a term used for sustainable agricultural practices that enhance the quality and health of the soil to promote higher and stable crop yield at a reduced cost by maintaining a year-round soil cover with organic matter[45,46]. Ignoring CA in crop residue removal, either for animal feeding or industrial purposes like energy generation can have a ripple effect on future crop yield[43,47]. This is because crop residue removal results in nutrient depletion which leads to erosion and degradation of soil quality and water retention[43].

Also, according to the findings of Food and Agriculture Organization Statistics (FAOSTAT)[48], 876 166 469 t of dry matter (DM) was required for feeding animals in 2010, which confirms the importance of accounting for animals' demand for DM in energy potential estimations from crop residues. Many studies[19,35,39,49] have used a guessed value (recovery factor) to represent residues that will not be available after accounting for technical losses, which is presumed to include animal consumption. The usage of residue recovery factor (RF) without proper estimation can lead to misleading results, especially in locations where there is intensive animal farming. Therefore, this current study seeks to estimate the agricultural residue potential for electricity generation using gasification, taking cognizance of residues needed for animal consumption and soil enhancement in the Sawla-Tuna-Kalba district, located in the Savannah region of Ghana.

2 Electricity generation through biomass gasification

Agricultural wastes have great energy potential that can be used as fuels for electricity generation. Technologies for converting biomass to intermediate fuel for electricity generation include gasification[50-54], pyrolysis[55,56], and anaerobic digestion[8,57,58]. Biomass gasification is the common and most preferred thermochemical conversion technology for obtaining intermediate fuel (syngas) from biomass feedstock, which can be fed into a generator set to obtain electrical energy[50,59,60]. The energy is more suitable for rural applications due to the small energy needs of rural areas due to their low population density and the flexibility in generation capacity of the technology[51,52]. Gasification process involves the heating of carbonaceous substances to a temperature of about 1000°C at atmospheric conditions or 1600°C at pressurized conditions to produce gaseous products called producer gas (syngas). The syngas comprises of CO, H_2, CO_2, H_2O, hydrocarbons, tar, and char[51,53,61]. Among gasification systems, which include the fixed and fluidized bed (circulating, bubbling, spouted, and swelling) gasifiers[50,51,54], the fixed bed downdraft gasifier is usually considered a preferred choice for small-scale (<100 MW) biomass gasification for electricity generation due to the following reasons:

1) Its ability to produce syngas with low tar content[62].
2) High tolerance for moisture[63].
3) Suited for small-scale applications[53].
4) Simple to construct and operate[64].
5) Minimal investment cost[65].
6) Ability to reliably operate with a wide range of feedstock.

2.1 Downdraft biomass gasifier system

The downdraft gasifier system is made up of a reactor unit for the production of syngas, gas cleaning system, and a generator unit as shown in Figure 2.

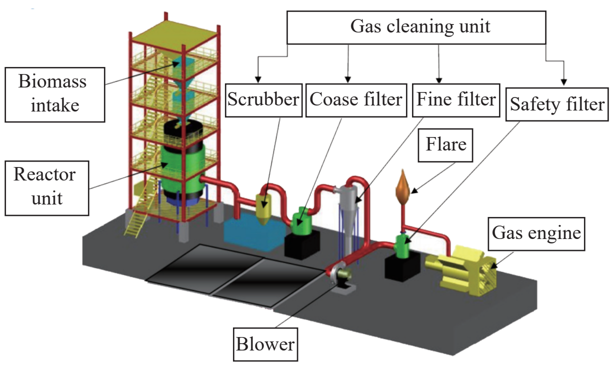


Figure 2 A fixed bed downdraft gasifier system

2.1.1 Reactor unit

The reactor unit of the gasifier system is the part where the biomass feedstock is converted into intermediate fuel known as syngas. This is done through a series of processes like drying, pyrolysis (devolatilization), oxidation, and reduction as shown in Figure 3.

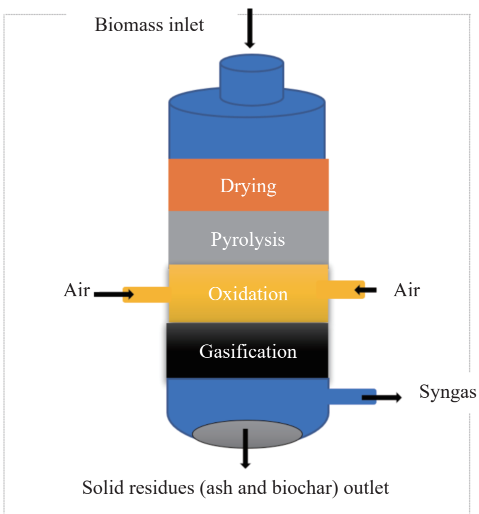


Figure 3 Gasification process of a fixed bed downdraft gasifier

1) Drying

The moisture content of the gasification feedstock shall not exceed 25%[64]. Higher moisture content (>25%) results in a higher amount of energy loss. Hence it is recommended that feedstock be dried to a moisture content <25%, which takes place at the drying chamber[61].

