

Prospects of Bioenergy Production for Sustainable Rural Development in Ghana

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Abstract

Biomass supplies about 80% of the energy needs for cooking and heating in rural Ghana. It is predominantly used in traditional and inefficient forms (firewood and charcoal), which presents environmental and health concerns. In order to better the living standard in rural Ghana, efforts must be made to provide modern energy services. Most rural communities in Ghana are so remote that an extension of the national grid is uneconomical, hence biomass electricity provides a viable alternative. Biomass is pivotal to the socio-economic development of rural Ghana due to its easy accessibility and enormous potential in the production of varied energy forms. In this paper, a comprehensive review of biomass resources, biomass energy conversion technologies and bioenergy production potential for rural development in Ghana is provided. The most important feedstock from an energy perspective was found to be crop residues. Based on 2017 statistics, Ghana has a theoretical potential of 623.84 PJ of energy from agricultural crop residues and 64.27 PJ of energy from livestock production. Evidence from literature suggests that biomass gasification is the best conversion technology to expand electricity access rate for rural households in Ghana. The paper concludes that although ample biomass resources exist, cocoa pod husks (CPH) which is very common in rural Ghana can be pelletized and used as feedstock for rural power generation systems.

Keywords

Biomass, Bioenergy, Biofuel, Feedstock, Conversion Technologies

1. Introduction

Ghana's energy sector faces two main challenges; the inability to provide decent power supply, and the upsurge in the use of woodfuel as the principal cooking fuel for families with no access to modern cooking fuels [1]. Currently, approxi-

mately 84% of urban households are grid-connected [2] whereas less than 30% of the rural population are connected to electricity [3]. Most rural communities in Ghana are very deprived with limited access to potable water, basic sanitation and healthcare facilities due to inadequate energy services. The total population below the poverty line in Ghana is about 24.2% with rural poverty almost 4 times as high as urban poverty [4] [5] [6]. Determinants such as cultural inclination, economic considerations and resource accessibility necessitate the use of more biomass resources compared to other conventional energy reserves in rural communities [7]. In Ghana, biomass provides a large proportion of energy services but in overly unproductive forms, notably firewood and charcoal for domestic purposes [8]. The current inefficient application of biomass in conventional form raises serious environmental and health concerns including indoor air pollution. The sourcing strategy for firewood or wood for charcoal production apart from being unsustainable, also puts Ghana's dwindling forest under extreme stress and could subsequently lead to far-reaching deforestation, with severe ramifications on climate change, crop production and water resources [9]. Modern application of biomass such as biofuel development is gradually gaining ground in Ghana and efforts are being made to control woodfuel consumption and indoor air pollution with the introduction of improved cook stoves in the country [10]. Notwithstanding, Ghana is far from harnessing half the energy potential of the country. The electricity generation mix in Ghana predominantly comes from hydro and thermal sources [11]. At the end of 2016, 57.21% of Ghana's electricity supply was from thermal power sources and 42.79% from hydropower stations. Renewable generation sources only contributed an infinitesimal 0.2% to the generation mix [12]. The power plants in current use are unable to reach full power capacity due to fuel supply limitations. The insufficient and unreliable rainfall patterns due to climate variability have also resulted in low water influx into the hydroelectric power dams, consequently leading to the dominance of thermal power usage in Ghana. Other challenges such as high levels of transmission losses and the remoteness of some rural communities have necessitated the need to decentralize the power supply in Ghana [3] [10] [12]. Currently, more than 50% of rural communities without access to electricity live in communities with a population of less than 500. Since there are no indications of these rural communities increasing in population any time soon, chances are that these rural communities would never be connected to the grid by Ghana's current electrification criteria [2]. Rural communities far from the national grid are therefore principal candidates for stand-alone and mini-grid systems as they have been found to be an economical means of connecting the rural populations instead of main grid extension [13]. As most of these rural communities in Ghana are involved in agriculture and produce huge amounts of biomass resources, bioenergy development could be promoted as an energy security and rural development strategy [14]. Biomass resources used in the production of bioenergy typically enhance regional energy access and reduce dependence on fossil fuels.

Bioenergy can also strengthen the forestry and agriculture sectors of an economy while increasing the use of renewable resources as feedstocks for a wide range of industrial processes. Biomass utilization helps to mitigate climate change, reduce risks to life and property, and helps provide a secure, competitive energy source which is sustainable. Bioenergy provides opportunity for social and economic development in rural communities such as safe management and disposal of waste, clean electric power generation, alternative source of cooking fuel, rural economic upliftment, decentralized power generation, job creation and alleviation of poverty. Without a shadow of doubt, provision of sustainable energy services for food and medical refrigeration facilities, water pumping for irrigation, water purification for clean drinking water, cooking and general lighting as well as information/communication technologies (ICTs) would improve the quality of life of rural inhabitants to a large extent.

The objective of this paper is therefore to review available biomass resources, biomass energy conversion technologies and bioenergy production potential for rural development in Ghana. Although other researchers like Duku *et al.* [15] and Mohammed *et al.* [7] have studied biomass resources in Ghana, both studies are dated and hence do not reflect on the current situation in the country. Besides, this review paper is focused on rural development and hence extensive on biomass conversion technologies unlike the aforementioned research which considers urban categories of biomass resources such as municipal solid waste. It is anticipated that the outcome of this review will provide a baseline for further research on the application of biomass conversion technologies on specific biomass resources.

2. Literature Review

2.1. General

Biomass is any material of contemporary biological origin through which different forms of energy or chemicals can be derived [16]. Biomass contains stored energy from the sun and hence can be described as a stored form of solar energy [17]. Biomass releases heat during combustion and could be combusted instantly as energy or transformed to biofuels or biogas for other uses [18]. Biomass comes from a number of sources including waste and residues. During processing of rice for example, both straw and rice husks are generated which can be easily transformed into energy. While maize and sugarcane harvesting produce significant quantities of biomass in the likes of cob and bagasse, coconut harvesting and processing produce piles of shell and fibre for energy production [19].

2.2. Biomass Resources in Ghana

Ghana's economy is traditionally oriented towards agriculture and hence produces significant amount of biomass materials. The most easily accessible biomass resources are derived from agriculture, forestry and industry. Wood from

natural forests, forest plantations and residues, agricultural residues, green waste, agro-industrial waste, animal waste, industrial waste, and food processing waste are all examples of biomass resources [20]. The importance of biomass is more predominant in rural communities in Ghana where most of the primary energy needs are provided by biomass, although in pretty inefficient manner such as firewood and charcoal [8]. Firewood is a major cooking fuel for about 80% of the rural inhabitants in Ghana. A 2018 report by the Energy Commission of Ghana reveals that woodfuel consumption in Ghana has increased approximately 6% from 2517.8 kilo tonnes in 2008 to 2829.4 kilo tonnes in 2017 [21]. Biomass resources occupy 20.8 million hectares of Ghana's surface area and supply up to 60% of the energy consumed in the country [22]. Biomass resources in Ghana include crop and crop residue, wood and wood residue, municipal solid waste, animal waste, food-processing waste, aquatic plants and algae. Due to the economic and environmental relevance of biomass resources, they have competing uses [15]. The Ghana Energy Commission acknowledges that woodfuel consumption in Ghana was second to petroleum at 40.5% in 2017, making woodfuel a dominant primary energy source in Ghana today [20]. Ghana's agricultural sector is made up of many scattered peasant producers who employ manual cultivation methods and depend mainly on rainfall for irrigation. Nonetheless, more than 90% of the food requirements in the country are provided by these small-holder producers. Although crop production is impeded by land degradation, improper field preparation, use of low quality breeds, ineffective seed nurturing and allocation, and lack of storage infrastructures, Ghana still produce major crops such as maize, sorghum, groundnut, rice, cassava, yam, plantain, cocoa, rubber, coconut, oil palm, pineapple and coffee [15].

