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Review article

A comprehensive review of the production, adoption and sustained use of biomass pellets in Ghana

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ABSTRACT

Ghana's Renewable Energy Master Plan of 2019 includes the production and use of biomass pellets. However, pellets have neither been developed commercially nor included in Ghana's energy mix. This paper reviewed the prospect of production, adoption and sustained use of pellets in Ghana. Besides having abundant biomass resources, Ghana has high market demand and relevant policies for pellet development. The production of pellets can significantly replace traditional household biomass demand and improve environmental and health quality. However, the production and use of pellets are limited due to technical, financial, social and policy issues. Our estimates show that 3% of the annual national average household income will be spent on pellet demand for cooking, with the highest burden on rural households in Ghana. Practical measures are required since the cost of pellets and gasifier stoves may limit pellet adoption and use in Ghana. Based on study findings, it is recommended that the government of Ghana establishes a robust supply chain and provides infrastructure for pellet production and use. Existing renewable energy policies should be reviewed to remove ambiguities, attract investment, and build capacity in the renewable energy sector. Apart from raising public awareness of the benefits of pellets use, the government of Ghana should ensure that continuous and thorough impact assessments are undertaken to assess the implications of pellet production and use. This review will inform policymaking on achieving sustainable production, adoption and use of pellets and assess Ghana's contribution to achieving the United Nations' sustainable development goals.

1. Introduction

Traditional biomass fuels like wood, charcoal, crop residues, and animal dung remain the predominant source of household energy for more than half of the world's population [1]. Despite the recent impetus to enhance clean energy production, access to clean fuels and technologies only grew by 1% from 2010 to 2019 [2]. Within that same period, the number of people who relied solely on traditional biomass fuels in sub-Saharan Africa increased from 750 million to about 900 million [3]. The adverse effects of biomass use on human health and the climate have garnered much attention [4–6]. However, many households in developing countries continue to use traditional biomass fuels for cooking and heating; 89% in Africa, 77% in Asia, and 35.3% in Latin America [7]. With the current human population growth rate, it is estimated that the number of people who depend on biomass for household energy will remain

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unchanged by 2030 [8].

Household air pollution (HAP) associated with biomass use is exacerbated because they are usually burned in inefficient stoves [9,10]. Due to international recognition of the adverse effects of unclean cooking and heating, and progress toward sustainable development goals (SDGs), transitioning to clean fuels in developing countries has gained significant attention [11,12]. Notably, efforts over the years have boosted the use of biomass pellets and advanced stoves for residential and industrial use [4]. These fuels are formed by condensing crop residues or wood waste into cylindrical forms with low moisture content and high energy potential [13]. They produce low emissions and have other desirable characteristics that make them suitable for direct use in residential and industrial energy production [14]. The biomass pellet market and use scenario has become a vital part of the energy sector and thus is evolving continuously at a faster rate [15–17]. Global consumption of pellets grew from about 16 million tons in 2010 to 59 million tons in 2020 [18–20].

Like many developing countries, Ghanaians' primary energy source is biomass [7]. Population growth is projected to cause a surge in household demand for biomass, forming 23% of total energy demand by 2030 [21]. Ghana has lost 85% of its forest cover in the last century and has an annual deforestation rate of 2%, one of the highest in the world [22]. The present heavy reliance on biomass accounts for 60% of the decline in forest cover [22,23] and could ultimately destroy Ghana's forests by 2050 [24]. Also, exposure to HAP from using biomass accounts for the premature death of 18,000 people every year [7], a disproportionate part of which are women and children below five years [25]. To reduce HAP and deforestation by providing clean energy and advance the united nation's SDGs; SDG 7 (affordable and clean energy) and SDG 13 (climate action) [26,27], the government of Ghana (GoG) developed the Renewable Energy Master Plan (REMP) in 2019 [28]. The REMP includes promoting 3 million advanced pellet stoves and use of wood pellets by cultivating 430,000 ha of woodlots by 2030 [29].