2) Pyrolysis (devolatilization)

In the pyrolysis zone, the gaseous products are heated at a temperature between 400°C and 600°C in the absence of oxygen to produce vapor and char[66].

3) Oxidation

In the oxidation region, there is cracking and reforming of the volatiles through the addition of a gasification agent which can be either oxygen, air, or steam to products of the pyrolysis zone to facilitate gasification.

4) Reduction (gasification)

At the reduction or gasification zone, light gases like H_2, CO, and CO_2 are produced from the char generated by the pyrolysis chamber at an elevated temperature of 800°C to 1000°C in the presence of the gasification agent introduced at the oxidation chamber[66].

2.1.2 Gas cleaning system

Gases produced in the reactor unit are usually characterized by high temperature and impurities like tar, fly ash, soot, moisture, and other impurities which are not recommended for use in generator sets, this is because they can lead to fouling and corrosion in generators[64]. The cleaning system consists of a series of filters and gas condition units, which cool down the syngas to ambient temperature and remove impurities from it to meet the fuel requirement of the generator unit. Among the impurities contained in syngas, tar is considered as the one with a severe damaging effect on engines. Most internal combustion engines (ICE) can run on syngas with tar content of 50-100 mg/Nm^3[67,68].

2.1.3 Generator Unit

The power generating unit is the part that converts the intermediate fuel (syngas) produced from the gasification process into electrical energy. This unit can be an ICE, a gas turbine, or a fuel cell. However, ICE is the most recommended for power generation from syngas due to their high contaminant tolerance as compared to the other conversion engines[69]. Table 2 presents different suppliers of gasifier systems and the characteristics of the systems.

2.2 Feedstock requirement for gasification

To achieve maximum and efficient syngas production, it is required that the feedstock meets the requirement of the gasifier. Even though the biomass requirement is based on the type of gasifier system and the manufacturer's specification, there are general requirements that apply to almost all downdraft gasifiers[62,64,70], which include:

• The diameter of the particle size must be higher than 5 mm but lower than 60 mm;
• Moisture content must not be more than 25%;
• Ash content must be lower than 8%;
• Lower heating value (LHV) must be higher than 13 MJ/kg;

3 Case study: Sawla-Tuna-Kalba district of Ghana

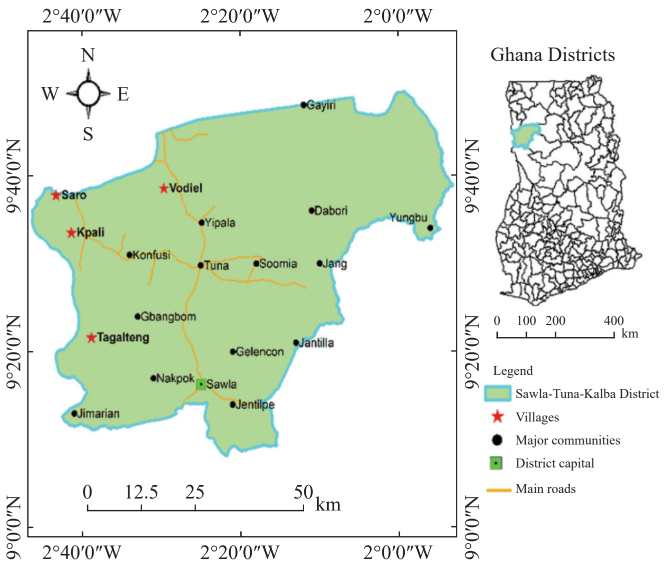
The Sawla-Tuna-Kalba (STK) district in the Savannah Region of Ghana, is selected as the location for the study. The district has a total land area of about 4173 km² and a population of 112 664 according to the 2020 Population and Housing Census (PHC) of Ghana[71]. The district's predominant economic activity is farming

Table 2 Advantages and disadvantages of different downdraft gasifier systems from various manufacturers