2.3. Energy Crops in Ghana

Energy crops like maize, sugarcane, cassava and sweet sorghum are suitable for ethanol production whereas coconut, sunflower, jatropha, and palm oil are great feedstock for biodiesel production [22].

Maize is grown in almost every part of Ghana, hence one of the most predominantly grown crop in the country. In 2017, about 1.96 million-tonnes of maize was harvested over 1,000,000 ha of land [23]. Maize is the second largest commodity crop after cocoa and grows across a broad range of agro-ecological zones [24].

Sugarcane production has gone up steadily from 149,584 tonnes in 2015 to 151,762 tonnes in 2017 [23]. However, production is still relative low compared to other crops like cassava, maize, oil palm and cocoa. Sugarcane molasses contain 1688 g/l total sugars and produce high yield of ethanol [25].

Cassava production in Ghana has seen a massive increase from 11.35 million tonnes harvested in 2008 to 18.47 million tonnes in 2017 [23]. The increase in cassava production can partly be attributed to the Government's Special Initiative on cassava production and the influx of new high-yielding breeds in the

country. Cassava is currently cultivated in eight of the ten regions in Ghana [15] thus making it a potential feedstock for ethanol production.

Jatropha curcas has enormous potential for biodiesel production in Ghana. The crop has received substantial capital input from both private and government sectors. A National *Jatropha* Plantation Initiative (NJPI) was introduced in 2006 to bolster *jatropha* plantation on marginal lands. Currently, over 20 private companies (mostly foreign) have cultivated acres of *jatropha* plantations across Ghana [26]. Over 1500 ha of *jatropha* plantation has been cultivated under the supervision of organizations like UNDP, New Energy, *Jatropha Africa Ltd.*, AngloGold Ashanti Ltd and Valley View University. This puts Ghana at an advantage as a potential leader in biodiesel production from *jatropha* in the sub-region [7]. *Jatropha* is drought-resistant, poses no food-fuel conflict and its seed contain 40% - 60% oil [27].

Palm oil plantations cover about 365,000 ha in Ghana and are usually situated in the rainforest and deciduous zones of the country. The quantity of oil palm produced in Ghana in 2017 was about 2.5 million tonnes [23]. Palm oil production is executed in different scales like peasant farms, and medium to large-scale plantations [28]. Oil palm is a leading cash crop in the rural communities of the forest belt of Ghana and provides a number of jobs for rural households especially women [29]. Oil palm has a good proportion of palmitic and oleic acids, making it the most preferred feedstock for bio-diesel generation. Oil palm bio-diesels have comparable properties to petro-diesels [30].

Coconut is one crop that is littered along the coastal belt of Ghana. In 2017, approximately 383,960 tonnes of coconut were harvested across an area of 71,288 ha in Ghana [23]. The Coconut Sector Development Project initiated between 1990 and 2005 was to harness the economic potential of coconut plantations and to help in the fight against the lethal yellowing disease which affects most coconut plantations along the shores of Ghana. The project paid off handsomely with about 800 ha of coconut farms being restored [15]. Coconut is an oil-bearing crop with enormous potential for biodiesel production.

Cocoa is not a traditional energy crop but due to its enormous economic value as the major export of Ghana, it is produced in large quantities and over considerable areas of land. In 2017 for instance, 883,652 tonnes of cocoa beans was produced across 1,690,237 ha in the country. Studies such as [31] and [32] have proved that bio-ethanol, bio-oil and bio-gas can all be produced from cocoa pod husk and hence an important energy crop.

Groundnut farming is a major agricultural activity for the people of the northern and parts of Brong Ahafo regions of Ghana [33]. It is entirely a rain-fed cropping system grown on both commercial and subsistence basis [34]. Ghana produced 420,000 metric tonnes of groundnut over 338,000 ha in 2017. Groundnut oil has a low content of saturated free fatty acid and hence suitable for the production of biodiesel [35].

Rice is regarded as a central staple in parts of Ghana and its demand keeps soaring especially during various festivities. Rice production covers approxi-

mately 258,587 ha. In 2017, Ghana produced 721,465 tonnes of rice. With current support policies such as Planting for Food and Jobs, and the One district-One factory, rice production is expected to hit an all-time high in the coming years [36]. Rice processing produces both husk and straw which are important feedstock for ethanol production.

Sorghum is the third most produced cereal crop in Ghana after maize and rice. It is grown mostly by peasant farmers with an average acreage of less than 2 ha and largely for domestic consumption (food and beer) [37]. Ghana produces 230,000 tonnes of sorghum on an average land holding of 220,681 ha annually. Sorghum has a short growing period, high levels of sugar and withstands adverse conditions well. It is therefore seen as one of the most attractive feedstock for ethanol production [38].

Cocoyam production in Ghana is done mainly by subsistence farming with farmlands measuring between 0.2 ha and 0.5 ha [39]. Cocoyam production sits at 1,200,244 tonnes annually with an average yield of 6.5 tonnes per hectare. Braide and Nwaoguikpe [40] produced a maximum ethanol yield of 12.9% from cocoyam fermentation while Adelekan [41] generated an ethanol yield of 139 litre/tonne from cocoyam.

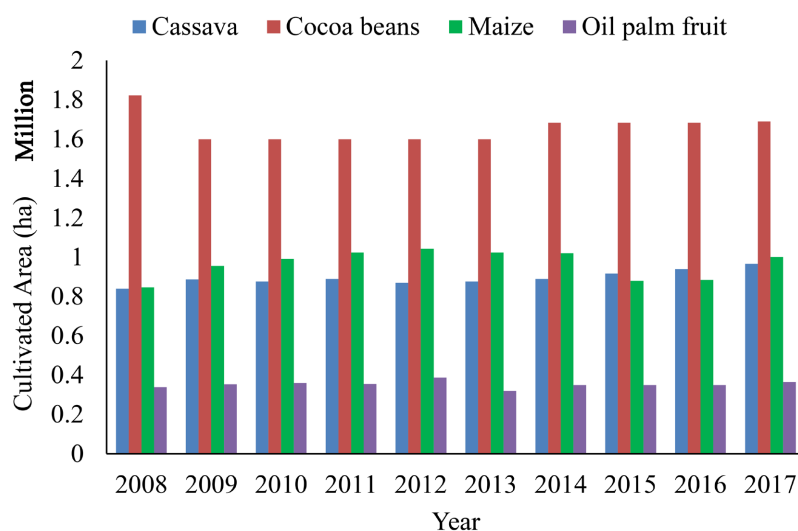
Yam is the third most essential energy source in the Ghanaian diet and is produced nation-wide. It grows well in places where the annual rainfall pattern is steady over six to seven months of the farming season at 1000 - 1500 mm [42]. 7,952,750 tonnes of yam were produced over an area of 465,906 ha in 2017 which accounts for an average yield of about 17 tonnes per hectare. Yam like other starchy crops is a good substrate for ethanol production.

Plantain is an important food crop for many rural dwellers in the southern part of Ghana and over 90% of its cultivation belongs to smallholder farmers. While the plantain fruit itself is consumed in many households, the non-edible parts such as the leaves are used as fodder for animals or as wrapper for food and hence an under-utilised resource [43]. Ghana produces 4,050,630 tonnes of plantain annually with an average yield of about 11 tonnes per hectare. Plantains are potential feedstock for both liquid and gaseous biofuels due to their generous amount of starch and ability to ferment readily [44].

Table 1 shows the major agricultural crops produced in Ghana and the areas allocated for their cultivation. Cocoa beans, maize, cassava and oil palm are potential bioenergy feedstock that occupies the biggest land masses in Ghana. Other bioenergy crops like coconuts and sugarcane are cultivated on smaller land masses. Based on acreage used in cultivation, four crops (cocoa, maize, cassava, and oil palm) were identified as potential biofuel feedstock that could be exploited instantaneously. Trends in production pattern and land allocation have been considered for the 4 major crops over the last 10 years. Cocoa beans are the most dominant crop in Ghana for cultivated areas followed by maize and cassava (**Figure 1**). Based on crop production trends, cassava has had the biggest output in the last 10 years with oil palm and maize closely behind (**Figure 2**).