Manufacturer	Type of reactor	Cleaning system	Suitable biomass	Generation capacities available/kW	Efficiency ratio/kg·(kW·h)$^{-1}$	Advantages	Disadvantages
Ankur[93]	Downdraft (open top)	Wet	Rice husk, sunflower husk, peanuts shells, cashew shells, corncobs, sugarcane bagasse, coffee husk, barley husk, wood pellets, wood chips, and sorghum husks.	20, 50, 60, 100	1.2-1.4	Excellent biomass flexibility, acceptable price, high tolerance to fines.	Wet cleaning (use of process water), fair efficiency ratio.
Spanner Re[94]	Downdraft (throated)	Dry	Briquettes of diameter 30 mm, wood chips (G30), pellets and industrial pellets, coconut shells, macadamia nut shells.	35, 50, 70, 100	0.9	Compact solution (easy to install), high reliability, high efficiency ratio, dry cleaning	Fair biomass flexibility, fair tolerance to fines (<30%, <4 mm), high price
Fröling[95]	Downdraft (throated)	Dry	Wood chips (G30) and wood pellets.	46, 50, 56	0.8	Compact solution (easy to install), high reliability, high efficiency ratio, dry cleaning	Extremely high price, bad fuel flexibility, poor tolerance to fines
All Power Labs[96]	Downdraft (throated)	Dry	Wood chips, coconut shells, tree nuts shells (except almond and cashew shells).	25, 50, 130	1.0	Fair price, compact solution (easy to install), good efficiency ratio, and dry cleaning	Poor biomass flexibility, bad tolerance to fine particle, not suitable for pellets

Note: G30 (wood chips of an average size of 30 mm and moisture content of not more than 30%); Efficiency ratio is the ratio of biomass consumed by gasifier to the electrical energy produced measured in kilograms per kilowatt-hour electric kg/kW·h.

(crop and animal), with 97.1% of the population engaged in crop farming and 64.4% of the farmers engaged in animal farming. The private informal sector is the largest employer in the district, employing 96.9% of the population followed by the public sector with 2.0%. Out of the employed population, 82.3% are engaged in skilled agricultural, forestry, and fishery jobs, 7.9% are in craft and related trades, and 5.5% are in services provision. The district contributes about 58% of total crop production in the Savannah Region[72,73]. The energy statistics presented by the Energy Commission in 2020 indicated that the Savannah region has the lowest electricity access rate in Ghana, in terms of both population and household access of 60.1% and 59.5%, respectively[18]. When it comes to the Savanna region, the STK district has the lowest electricity access, with a rate of 31% for residential[74,75]. The administrative map of STK is shown in Figure 4.



Note: This map is produced and gazetted by the Sawla-Tuna-Kalba District Assembly (http://sawlatunakalbadistrict.gov.gh/map.html) and adapted as presented here by [76]

Figure 4 Administrative map of STK[76]

3.1 Agricultural production of STK

Data on types of crops cultivated, land size, crop yield, and animal population in the district were obtained from the Data and Statistical Department of STK District Assembly for 2014-2017. The average of this data is computed for crop and animal production, which is used in this study. According to the district report of STK, the major challenge faced by the agricultural sector is the decreasing crop yield due to soil nutrients depletion, which is caused by over-application of agro-chemicals, tree felling for fuel wood or charcoal, overgrazing, bush burning, and uncontrolled surface mining. Proper utilization of agricultural residues has the potential to mitigate all these challenges, while providing electricity to this highly unelectrified area.

3.2 Crop production

The percentage share of crops cultivation by land size and yields of the six major crops (yam, cassava, maize, millet, sorghum, and groundnut) in the STK district are presented in Figures 5 and 6 respectively.

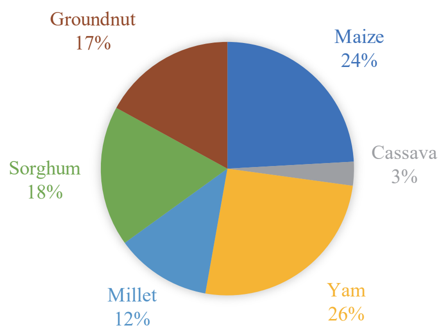


Figure 5 Percentage share of average crop cultivation by land size in the STK district

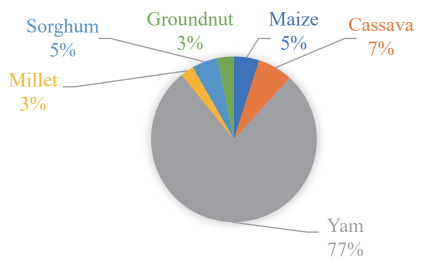


Figure 6 Percentage share of average crop production in the STK district

Yam occupies the largest share (26%) among six most important crops in the STK district as shown in Figure 5, while maize takes the 2nd largest share of planting land size in the district, i.e., 24%, followed by sorghum, groundnut, millet and cassava as 3rd, 4th, 5th, and 6th respectively.

In terms of production, yam production in the district is more than half (74%) of the total production of the six crops considered in the district as can be seen in Figure 6. Cassava production is the 2nd highest in the district, even though in terms of planting land size, is the least in the district (7%) (see figure 4). Both Figures 5 and 6 show that crops like yam and cassava have high yield since their percentage share of production increased as compared to their percentage share of cultivation.

3.3 Average animal production of STK

In terms of animal production, cattle rearing constitutes the largest share of animal production in the district (39%), followed by goats (37%) and sheep (24%) respectively, as shown in Table 3 and Figure 7. This implies, the district's most reared animals are ruminants which require some amount of crops residues as feed, since most of the farmers in this district are low-income earners and will find it difficult to afford exotic feed, hence rely on crop residues as feed for their animals.

Table 3 Average animal population of STK

Type of animal	Average population
Cattle	32 058.3
Sheep	19 591.7
Goat	30 453.7

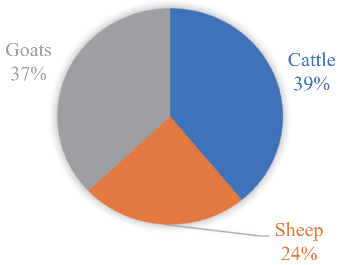


Figure 7 Percentage share by population of three most popular animals reared in the STK district

4 Method

The study used the average of crop planting land size and yield, and animal production figures of the STK district to estimate the residues potential, soil enhancement requirements, and animal demand for residues as feed. The residues-to-production ratio (RPR), moisture content (MC), and lower heating values (LHV) of crop residues were adopted from the method of the references[27,39,77]. Also, gasification technology was to analyze the electricity generation potential from crop residues after accounting for residues required for soil organic amendment and animal feeding. The study followed a methodological approach for estimating the residues demand for animal feeding, the residues demand for soil organic amendments through mulching, and the electrical energy potential from the residues. The steps followed are outlined in sections 4.1 to 4.4.

4.1 Residues demand for animal feeding

The dry matter consumption (DMC) of cows was estimated using the model developed by Uresk[78]. According to Uresk's model, the DMC of matured cattle of an average weight ranging from 363 to 636 kg can be estimated using Equation (1).

$$\mathrm{DMC} = 6.34 + 0.014 \times \mathrm{cowweight} \tag{1}$$

While the DMC of calf is estimated as:

$$\mathrm{DMC} = 2.95 + 0.02 \times \mathrm{calfweight} \tag{2}$$

The average weight of calf was found to be between 90 and 320 kg. The model of NRC[48] for DMC of small ruminants was adopted for the DMC of sheep and goats as shown in equation (3), in which BW represents the body weight.

$$\mathrm{DMC} = 0.04 + \mathrm{BW}_{\mathrm{actual}}\left(1.7 - \frac{\mathrm{BW}_{\mathrm{actual}}}{\mathrm{BW}_{\mathrm{matured}}}\right) \tag{3}$$

4.2 Residues demand for mulching

The amount of residues demanded for soil organic amendment through mulching was estimated using the United States Department of Agriculture (USDA) mulching guide[79]. According to the guide, the standard quantity of residues needed for mulching of cropland is in the range of 2.5-3.75 t/hm² Since tubers require more nutrients, a higher value of 3.5 t/hm² was assigned to tubers, while 3.0 t/hm² and 2.5 t/hm² were allocated to cereals and legumes respectively.

4.3 Electrical energy potential estimation

The electrical power potential (P_{Ei}) of a particular crop residue (C_{Ri}), considering its moisture content ($\mathrm{MC}_{\mathrm{Ri}}$) can be computed using equation (4)[80,81].

$$P_{\mathrm{Ei}} = A_{C_{\mathrm{Ri}}} \times \mathrm{LHV}_{C_{\mathrm{Ri}}} \times \beta_{C_{Ri}} \times \eta \times \left(1 - \frac{\mathrm{MC}_{\mathrm{Ri}}}{100}\right) \tag{4}$$

where, $A_{C_{\mathrm{Ri}}}$ is the amount of crop residue i available after taking out residues for animal consumption and soil enhancement and $\mathrm{LHV}_{C_{\mathrm{Ri}}}$ is the lower heating value. $\beta_{C_{\mathrm{Ri}}}$ is residues availability factor considering residues lost through transport, feedstock preparation, and pretreatment. It also accounts for secondary usage aside from animal feeding and soil enhancement like residue usage for traditional dishes such as wasawasa in the case of yam peels, traditional shelter in the case of millet and sorghum straw, and replanting in the case of cassava stalk. The values of $\beta_{C_{\mathrm{Ri}}}$ were chosen between 0.6 and 0.8[27]. Also, $\mathrm{MC}_{\mathrm{Ri}}$ is the moisture content of residues, η is the gasification efficiency, taken to be 20%, which is within the range of (15-22)% suggested by the reference[82]. The annual runtime of the plant (t) is taken to be 5500 h/a[42].

$$A_{C_{\mathrm{Ri}}} = \sum_{i}^{n} Y_{C_{\mathrm{Ri}}}(A_i)\mathrm{RPR}_{C_{\mathrm{Ri}}} - \sum_{i}^{n} S_{C_{\mathrm{Ri}}}(A_i) - \sum_{j}^{k} A_{\mathrm{DMC}j} \tag{5}$$

where, i and j are real numbers, while n and k are the maximum number of crop residues and animals, respectively. $Y_{C_{\mathrm{Ri}}}$ is the yield crop i per unit area, A_l is the total area planted by crop, $\mathrm{RPR}_{C_{\mathrm{Ri}}}$ and $S_{C_{\mathrm{Ri}}}$ are the RPR and the residues required per unit of area for soil fertilization of crop i. Also, $A_{\mathrm{DMC}j}$ is the amount of crop residues consumed by animal j.