Table 1. Harvested areas and quantities of major crops produced in Ghana, 2017 [23].

Crop type	Production 2017 (t)	Area harvested 2017 (ha)	Yield (hg/ha)
Cassava	18,470,762	965,514	191,305
Cocoa beans	883,652	1,690,237	5228
Coconuts	383,960	71,288	53,860
Groundnuts	420,000	338,000	12,426
Maize	1,965,000	1,000,000	19,650
Oil palm fruit	2,469,763	364,595	67,740
Rice	721,465	258,587	27,900
Sorghum	230,000	220,681	10,422
Sugar cane	151,762	6108	248,451
Cocoyam	1,200,244	183,960	65,245
Yams	7,952,750	465,906	170,694
Plantain	4,050,630	368,505	109,920

**Figure 1.** Pattern of cultivation for chosen crops in the last 10 years. Data source [23].

Generally, there has been a reasonably even trend in land use pattern and production trend over the last decade with minimal upsurge and downturn.

In summary, there is tremendous bioenergy production potential from energy crops in Ghana with maize, cassava, sugarcane and sorghum as potential feedstock for bio-ethanol production. Oil-bearing energy crops such as sunflower, groundnuts, oil palm, coconut, jatropha and soybeans are also gaining attention as feedstock for biodiesel production. There is however limited research on the production of bio-ethanol and bio-diesel in Ghana. The food-fuel competition remains the major hurdle in any biofuel production breakthrough. Nevertheless, jatropha and other non-food energy crops like switchgrass, elephant grass, and

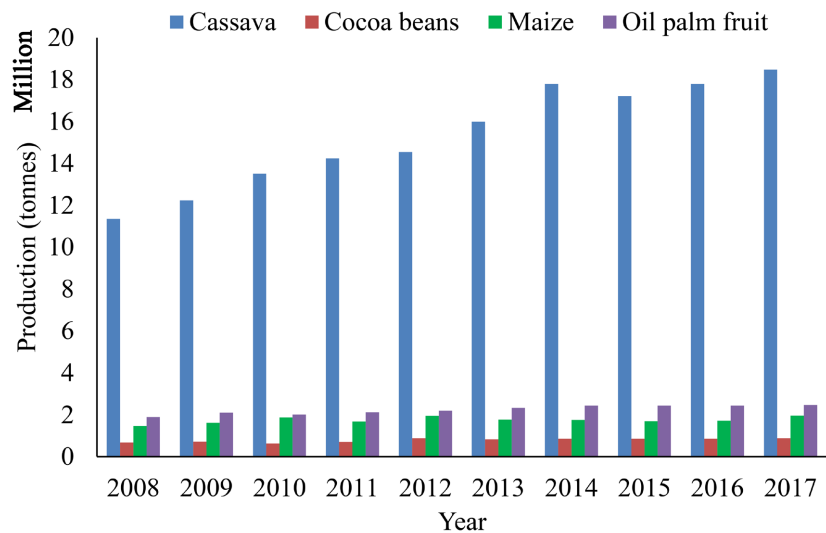


Figure 2. Production pattern of some major crops in Ghana. Data source [23].

guinea grass which are already growing on marginal lands in Ghana can be promoted for bioenergy generation [45]. For instance switchgrass, elephant grass, and guinea grass can be exploited in ethanol, heat, and power production. Along the coastal belts of Ghana, there are also species of microalgae and aquatic plants such as diatoms, cyanobacteria, green algae and red algae that can all be exploited in biofuel production.

2.4. Agricultural Crop Residues

Agricultural crop residues fall into two main categories: crop residues and agro-industrial by-products. While crop residues are the leftover materials on the farm after the crops have been harvested, agro-industrial by-products are derived during the processing of crops in industries [15]. Ghana produces crop residues such as rice straw, maize/corn stalk, and cocoa pod husk. Meanwhile, agro-industrial by-products in Ghana include corn cob, cocoa husk, sugarcane bagasse, coconut shell and husk, rice husk, oil seed cake, and oil palm empty fruit bunch (EFB). The harvesting and processing of maize produces major residues such as stalk, cob and husk which can be used for biofuel production. While sweet sorghum produces a sugar-rich stalk for ethanol production, coconut produces husk and shells, and sugarcane produces bagasse which is all suitable for the production of biochar. Oil palm produces empty fruit bunches (EFB), shells and fronds which compete as fertiliser, and as feedstock for activated carbon and mulching. Coffee husk which is a residue from coffee processing can be used in biochar production, as fertiliser or for electricity production [15] [46]. Rice husk and straw are also potential feedstock for biofuel generation that are virtually unutilised in Ghana. Traditionally, crop residues are burnt on the farms as a pest control mechanism while others are used as substitutes for wood fuel. Cocoa is the lifeblood of Ghana's economy and its production occurs in forested areas. The main residue generated from cocoa production is the co-

coa pod husks (CPH) which at present are left on the farms to decompose. Recent studies conducted by Syamsiro *et al.* [47], Tsai *et al.* [48] and Adjin-Tetteh *et al.* [49] reveal that CPH has a relatively high energy density of 17 - 18 MJ/Kg. Given the high abundance of CPH in rural Ghana and the fact that cocoa is a major export of the country, any attempt to use CPH for energy generation will not only help to reduce power crisis but also boost cocoa production in Ghana. According to Adjin-Tetteh *et al.* [49], factors such as cultivation methods, environmental influences and differences in soil contaminations can impact greatly on the energy density of CPH. Hence, the thermal properties of CPH samples from different localities need to be determined to inform decision on which samples have the highest calorific values and where operational conditions need to be optimized.

The trunks, leaves, stems, straws, stalks and peels of cassava, yam and plantain are also potential bioenergy feedstock that has not yet been fully exploited. **Table 2** gives a general overview of the energy potential of crop residues generated in 2017. Approximately 50 million tonnes of crop residues were produced, which is equivalent to a theoretical potential of 623.84 PJ of energy. Theoretical potential presumes that all the residues used in the calculation are available. Practically, not all generated residues are available for energy production due to a number of reasons. Firstly, some of the residues may be left on the farmland intentionally to mulch and also for re-fertilisation. Secondly, there may be practical difficulties in collecting some field residues due to bad road conditions notably when it comes to peasants and their farm locations.

In other words, it is not possible for all residues generated to be collected for energy production due to technical hindrances and competing uses such as animal feed, fertiliser, and cooking. Utilisation of all these residues in bioenergy production can potentially have adverse impacts on soil fertility [50]. Hence, it is expedient to assume recoverable percentage in order to get the technical potential of generated residues. At 60% recoverable rate of crop residues, Ghana has a technical energy potential of 374.30 PJ. There is a huge difference in estimated energy potentials of crop residues between our paper and that of Duku *et al.* [51] and Mohammed *et al.* [9] who estimated 75.20 PJ and 91.60 PJ respectively. The differences in estimated potential may be attributed to the number of crops considered. While the current paper considered 15 crops, the previous research only considered 8 - 9 crops and left out staple Ghanaian food crops like cassava and yam which have enormous energy potentials as per **Table 2**.

2.5. Forest Resources

The forest sector of Ghana is very diverse with both open and closed forest as well as semi-deciduous and wet evergreen ones. Ghana's forest resources have gradually been diminished by needless logging, bad farming practices, bush fires, mining, quarrying, settlement and migration to forest areas [15] [53] [54]. It is therefore preminent that Ghana explores its potentials for residue-based bioenergy

Table 2. The energy potential of crop residues in Ghana.