4.4 Crop residues suitability and pretreatment required for gasification

The suitability of crop residues for usage is determined based on the general biomass requirement for gasification, such as biomass LHV, MC, size, and ash content as stated in Section 2.2. The LHV and the MC were the parameters used to determine the suitability as listed in Table 4. Ash content was not considered since it largely depends on the LHV. Pretreatment requirements such as drying (sun or thermal), chipping, pelletization, or briquetting are determined based on the MC, LHV, and the crop residues size as collected from the field[62,64,70]. MC and LHV are taken from the studies[27,39,77].

5 Results

5.1 Theoretical residue yield

Tables 5 and 6 give the theoretical crop residue yield and the theoretical DM yield respectively. The DM of crop residues is the actual amount available after taking out all moisture[83,84].

Table 4 Crop residues suitability and pretreatment required for gasification

Crop	Residues	MC/%	LHV	Suitability for gasification	Necessary pretreatment
Maize	Stover	15.02	17.71	Suitable	Chipping, pelletizing or briquetting
	Cob	8.01	19.32	Suitable	Chipping, pelletizing or briquetting
	Husk	11.23	17.22	Suitable	Chipping, pelletizing or briquetting
Cassava	Stem	20.00	17.50	Suitable	Chipping, pelletizing or briquetting
	Peels	20.00	19.41	Suitable	Chipping, pelletizing or briquetting
Yam	Straw	15.00	10.61	Suitable	Chipping, pelletizing or briquetting
	Peels	18.50	15.15	Suitable	Chipping, pelletizing or briquetting
Millet	Stover	17.55	15.51	Suitable	Pelletizing or briquetting
	Husk	11.60	14.83	Suitable	Pelletizing or briquetting
Sorghum	Stalk	16.23	14.91	Suitable	Chipping, pelletizing or briquetting
	Husk	2.74	16.50	Suitable	Pelletizing or briquetting
Groundnut	Straw	18.86	17.58	Suitable	Chipping, pelletizing or briquetting
	Pod	13.82	17.43	Suitable	Pelletizing or briquetting

Table 5 Theoretical residue yield of crops

Type of crop	Planting land size/hm²	Yield/ t·hm⁻²	Production/t	Residue type	RPR	$\beta_{C_{Ri}}$	Residue yield/t
Maize	10 141.330	1.22	12 372.43	Stover	1.15	0.8	11 382.630
				Cob	0.57	0.7	4936.598
				Husk	0.23	0.8	2276.527
Cassava	1279.047	13.05	16 695.82	Stem	1.24	0.6	12 421.690
				Peels	0.25	0.7	2921.769
Yam	10 777.730	17.56	189 256.90	Straw	0.50	0.8	75 702.750
				Peels	0.40	0.7	52 991.930
Millet	5149.440	1.25	6436.80	Stover	5.53	0.8	28 476.400
				Husk	0.29	0.8	1493.338
Sorghum	7535.133	1.63	12 282.27	Stalk	4.75	0.7	40 838.540
				Husk	0.14	0.8	1375.614
Groundnut	7163.000	1.11	7950.93	Straw	1.73	0.8	11 004.090
				Pod	0.35	0.8	2226.260
		Total Residues					248 048.100

Table 6 Theoretical DM yield from crops

Type of crop	Type of residue	MC/%	DM/t
Maize	Stover	15.02	11 523.44
	Cob	8.01	1991.74
	Husk	11.23	2284.46
Cassava	Stem	20.00	9937.35
	Peels	20.00	3178.88
Yam	Straw	15.00	64 347.33
	Peels	18.50	43 188.42
Millet	Stover	17.55	23 478.79
	Husk	11.60	1320.11
Sorghum	Straw	16.23	34 210.44
	Husk	2.74	1337.92
Groundnut	Straw	18.86	8928.71
	Pod	13.82	1918.59
	Total DM		207 646.22

From Table 5, a total of 248 048.10 t of residues can be theoretically produced from the six crops from the district which yields 207 646.22 t of DM (see Table 6). This represents a 16.3% reduction between the theoretical potential and the DM. This implies that 16.3% of the residues is moisture, which needs to be dried before use for power generation because moisture reduces the LHV of residues and subsequently causes the production of tars in gasification technology.