Crop	Annual production (10 ³ t) ^a	Residue type	Residue to product ratio (RPR) ^b	Total residue produced (10 ³ t)	Lower heating value (MJ/kg) ^c	Residues Energy potential (PJ)
Cassava	18471	Stem/Stalk	1.24	22,904.04	17.50	400.82
Cocoa, beans	884	Husk	1.00	884	15.48	13.68
Coconut	384	Husk/Shell	0.54	207.36	14.71	3.05
Coffee, green	0.73	Husk	2.1	1.53	12.56	0.02
Groundnut	420	Husk/Shell/Straw	2.08	873.6	17.50	15.29
Maize	1965	Stalk/Husk/Cob	0.63	1237.95	18.08	22.38
Millet	167	Stalk	5.53	923.51	15.51	14.32
Oil palm fruit	2470	EFB/Kernel Shell/Fibre	0.44	1086.80	15.23	16.55
Plantain	4051	Trunk/Leaves	0.50	2025.50	15.48	31.35
Rice, paddy	721	Straw/Husk	3.28	2364.88	14.30	33.82
Sorghum	230	Stalk	4.75	1092.50	17.00	18.57
Sugarcane	152	Bagasse	0.2	30.4	13.38	0.41
Sweet potato	146	Straw	0.50	73	10.61	0.77
Cocoyam	1200	Straw	0.50	600	17.70	10.62
Yam	7953	Straw	0.50	3976.50	10.61	42.19

^aAnnual crop production in 2017 [23]; ^bResidue to product ratio (RPR) based on [52]; ^cLower heating value based on [7] [51] [52].

in order to reduce the stress on our forest reserves. Forest biomass in Ghana is predominantly woodfuel, used mainly for cooking in rural households. Approximately 90% of the woodfuel used in Ghana come from the natural forest and the savannah woodlands. The other 10% comes from wood waste like logging and sawmilling waste [55] [56]. Wood residues are generated as co-products of loggings and timber processing. Hence there are two categories of forest residues namely: logging residues and wood processing residues [8]. Logging residues include off-cuts, stumps, sawdust etc. and the average logging recovery in Ghana is approximately 75%. Wood processing residues on the other hand include scrapped logs, bark, sawdust, off-cuts, sander dust, chips, trim ends and shavings [51]. Wood processing residues are produced via sawmill and plywood mill processing operations. Wood residues are mostly available at centralized locations and hence fairly easy to recover significant amounts for use as feedstock [8]. Estimate by Kemausuor *et al.* [52] place bioenergy potential from wood residues at 4.8 PJ which can reduce Ghana's dependence on firewood and charcoal as cooking fuel.

Timber logging in Ghana generates about 1.4 million cubic metres of logging

residues annually. These residues include edgings, offcuts, peeler cores, slabs, sawdust and plywood industry residues. A number of self-employed carpenters who operate their mini-furniture mills are spread all over the country. There are also designated locations in the country where the quantities of residues are higher due to wood processing mills sitting next to each other on a large stretch of land. Activities such as road construction, and forest clearing for mining and agricultural purposes also generate forest biomass. Timber logs and uprooted trees that are of lesser economic value as well as their residues are potential biomass resources in Ghana [56].

2.6. Animal Waste/Manure

Animals produce a lot of waste which is generally referred to as livestock manure. Animal waste such as dung and slaughter waste are suitable feedstock for biogas generation. When the waste from livestock production is treated by anaerobic digestion, it improves sanitation by diminishing the amount of pathogens in the substrate [57]. The process also benefits farmers as it provides an opportunity for secondary income generation via biogas generation for commercial purposes. Livestock production in Ghana contributes a substantial amount of biomass in the form of manure, however factors such as the amount of forage eaten, the quality of the forage, the physiological conditions (pregnant, on heat, sick, etc.), the type of animal, and the body weight of the animal determines the amount of manure they produce [4] [58]. The total amount of livestock manure can be calculated via the number of livestock, average annual manure production per livestock, and the dry manure fraction. Numerically, cattle, sheep, goats, pigs and chicken are the most popular livestock types in Ghana [59] [60]. **Table 3** shows that small quantities of waste are generated per chicken, however generous amount of manure is expected from large production quantities. Cattle by virtue of their big body sizes generate the highest amount of excrement per head as well as the highest total energy potential among livestock in Ghana. Livestock production in Ghana could generate a total energy potential of

Table 3. Livestock types and their total energy potential in Ghana.

Livestock type	Production (1000 head) ^a	Dry dung output (Kg·h ⁻¹ ·d ⁻¹) ^b	Total annual dung output (tonnes)	Energy value (GJ·t ⁻¹) ^c	Total energy potential (PJ)
Cattle	1764	1.80	1,158,948	18.5	21.44
Chickens	74,478	0.06	1,631,068	11.0	17.94
Goats	6400	0.40	934,400	14.0	13.08
Pigs	742	0.80	216,664	11.0	2.38
Sheep	4612	0.40	673,352	14.0	9.43
Total					64.27

^aProduction based on [61]; ^bDry dung output [7]; ^cEnergy value [7].

64.27 PJ. This is comparable to the estimated theoretical potential of 47.59 PJ documented by Mohammed *et al.* [9]. Similar to crop residues, not all produced manure are practically attainable. Cattle farmers in Ghana feed their cattle by open grazing in the fields thereby making the excrement they generate at munching uncollectible. Cattle are also used in farmlands for various field operations such as ploughing. During such activities, their excrement may not be reachable. Hence, at a recoverable rate of 50%, there is still a technical energy potential of 32.14 PJ. For the purposes of modern energy generation, this is a huge potential that can be exploited in biogas generation. It is promulgated that in India, a 2 cubic meters (m³) domiciliary biogas plant can be fed by five cattle at most, hence a small to medium livestock farm would be adequate for biogas generation in a Ghanaian household [58]. Animal dung especially dried dung is competitive with wood as fuel and can be modified into fuel pellets for domestic cooking [17].

3. Assessment of Biomass Energy Conversion Technologies

Biomass can be transformed into several forms of energy by different conversion technologies. Generally, the choice of biomass conversion technology depends on the type, quantity and characteristics of biomass feedstock available, infrastructural requirements, environmental standards, economic conditions, project-dependent factors and end-use applications [7] [62]. However, it is usually the end-use application (manner in which the energy is needed) and the biomass feedstock availability (type, quantity and characteristics) that determine the biomass conversion technology and process pathway. Thermo-chemical conversion technologies favour biomass feedstock with lower moisture content while biochemical conversion technologies are preferable for higher moisture content feedstock [63]. Anaerobic digestion, gasification, direct combustion, pyrolysis, fermentation, liquefaction, and pelletization have great potential for bioenergy conversion in Ghana.

3.1. Anaerobic Digestion

Anaerobic digestion breaks down biological materials by the action of micro-organisms to produce biogas and digestate in the absence of oxygen [64]. Anaerobic digestion is commercially used for treating organic wastes with high moisture content and waste waters [65]. Gas produced by anaerobic digestion can be used explicitly for cooking and heating or for electricity generation by secondary conversion. Essentially, any biomass apart from lignin can be used in biogas production. This is inclusive of animal and human waste, industrial processing by-products, landfill materials, sewage sludge, and crop residues. Biogas production from animal waste has environmental and health benefits. Aside avoiding greenhouse gas impacts by trapping and utilizing methane, germs that breed from manure are eradicated by the temperature conditions in the bio-digester and the digestate is a good source of fertilizer [65]. Anaerobic

digestion is a rapidly thriving bioenergy technology in Ghana with flexibility in design, dependent on the context within which it is intended to operate. Approximately 400 biogas digesters have been built in Ghana, predominantly using the fixed-dome, floating drum and puxin technologies [66]. The number of biogas systems in Ghana is comparably nominal to the estimated capacity of the country. According to Netherlands Development Organization (SNV), the technical potential of biogas in Ghana far exceeds 278,000 digesters and has the capability of boosting agriculture by 25% [67] [68]. The Apollonia biogas plant initiated by the Ministry of Energy to provide electricity and lighting system for the community was fed with animal dung and human excreta [69]. The Ghana Oil Palm Development Company currently has a 2000 m³ biogas plant that treats oil palm waste whiles HPW Fresh and Dry Ltd has a biogas plant that feeds on fruit processing waste. Safisana which feeds on human excreta and market waste is the only biogas plant in Ghana that is connected to the national grid [67] [68] [69] [70]. There are several other biogas systems that have been installed in public places such as schools, prisons, healthcare centres and district assemblies, by the Council for Scientific and Industrial Research (CSIR), as a way of managing Ghana's sanitation [7] [15]. The use of biogas for cooking is a feasible option with a 5-year recompense period [68]. Biogas for cooking could reduce indoor pollution associated with respiratory diseases and eye infections caused by exposure to smoke in the use of wood fuel.