From Figure 8, yam wastes take 52% of all the six crop residues generated in the district. This implies that energy generation from crop residues in the district needs to consider yam wastes as an important biomass source. After yam residues, sorghum, millet, maize, cassava, and groundnut occupy the 2nd, 3rd, 4th, and 5th positions respectively, with maize and cassava having the same percentage residues yield (7%).

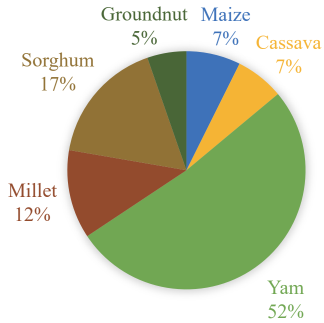


Figure 8 Percentage share of residues generation from crops

In as much as yam residues yield is high, comparing it (see Figure 8) with production (refer to Figure 6) indicates that the residues generation of yam is relatively low as compared to other crops due to the decrease in percentage share of residues yield (52%) in comparison with production (77%). Sorghum has a high residue yield since its percentage share increased by 10% as compared to production. This implies in an area where more sorghum is produced, more residues are likely to be generated. The same argument can be made about millet, whose percentage share also increased from 3% production to 12% residue yield (see Figures 8 and 9).

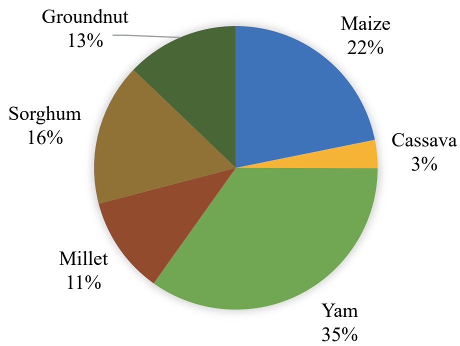


Figure 9 DMD Percentage share of soil as mulch for various crops planted at STK

5.2 Residues demand by animals

Since animal farming forms a major economic activity of STK, with about 64% of farmers engaged in animal farming, it is very important to consider animal consumption in the utilization of crop residues that serve as feed for animals, especially ruminants which are the main animals reared in the district. The results presented in Tables 7, 8, and 9 show the number of residues (dry matter) needed for feeding goats, sheep, and cattle in the district, respectively.

From the results, a total of about 26 830 t of DM is required for feeding all the sheep, goats, and cows in the district. The total amount of DM required by sheep, goats, and cows is about 12% of all the residues generated from the six crops considered in the study. Figure 10 shows that cows will demand the larger portion of DM (48%), followed by goats (31%) and sheep (21%).

Table 7 DMC of goats in STK

BW/kg	Total%	Number	DMC/t·a⁻¹
20	5	1523	171.13
40	15	4568	914.64
60	25	7613	2007.40
80	25	7613	2304.63
100	15	4568	1449.65
120	10	3045	936.71
140	5	1523	416.34
	Total	30 454	8200.51

Table 8 DMC of sheep in STK

BW/kg	Total%	Number	DMC/t·a⁻¹
40	5	980	196.14
60	15	2939	774.85
80	25	4898	1482.63
100	25	4898	1554.34
120	15	2939	903.92
140	10	1959	535.69
160	5	980	210.48
	Total	19 592	5658.04

Table 9 DMC of cows in STK

Category	BW/kg	Total%	Number	DMC/t·a⁻¹
Calf	90	5	1603	278.67
	200	15	4809	1223.20
	350	25	8015	2918.67
Matured	360	15	4809	2002.88
	500	25	8015	3913.07
	600	10	3206	1729.49
	650	5	1603	905.81
	Total		32 058	12 971.80

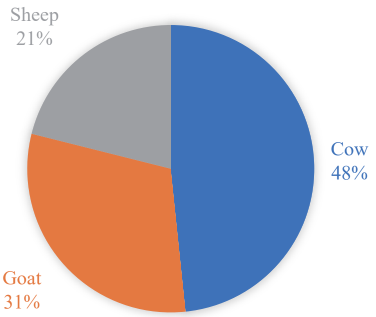


Figure 10 Percentage demand of crop residues by animal type

5.3 Residues demand for soil mulching

Crops residues play a key role in conserving the fertility of soil by serving as surface cover and subsequently decomposing to add nutrients back to the soil. Crop residues are noted to contain a higher percentage of organic carbon, which are very essential for improving the fertility of the soil. Mulching is one of the best ways to improve the fertility of soil organically, where the organic carbon component of crop residues is returned to the soil. Table 10 and Figure 10 give the amount of dry matter and the percentage share of the demand by crops planted in STK respectively. From the results, a total of 139 361.7 t of DM is required by all the crops in the district, representing approximately 1% of all dry matter generated from the six crops. From Figure 10, yam plantation will require the greatest share of dry matter for mulching (35%), while cassava will need the minimum share (3%) of total residues demand by crops.