One of the technical limitations with biogas digesters is their relatively slow degradation rate (3 weeks or more) dependent on the digester type, fermentation and operating conditions [71]. This has necessitated the need for bio-digesters with larger capacities. In order to improve the efficiency and processing time of anaerobic digestion, ultrasound technology has been found to be very effective in speeding up the biodegradation process. Ultrasonic pre-treatment facilitates the disintegration of chemical oxygen demand and improves the performance of the anaerobic digestion [72]. Odour nuisance is another limitation that can occur if the biogas plant is not run efficiently. However, biogas for electricity generation is competitive with diesel plants if the feedstock is obtained at little or no cost to the site [70]. The use of animal waste for bioenergy generation in rural communities in Ghana would enable farmers to diversify their income thresholds and also increase productivity whiles converting animal waste to an asset.

3.2. Gasification

Gasification converts carbon-containing feedstock to fuel gas via partial oxidation [73]. A diverse range of biomass feedstock including crop residues, forestry residues, industrial food processing waste, and organic municipal waste can be gasified. In contrast to ethanol production and anaerobic digestion which converts just a fraction of the biomass material to fuel, gasification traditionally converts the entire carbon content of the feedstock and hence more appealing.

Gasifiers come in different types and have diverse scales of acceptable reaction

conditions, feedstock requirements, and ash contents [74]. Fixed bed gasifiers for example are simple built and operate at small scale with high carbon conversion rates, low gas velocity and residence time [75]. Hence, thought must be given to the scale of operation (small, large, centralized, decentralized), feedstock flexibility (size and characteristics), sensitivity to ash, and tar yield in making a choice of a gasifier [76] [77].

Syngas produced by gasification usually contain impurities such as tar, particulate matter, SO_x, NO_x and NH₃, which need cleaning to get a high quality fuel. Tar is the most critical as it can cause blocking problems, fouling, and soot formation in the reactor [75] [78]. The design of a gasifier, selection of optimal operating parameters and catalytic conversion techniques have a direct impact on the quantity of tar that is generated in the syngas. Current advances in gasification technologies are aimed at tar mitigation, increasing hydrogen content in syngas and increasing energy efficiency of biomass gasification [75]. Baldwin *et al.* [50] have developed a tar and hydrocarbon reforming catalyst that is about 99% effective in destroying tar through reformation and 90% effective in reforming methane in a high sulphur environment to produce more syngas.

There are two categories of tar removal techniques namely primary (in-situ) and secondary removal techniques (post-gasification). While primary removal technique minimizes the tar yield in syngas internally through optimization of the design and operating conditions of the gasifier without the need for an additional reactor, secondary removal technique requires additional reactor to destroy and reform the tar yield to acceptable levels in the syngas [79]. Primary tar removal technique avoids tar formation through the use of catalysts and total control of the process operation, thus reducing the tar yield in the gasifier. On the contrary, post-gasification does not interfere with the process in the gasifier as tar can be removed from the syngas after it has been produced using physical and chemical processes such as cyclones, cooling towels, electrostatic precipitators, thermal cracking, among others [80]. Post-gasification has been tried and tested, however in-situ tar removal techniques are becoming more popular as they may phase out the need for an additional clean up [81]. On the whole, a synthesis of both primary and secondary treatment methods is more productive since it may not always be possible to achieve a desired tar reduction and maintain the quality of the product gas using one gas cleaning technique.

The new advances in multi-staged gasification integrates pyrolysis and gasification in single controlled stages which facilitates the efficiency of the process and results in the production of high quality syngas with low tar content [78]. Henriksen *et al.*'s [82] research on the two-staged 75 kW Viking gasifier employed pyrolysis and char gasification in separate reactors. The operation was successful as tar content was significantly reduced by a factor of 100 in each stage and the resulting tar content in the syngas was less than 15 mg/Nm³. Leijenhorst *et al.* [83] assert that multi-staged gasification is appropriate for the conversion of ash-rich biomass materials and could produce a tar free syngas

(<10 mg/Nm³) of high quality. A new three-staged gasification process has also been developed which further improves product gas quality. The new process promotes flexibility and has a gasification efficiency of 81%, char conversion rate of 98% and a significantly low tar content of 0.01 g/Nm³ in the produced gas compared to a single-stage gasification which has a gasification efficiency of 67%, char conversion rate of 59% and tar content of 31 g/Nm³ [57]. Biomass gasification can be made economically viable and highly efficient through the concept of poly-generation for the production of numerous energy products from the remaining syngas after the target product has been produced looks promising [78].

Gasification could enhance rural bioenergy development in Ghana due to the varied nature of its feedstock requirement. Potential feedstock for biomass gasification include agricultural residues such as coconut shells, coconut husks, corn cobs, cocoa pod husks, palm kernel shells, rice husks, rice straw, wheat straw, sawdust, and empty fruit bunch. The fibrous nature of coconut husks and empty fruit bunch means they require pre-treatment (densification, briquetting, and pelleting), without which they may cause blockages in the gasifier [75]. Conversely, cereal crops like rice husks, rice straw and wheat straw generally have higher ash contents (>10%) and can cause slagging, fouling, and blockages in the gasifier [84]. Ash content can however be controlled by optimizing the operating conditions in order to get the required output.

A 40 kW downdraft gasifier that operates 365 days a year at 12 hours a day would require approximately 735 tonnes of maize residues to generate 1103 MWh of electricity and the least maize residue producing district in Brong-Ahafo Region could feed the plant on a sustainable basis [85]. Electricity generation by gasification of rice husk could also supply 7% of the electricity needs of rural communities in Northern Ghana [84].

3.3. Direct Combustion

Direct combustion is the most entrenched technology for converting biomass to heat, which can further be processed to generate electricity [86]. Combustion accounts for 97% of the world's bioenergy generation and is the oldest energy production process in the history of humanity [87]. Although any type of biomass can be combusted, combustion is practically viable for pre-dried feedstocks or feedstock with moisture content less than 50% [62]. Biomass combustion can produce large quantities of pollutants such as Carbon monoxide, Soot and Polycyclic aromatic hydrocarbons when incomplete combustion occurs. Fuel components such as Nitrogen, Potassium, Chlorine, Calcium, Sodium, Magnesium, Phosphorus, and Sulfur can also result in the production of pollutants such as NO_x and particulate matter. In order to minimise emissions during biomass combustion, furnace designs need to be optimized [88]. A modern biomass combustion plant is able to achieve as much as 90% efficiency with minimal environmental effects [7]. Woody biomass such as native wood is the most prefer-

able for biomass combustion due to its relatively low ash and nitrogen content. Non-woody biomass like switch grass, straw, and bagasse have higher contents of nitrogen and sulphur thereby giving off more emissions of NO_x, particulate matter and higher ash content. Despite these drawbacks with non-woody biomass, they are best used in larger combustion plants with effective flue gas cleaning sub-system to reduce toxic emissions [88]. The performance of combustors generally depends on feedstock characteristics such as ash content and chemical composition. Ash deposition is very crucial during biomass combustion as it can reduce burner efficiency due to the agglomeration of the ash particles in the furnace, damage the burner due to restriction of gas flow, and cause maintenance issues such as impulsive shutdowns for cleaning ash deposits [89]. One way to get rid of the negative properties of biomass feedstock during combustion is by considering the combustor type, shape and size of combustion chamber, rapping and blowing of combustor to eliminate the excessive amount of ash, or by adjusting the regulatory and management system [90]. Air staging is also an effective way of reducing NO_x emissions during combustion. Sher *et al.* [91] demonstrated that an introduction of the secondary air at higher location can reduce NO_x emission by up to 30% and also minimise emissions of CO by a significant amount due to the raised temperatures and protracted residence time. An increase in air staged level in the combustor reduces NO_x emissions steadily without necessarily increasing the carbon content in the fly ash [92].

There is currently no available record of biomass combustion in Ghana in spite of the availability of a diverse range of biomass resources which make combustion potentially viable for power production [7].

3.4. Pyrolysis

Pyrolysis is the breakdown of chemical species by the action of heat and in the absence of oxygen. A diverse range of products mainly fuel gas, bio-oil and char are produced out of pyrolysis and can subsequently be utilized in power production [87] [93]. Although a number of useful elements such as carbon monoxide, hydrogen, methane and other hydrocarbons are generated out of pyrolysis, their quantities depend wholly on the biomass type, rate of heating, operational temperature and residence time [94]. The operating condition under which biomass pyrolysis occur, is critical in regulating the quality and dispersal of the end products [95]. For example, high quality of solids are produced out of pyrolysis when the operating temperature is low to medium and the vapour residence time is delayed for 30 minutes, whereas a high temperature biomass pyrolysis and a long vapour residence time generally produces a higher quantity of gas. Alternatively, a moderate temperature pyrolysis coupled with a vapour residence time of less than 2 seconds results in the production of significant quantity of liquids and char [96]. Lesser quantities of gaseous products are generated out of pyrolysis compared to combustion and gasification, thereby making a gas cleaning sub-system irrelevant [97]. Biomass pyrolysis usually takes place at a tem-

perature between 300°C and 600°C which is lower than temperature ranges for gasification [98]. Slow pyrolysis takes place at reduced temperatures, slow heating rates and long residence times [99] [100]. Slow pyrolysis is used for char production and the process is more tolerant of feedstock with high moisture content. There are two categories of slow pyrolysis; carbonization and torrefaction. Carbonization is used in charcoal production whereas torrefaction is only a pretreatment process for increasing the energy density and biomass fuel properties like grindability [101] [102] [103]. Fast pyrolysis is a high temperature process that facilitates the production of bio-oil. Although fast pyrolysis is relatively new, it has attracted lots of attention due to the benefits that bio-oils offer in terms of easy storage, transport and comparatively higher power generating efficiencies at small scales of operation [104]. Nonetheless, bio-oils are highly corrosive in nature and hence pose genuine handling and transportation issues [105].

Pyrolysis of feedstock such as straw, rice husks, nut shells, miscanthus, corn cobs, empty fruit bunches and many others have been investigated with most studies aimed at optimizing the bio-oil yield without any consideration for its quality [100] [102]. Slow pyrolysis produces more syngas yield with increasing temperature whereas with fast pyrolysis, an increase in temperature increases solid yield and losses. Low temperature enhances the production of methane whereas high temperature promotes the production of hydrogen [106]. Mansur *et al.* [107] treated cocoa pod husks by pyrolysis to produce bio-oil that was further upgraded by catalytic reaction over iron oxide catalyst to produce aliphatic ketones, phenol and alkyl phenols. Heavy tar build up in the char bed during the pyrolysis was problematic as no solvent could get rid of it except by combustion using heated air. Cai and Liu [108] studied the performance of a fast pyrolysis plant that was fed with rice husks and reported that at a stable operational temperature of 550°C, bio-oil yield was 48.1%, char yield was 26% and non-condensable gas yield was 25.9%. There was consistency (40% - 60%) in bio-oil yield with other published literature such as [109] [110] [111]. Guedes *et al.*'s [100] database of 206 research papers analysed various biomass resources under different operating conditions using pyrolysis and concluded that characteristics of biomass (type of biomass and components e.g. elemental composition, ash content, moisture content, lignin content, energy density), and operational conditions (eg reactor type, heating rate, temperature, pyrolysis type) play major roles in the product yield and composition. The quality of the liquid product is dependent on the carbon and hydrogen contents of the product. Thus the higher the carbon and hydrogen contents, the higher the quality of the liquid product whereas a high oxygen content diminishes the energy density of the liquid product.

Feedstock for pyrolysis include sawdust, waste from wood processing companies, shells (almond, groundnut, palm kernel, coconut), husks (rice, coconut, cocoa), corn cobs, stalk (corn, cotton, cassava), straws (corn, cotton, wheat, rice), bagasse (sugarcane, sorghum, sunflower) banana leaves, jatropha residue, sun-

flower seeds, palm fronds, palm trunks, palm leaves, cassava rhizome, bamboo, elephant grass, cattle manure, poultry droppings, sewage sludge and used oils [71] [112] [113].

There has only been a single pyrolysis project in Ghana which was shut down due to low product yield, feedstock supply challenges, and utilisation of manual process controls [114].

3.5. Fermentation

Fermentation is the chemical breakdown of organic substrate by the action of enzymes to produce ethanol. The organic substrate for fermentation are mostly sugar crops like sugarcane, sugar beet, sweet sorghum and starchy crops like maize, cassava, yam, potatoes and wheat [7]. Bio-ethanol generation generally requires the activities of enzymes and yeasts with yeast fermentations carried out as continuous and batch fermentations. Batch fermentation is more popular because there is a lower risk of contamination [64]. During batch fermentation, a microorganism is injected into a portion of the substrate and the fermentation is carried out until the sugars are degraded. Batch fermentation has the added advantage of being simple, economical, less prone to contamination and sugars can be used efficiently [115]. For high quality ethanol, the raw ethanol produce needs to undergo further treatment or purification which can be energy-intensive. Approximately 450 litres of ethanol is produced from every tonne of dry corn. One of the advantages of fermentation is that the solid residue produced has other uses such as animal feeding, and also provide feedstock for electricity generation in gasifiers. By inference, the residue given off in the production of ethanol can be used simultaneously as feedstock to generate electricity to power the ethanol-making plant [7] [62]. There are three types of biomass feedstock for ethanol production; sugars, starches, and cellulose materials. While sugars are directly convertible into ethanol, starches must first be broken down to fermentable sugars by the activities of enzymes whereas cellulose must also be converted into sugars by the action of mineral acids before microorganisms can ferment them to ethanol. Fermentation of starch is complex compared to sugar because starch is first broken down into sugar by hydrolysis before ethanol production. This requires high-temperature cooking (140°C - 180°C) to raise starch saccharification efficiency and increase ethanol yield by sterilizing the harmful microbes [116]. Ligno-cellulosic materials including forestry, agricultural and agro-industrial wastes are rich in sugars and easily assimilated by microorganisms, making them good feedstocks for the production of biofuels by fermentation [117]. Pretreatment is an essential step in biochemical conversion of ligno-cellulose materials into biofuels and generally an acid catalyzed thermo-chemical treatment is mostly used for this purpose [118] [119]. Biological pretreatment is another promising option as it generates no inhibitors and is environmentally friendly. However it needs a long incubation period for effective delignification although this can somehow be reduced by a microbial consortium [120]. Effective pretreatment of

biomass feedstock is necessary to provide a broad surface area for enzymes to act, improve the feedstock solubility, and promote feedstock utilization to ensure high biofuel yield [121]. Ligno-cellulosic materials are great feedstocks for ethanol production because of their global abundance, their output/input energy ratio and their ethanol yields [122]. Ghana has a substantial capacity for ethanol production and any attempt to synthesize the use of petrol with ethanol would prompt a massive reduction in the amount of greenhouse gas it emits. The addition of bio-ethanol to gasoline facilitates gasoline combustion and minimise the exhaust emissions such as carbon monoxide [123] [124] [125] [126]. Feedstock that can be used for ethanol production in Ghana includes sugarcane bagasse, corn stover, corn stalk, rice straw, rice husk, sawdust, cassava, cocoa pod husk, coconut husk fibre, oil palm empty fruit bunch, among others [127] [128] [129].