Table 10 DMD of soil as mulch for various crops planted at STK

Type of crop	Planting Land size/hm²	Mulching rate/t·hm⁻²	Residues required/t
Maize	10 141.330	3.00	30 424.000
Cassava	1279.047	3.50	4476.663
Yam	10 777.730	3.50	48 499.770
Millet	5149.440	3.00	15 448.320
Sorghum	7535.133	3.00	22 605.400
Groundnut	7163.000	2.50	17 907.500
	Total		139 361.700

5.4 Technical residues and power generation potential from crops

The technical potential of residues as considered in this study refers to the quantity of crop residues available for power generation after accounting for the losses and demand by animals and soil. From Table 11, the technical residue potential of the selected crops is 194 066.4 t.

Table 11 Technical residue potential of crops at STK

Type of crop	Type of residue	Technical Residue ($A_{C_{Ri}}$)/t
Maize	Stover	10 576.94
	Cob	1688.84
	Husk	2007.30
Cassava	Stem	9688.92
	Peels	3099.41
Yam	Straw	59 048.15
	Peels	41 333.70
Millet	Stover	22 211.59
	Husk	1164.80
Sorghum	Stalk	31 854.06
	Husk	1072.98
Groundnut	Straw	8583.19
	Pod	1736.48
Total		194 066.40

The calculated potential is about 13% (1% for soil enhancement and 12% for animal feed) lower than the potential without considering the soil and animals. This confirms the findings of Ezealigo et al.[30] who predicted a reduction in the amount of residues for energy generation when other equally important environmental and socio-economic factors are taken into consideration. The electricity generation potential from the crops is presented in Table 12. From the results, a total of 592.17 MW·h of electricity can be generated from crop residues disregarding animal consumption and soil enhancement needs, while 461.89 MW·h could be generated from the residues, taking into consideration animal feed and soil enhancement. This represents a 22% reduction in power generation from crop residues, taking into account residues required for animal feeding and soil enhancement. The percentage share of power generation is presented in Figure 11.

From Figure 11, residues of yam contribute the largest share (45%) of total power generation, while groundnuts contribute the least share (6%). An increase in percentage from residues potential to power generation potential indicates a higher electrical energy yield from the residues and vice versa. From the results, maize had the highest increase from percentage share in residues potential to power one, while yam had the highest decrease as seen in Figures 11 and 10.

Table 12 Annual electricity potential of crop residues at STK

Type of crop	Type of residue	MC/%	LHV	Electrical potential without considering mulching and animal consumption/MWh	Electrical potential considering mulching and animal feeding/ MWh
Maize	Stover	15.02	17.71	40.82	31.84
	Cob	8.01	19.32	7.70	6.00
	Husk	11.23	17.22	7.87	6.14
Cassava	Stem	20	17.5	34.78	27.13
	Peels	20	19.41	12.34	9.63
Yam	Straw	15	10.61	136.55	106.51
	Peels	18.5	15.15	130.86	102.07
Millet	Stover	17.55	15.51	72.83	56.81
	Husk	11.6	14.83	3.92	3.05
Sorghum	Stalk	16.23	14.91	102.02	79.57
	Husk	2.74	16.5	4.42	3.44
Groundnut	Straw	18.86	17.58	31.39	24.49
	Pod	13.82	17.43	6.69	5.22
		Total		592.17	461.89

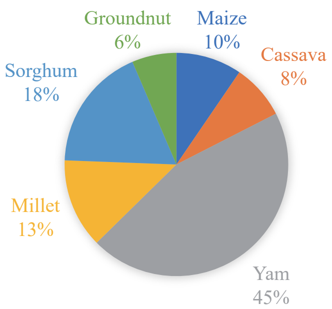


Figure 11 Crops potential percentage contribution to electricity generation from residues at STK

6 Discussion of results

The results presented in this study show that crop residue yield in the Sawla-Tuna-Kalba district is very high, which can be used for electricity generation. These findings relate well with other studies conducted in Ghana[19,39,84], which all obtained higher residues yield in different locations of Ghana, which is capable of supplying a greater share of the country's electricity demand. According to the study done by Seglah et al.[85], the Sawla-Tuna-Kalba district has the 4th highest crop residue potential for energy generation in the Savanna region. In terms of residue yield and energy generation in the district, yam plays a key role, capable of generating more than half of all the residues of the top six crops produced in the district. A similar to the study by Arranz-Piera et al.[86] estimated yam residues potential to be over 70% of all crop residues in Jaman Nkwanta, a rural community of the East Gonja district, located in the Savannah region. The low percentage share of residues yielded by crops like groundnut, cassava, and maize can be attributed to factors like the low cultivation of cassava and the lower yield of groundnut, and maize in the district.