3.6. Liquefaction

Liquefaction takes place in a liquid medium and is hence appropriate for high moisture content feedstock [130] [131]. Factors such as feedstock type, operating temperature, solvent type, reactor configuration and type of catalyst determine the products of biomass liquefaction [26]. Water is mostly used as a working medium for hydrothermal processes as it enhances heat transfer and biomass decomposition [132] [133] [134]. Temperature significantly affects product yield and composition during liquefaction [135]. Bio-crude yield increases with temperature increase, nonetheless there is an optimum temperature beyond which any further increase reduces the bio-crude yield [59] [58]. As shown by Chan *et al.* [136] in their liquefaction experiment on palm kernel shell, a temperature increase from 330°C to 360°C caused a rise in bio-oil yield from 6.48 wt% to 13.55 wt% while a further temperature increase to 390°C produced an optimum bio-oil yield of 15.55 wt%. Cheng *et al.* [137] also revealed in their studies on white pine sawdust that while char yield reduced from 70% to 5%, bio-oil yield more than doubled from 25% to 66% with an increase in temperature from 200°C to 300°C. On the contrary, when temperature was increased again to 350°C, there was a drop in bio-oil yield to 35%. A possible reason for the decrease in product yield after the optimum temperature is the counteraction involving hydrolysis and repolymerization during liquefaction [58].

Pressure potentially increases the bio-oil yield in conformity to Le Chatelier's principle [138]. Although pressure maintains liquefaction medium in the liquid phase, the impact of pressure on bio-oil yield and composition is insignificant after a certain threshold [131]. This is due to the very minimal pressure effect on water properties or solvent medium at supercritical region [139].

An increase in residence time increases the product yield, however after a certain threshold, product yield decreases with increasing reaction time [60] [140] [141]. Brand *et al.* [142] observed that an increase in reaction time to 60 minutes influenced the conversion efficiency positively from 65.9% to 89.6%, and bio-crude

yield also saw an upsurge from 37.1% to 52.0%. A further increase in reaction time to 240 minutes resulted in a further increase in conversion to 93.6% and a bio-crude yield increase to 59.2%.

Water performs a triple role during HTL, as it serves as a solvent, a reactant and a catalyst [135]. When the temperature and pressure of solvents are increased during liquefaction, they act as a good reactant for the breakdown of the complex biomass structure in bio-oil production [136]. Many biomass compounds for instance, are insoluble in water at ambient temperature but are readily soluble at elevated temperatures [135]. Huang *et al.* [143] argues that although using ethanol or methanol as liquefaction solvent generally produced higher conversion efficiencies and ester compounds whereas acetone basically favoured the formation of ketone and N-containing compounds. Overall, ethanol is the most suitable solvent for thermochemical liquefaction in terms of efficiency and renewability.

Catalysts are applied in biomass liquefaction for improvement in bio-oil yield and quality [131]. Sun *et al.* [132] analysed the influence of Fe and Na₂CO₃ catalysts in paulownia liquefaction and revealed that both catalysts effectively improved the formation of heavy oil products in the same way as they enhanced the formation of gas. Xu and Lancaster [60] in their studies on pulp/paper sludge powder acknowledged that there was a significant improvement in organic conversion when 0.1 M K₂CO₃ was used as a catalyst, meanwhile the formation of heavy oil and water-soluble oil were subdued. In stark contrast, Ca(OH)₂ and Ba(OH)₂ had no significant impact on organic conversion, however they facilitated the production of higher product yield and the formation of water-soluble oil. Thus the optimum selection of catalysts is key to product yield in liquefaction.

Biomass resources such as palm, corn stalk, rice straw, sawdust, swine manure, wood stalk, empty fruit bunch, sugarcane bagasse, palm kernel shell, bamboo, cassava rhizome, rice husk, coffee husk, peanut shell and sludge can all be used for energy production through liquefaction [140] [141].

3.7. Bio-Diesel Production

Primarily, bio-diesels can be produced from vegetable oils, animal fats, and recycled greases [145]. Mechanical and solvent extraction are the two main processes for oil separation from seed feedstock and once the oil has been extracted, the seed meal that remains can be used as animal feed [62]. Oil extraction from seed feedstock is the first step in bio-diesel production. However, the vegetable oil extracted is not great for direct use in compression ignition engines because it is highly viscous, less volatile and does not undergo complete combustion when used directly in diesel engines. Conversion of the vegetable oil to bio-diesel by transesterification is therefore favored as it lowers the viscosity and increase volatility [146]. Bio-diesels are eco-friendly as they contain no sulphur and the net CO₂ they emit is very minimal [147]. A study by Su *et al.* [148] reveals that

at an optimum temperature of 65°C, reaction time of 90 minutes, and a methanol:oil molar ratio of 10:1, a bio-diesel yield of 97.02% is achievable from sour-sop seed using 1% H₂SO₄ as catalyst. The same high bio-diesel yield of 97.02% was achieved using 0.6% NaOH as catalyst and operating at an optimum transesterification temperature of 65°C, reaction time of 30 minutes, and a methanol:oil molar ratio of 8:1. Kartika *et al.* [27] also produced a bio-diesel yield of 87% from jatropha seeds using a methanol to seed ratio of 6:1, 0.075 mol/L KOH catalyst in methanol, a stirring speed of 800 rpm, temperature of 50°C, and a reaction time of 5 hours. According to their research, an reaction equilibrium was attained after 3 hours, hence an increase in reaction time from 3 to 5 hours did not have a significant impact on bio-diesel yield. Nonetheless, a relatively long reaction time can reduce bio-diesel yield due to reverse transesterification reaction.

Ghana has a good potential to produce bio-diesel from sunflower, coconut, groundnut, oil palm, jatropha and soybean. However, jatropha and oil palm have generated the most interest for bio-diesel production in Ghana.

3.8. Biomass Pelletization

One of the main characteristics of biomass that limits its usage in power production is its relatively low bulk density. The lower the bulk density of a feedstock, the higher the cost of biomass storage, transport and handling. The behaviour of biomass during thermochemical conversion is also affected by the bulk density [149]. Generally, the bulk density of agricultural residues is under 100 kg/m³ while that of forest residues is under 400 kg/m³ [150]. Biomass pelletization increases the bulk density up to 700 kg/m³ and also provides a more uniform shape and structure for easy feed into boiler systems [151]. Biomass pellets are solid biofuels invented out of crammed organic matter. Pellets can be made out of any combustible organic material such as sawdust, straw, bark, wood shavings, and animal waste. Due to the compact nature of pellets, they tend to possess higher energy and mass density than raw residual biomass. Bio-pellets are easy to store, handle and transport. They also have improved energy efficiency and compete well with other fuels [152]. Biomass pellets give off lower emissions in comparison to their raw nature and other conventional biomass fuels [153]. Biomass pelletization is a very enterprising way of using biomass especially in rural communities as the technology is simple and biomass pellets can be bagged and marketed for domestic use as a replacement for charcoal and firewood. Pellets are also useful as feedstock for small scale industrial operations such as boilers and gasifiers. Bio-pellets can be produced from locally available biomass resources using waste cooking oil and waste lubricating oil for binding to minimise production cost [154]. The use of binder in pelletization enhances combustion properties, calorific value, increases strength, improves durability and decreases the tendency of wear and tear of pellets during combustion. Feedstock characteristics such as moisture, size reduction at pre-processing, pelleting conditions such as temperature, die pressure, feedstock combinations, and the use of

binders can affect the durability of pellets. For example, finer particle sizes with optimal levels of moisture and high pelleting temperature increases bio-pellet durability whereas grainy particle sizes with higher levels of moisture decreases durability [155]. A study on the impacts of various biomass blends and binder additions on bio-pellet properties demonstrates that groundnut shell pellets have a higher calorific value compared to sawdust and leaf litter waste. Meanwhile, groundnut shell pellets also have the lowest strength among the three. Hence the addition of sawdust and leaf litter waste as additives boosted the strength of groundnut shell pellets while the low calorific value of leaf litter waste was improved by the addition of groundnut shells as additives. Waste cooking oil and waste lubricating oil both boosted calorific value of pellets although they decreased strength by an insignificant amount. Waste cooking oil and waste lubricating oil can therefore be used as binders to improve calorific value of biomass feedstock like leaf litter waste during pelletization [154]. The abundance of agricultural and forest residues in Ghana makes decentralized biomass pelletization a promising option for low cost bio-pellet production. Given that biomass pellets are preferred feedstock for combustion and gasification, bio-pellet production in rural Ghana can arouse the urge to establish decentralized combustion and gasification systems for electricity generation.

Figure 3 summarises the pathways to potential biomass resources and the

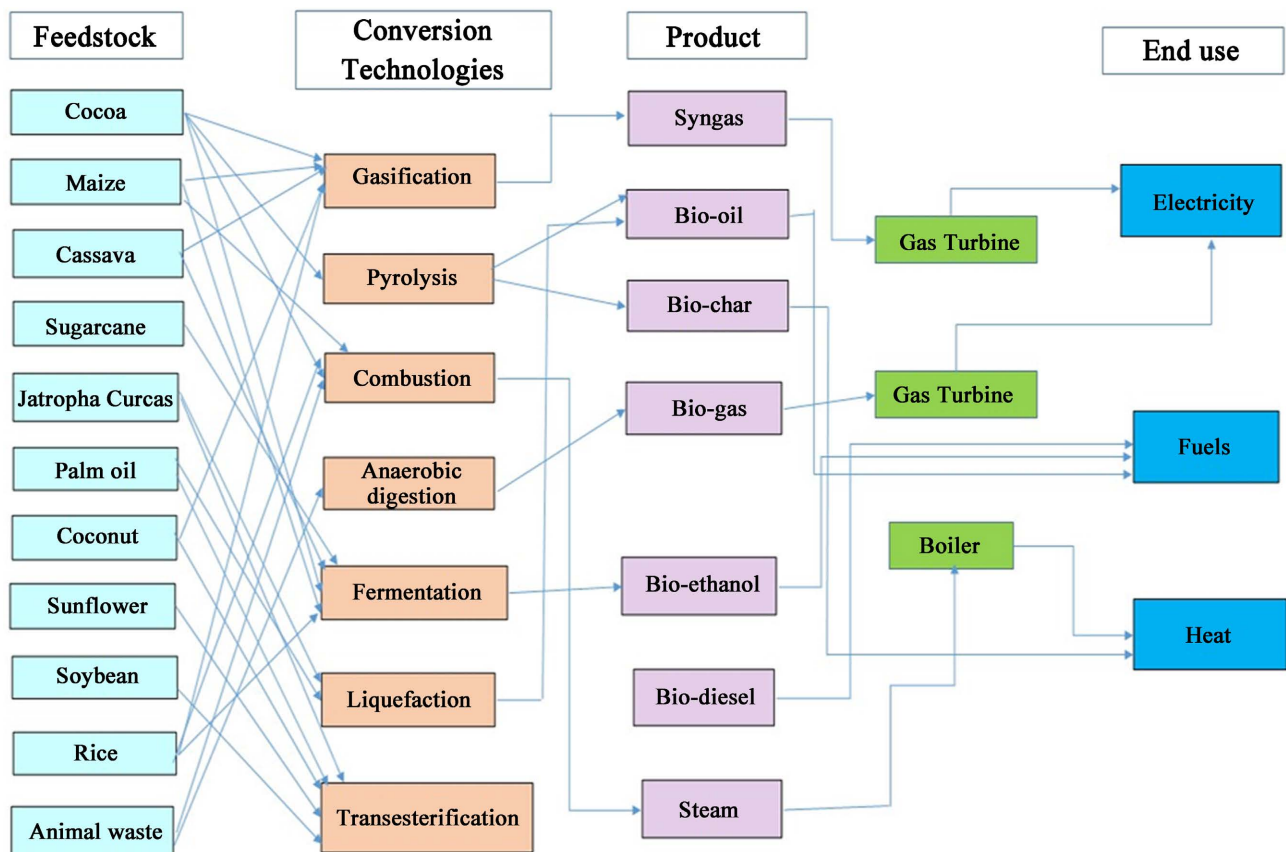


Figure 3. Bioenergy conversion pathways and end use application.

main biomass conversion technologies.

4. Discussion and Conclusions

In this review, biomass resources, biomass energy conversion technologies and bioenergy production potential for rural development in Ghana have been evaluated. Ghana has a substantial potential for power generation from biomass. Assessment of biomass feedstock availability reveals that agricultural crop residues have the greatest energy potential at 623.84 PJ with livestock production generating a total energy potential of 64.27 PJ. While most rural communities in Ghana remain remote and isolated with no access to electricity due to the expensive cost associated with grid extension, residual biomass could be relied upon to support a decentralized biomass electricity production on a sustainable basis since agriculture is a predominant livelihood activity for most rural communities. Compared to other renewable energy sources, biomass has the greatest socio-economic potential because the development of bioenergy in rural Ghana could deliver modern energy services, create employment, alleviate poverty and boost food production. Marginal lands on the verge of destruction could also be restored by growing energy crops like *Jatropha* on them for biodiesel production.

Based on the findings of this review, it is the end-use application together with the type and characteristics of the available biomass feedstock that determines the choice of conversion technology. Ghana currently has about 400 bio-digesters which is less than 2% of its technical potential. Other conversion technologies such as fermentation and pyrolysis produce solid residues in addition to their main end products which are useful for electricity generation. Strictly speaking, an integration of conversion technologies would enable concurrent production of power and other fuels. Nonetheless, evidence from literature testifies that biomass gasification is the best technology to fulfil the basic electricity needs of rural communities in Ghana. Gasification has diverse feedstock requirement and converts the entire carbon content of feedstock thereby providing higher calorific value product with better energy capture unlike other conversion technologies. Cocoa is the most common crop in rural Ghana and produces 858,720 metric tonnes of CPH annually. This abundant biomass resource could be utilized for electricity production through gasification. With a relatively high calorific value of 18 MJ/Kg, CPH is competitive as a source of energy. Pelletization of CPH for use in power generation through gasification would be a sustainable means of expanding electricity access to rural communities in Ghana. CPH pellets could also be used as cooking fuel as they compare favourably in energy density with firewood. Additionally, pelletization of CPH can provide a secondary source of income for rural households thereby improving their living conditions. Since biomass gasification is still at research and development stage in Ghana, a precautionary approach in the form of a prototyped CPH-fed power generation system would prepare the grounds for a full-scale implementation. It is recommended that research on CPH gasification in rural Ghana be intensified.

Future research may need to thermo-chemically characterise CPH samples from different rural communities in Ghana to determine whether environmental and soil conditions have an impact on the thermal properties of CPH.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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