Considering the residues demanded by animals in the district, the results show that animals require a significant portion of residues as feed, which when neglected in the potential estimation for energy generation, can be detrimental to animal production in the future. This is because the lack of available residues for animal feeding will imply farmers relying on exotic feed which will increase farmers' production cost, translating to a high cost of meat, since the cost of production will have to be incorporated into the sales of the animals. It is worth mentioning that subsistent animal farmers, mostly in rural communities usually rely solely on grasses and crop residues as feed for their animals and the complete removal of residues for energy generation can result in malnutrition and increased mortality in animal farming[87]. Also, the residue demand of soil for mulching is low, accounting for about 1% of the total residues considered in this study. Even though this percentage appears to be low, ignoring it can impact crop yield significantly, hence must be taken into consideration. Kassam et al.[46] stated that less than 30% of cropland cover violates sustainable agricultural practice and must be considered in all forms of soil organic cover removal including crop residues removal to prevent soil nutrients depletion. A study by Bationo et al.[88] and Powell et al.[89] stated that incorporating crop residues into low-nutrient soil types like sandy soil can improve the soil's organic matter content, PH level, exchangeable cations which leads to high crop yield when crops are planted on the soil. Lands in the northern part of Ghana which include the Sawla-Tuna-Kalba district in the Savannah Region are characterized by low fertility[90]. This implies removing all residues from land cover for energy purposes can lead to poor soil health and reduced crop yield[91]. This can further abase the already low standard of living of the people in the district since low crop yield leads to food shortage and increasing price of food which has the net effect of causing hunger and poverty[87,92]. Therefore, considering these two important parameters (animal consumption and soil cover) in residue estimation for energy generation will go a long way to promote both agriculture and energy sustainability which will be beneficial to the planet, people, and profit.

The results of the technical residues and electricity generation potential from the crops suggest that the residues can still present a good potential for electricity generation even after considering other parameters such as the ones used in this study. The impact of the 13% reduction in residues yield due to animal consumption and soil enhancement demand is minimal in the electricity generation potential of residues. It resulted in a 22% reduction in electricity generation potential, which is allowable since most residue generation potential estimations have found the potential of crop residues to exceed the amount required for power generation. Doe et al.[19] found that the Brong Ahafo, now divided into Bono, Bono East, and Ahafo regions can supply about 220% of their electricity demand from crop residues. While the Northern, Upper West, and Upper East regions can supply 420.0%, 241.9%, and 665.5% of their electricity demand from crop residues produced in the regions. Nevertheless, increased awareness of bioenergy potential can lead to a major diversion of residues which can affect areas with lower residue potential and higher animal rearing.

7 Conclusions

The global desire to achieve climate and energy sustainability targets has resulted in an increased awareness of renewable energy generation potential and the creation of technologies that can sustainably generate energy from renewables to meet the growing energy demand of the globe while keeping emissions at the minimal level of below 1.5°C as compared to a pre-industrial age, which is in line with the Paris Agreement. Renewable energy sources like solar, biomass, and wind for energy generation are gaining great interest in research and industry. Among these renewable energy sources, biomass seems to be gaining great interest due to its low intermittent nature and its potential to create local jobs as compared to other renewable sources. Crop residues have become very popular among the several biomass sources due to their abundant nature, especially in agricultural areas where crop farming is the main source of income for the majority of the inhabitants.

This study estimated the crop residue potential for electricity generation using gasification technology, taking into consideration the quantity of residues required for animal feeding and soil enhancement in the Sawla-Tuna-Kalba district of Ghana. The results showed that there is a great potential for electricity generation from crop residues in the district, even after accounting for residues required for soil organic amendment through mulching as well as the residues required for feeding animals in the district. It was found that about 1% of residues generated from the crops considered in the study will be required for soil enhancement, while 12% of the residues will be needed for feeding animals. Considering animal consumption and soil enhancement requirements in electricity demand estimation resulted in a 22% reduction in electricity generation as compared to their neglect.

It is concluded that considering animal and crop demand for residues is crucial in energy potential estimation from crop residues and ignoring these can lead to a negative impact on crop yield and animal production. Therefore, awareness of soil enhancement needs and animal consumption of residues in energy estimation potential is very important, and being neglected can affect agricultural productivity as well as animal production in the near future. Therefore, it is recommended that, to achieve sustainable energy and food nexus, countries must begin to include acceptable residues removal rate in their agricultural development policies, with this also clearly indicated in the bioenergy development plan of the countries. This will avoid the situation where residues removal for the purposes of energy violates the principle of conservation agriculture.

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