To date, pellets have neither been commercially developed nor included in Ghana's energy mix [7]. Whereas past studies [7,30–32] emphasize that pellets would significantly supplement about 91% of electricity and 53.6% of cooking fuel demand, there is still no access to the fuel. However, the production and use of pellets in Ghana is a multifaceted issue that requires a critical evaluation. To the best of our knowledge, no study has comprehensively assessed how pellets can be developed, adopted, and used sustainably in Ghana. We conducted a comprehensive literature review to recognize the need for such an evaluation. The review focused on the factors that favor the production and sustained use of pellets in Ghana. We also estimated the potential amount of pellets production from available raw materials and the potential substitution of current household cooking energy demands. We further conducted an economic analysis of the impact of pellet production and use in Ghana. The review also identified the implications of pellet production in Ghana and concludes with a synthesis of the steps followed by countries that have undertaken pellet production and the barriers identified in the Ghanaian setting to suggest a possible route for the production, adoption and sustained use of biomass pellets in Ghana.

2. Methods

2.1. Literature search

A literature review was conducted using electronic databases to select published papers that reported articles of interest. Standard web-based searches were done in Google Scholar and Web of Science. The keywords used were "wood waste", "crop residue", "bioenergy", "renewable energy", "Ghana", "briquettes", "market access", "renewable energy policy", "biomass pellets", "solid fuel" and "sustainable development". Research papers were searched for by matching up to 3–5 keywords. The detailed flowchart for the literature search and a compiled list of literature referred to for this review are shown in the supporting information (SI) and Appendix A, respectively.

2.2. Estimation of pellet potential from available biomass waste

The potential amount of pellet production from wood waste and crop residues was estimated by Ref. [31]:

$$\sum M_{Pellets} = 0.90 \times \sum M_{Biomass\ waste(i)} \tag{1}$$

Where, $\sum M_{Pellets}$ is the total mass of pellets (tons); $\sum M_{Biomass\ waste}$ is the total mass of biomass waste (i) (tons) generated in Ghana; and 0.90 is the conversion factor based on an assumed 10% production loss due to moisture regulation and conditioning of the biomass feedstock and the finished pellet fuels [31,33]. The quantity of biomass waste was taken from previous studies; wood waste (3 million tons) [34] and crop residue (38.7 million tons) [31]. The moisture content of raw materials influences the durability and other properties of the final pellet fuels and are important parameters to be considered when designing biomass pellets production projects [35,36].

2.3. Estimation of pellet potential to replace regional energy demands

In this study, we assessed the potential of biomass pellets to substitute household cooking demand for wood, charcoal and Liquified Petroleum Gas (LPG). Electricity was not included in the analysis since it is the least used cooking fuel (less than 1% of households) [37]. Data on households was obtained from the 2021 national census report [38]. The average annual per capita household biomass consumption (0.1 toe) was obtained from the National Energy Statistics [39]. The lower heating value of fuels was obtained from a past lifecycle assessment of cooking fuels in Ghana [40]. More details are in Section S2 of the SI.

Thus, the regional cooking energy demands were estimated by:

$$RCD_i = \left[\frac{x \bullet 41868 \bullet y \bullet z}{\text{Lower Heating Value of Fuel} \left(\frac{MJ}{kg}\right)} \right] \tag{2}$$

Where, RCD_i (tons) is the regional cooking energy demand of fuel (i); 41868 is the energy conversion factor from toe to MJ; x, y and z are per capita household biomass consumption (toe), average household size in region (i), and total number of households in region (i), respectively.

2.4. *Impact of cooking energy cost on annual household income*

The impact of cooking energy cost on national, regional and locality (rural and urban) average annual household income were analyzed. Average household income was taken from a national survey [41] with details on the former ten regions of Ghana. This was done because a recent survey after the referendum that changed the number of regions in Ghana (currently 16) is yet to be conducted. Thus, all estimations were based on the former ten regions of Ghana. However, our estimates still represent the current situation since some of the former regions were demarcated to form new ones; Brong Ahafo (Bono, Bono East, and Ahafo regions), Northern (Northern, Savannah, and North East regions), Volta (Volta and Oti regions), and Western (Western and Western North regions). The cost of cooking energy per ton (USD) was taken from Ghana's Strategic National Energy Plan and a past report [42–44]. Further information is in Section S3 of the SI.

Annual household cooking energy demand was estimated as follows:

$$\text{Cooking Energy Demand Per Household}_{\text{Annual}}\ (\text{tons}) = \left[\frac{x \bullet 41868 \bullet y}{\text{Lower Heating Value of Fuel} \left(\frac{MJ}{kg}\right)} \right] \tag{3}$$

Annual household expenditure on cooking energy demand was estimated as:

$$\text{Annual Household Expenditure on Cooking Demand (USD)} = a \bullet \text{Cost of Cooking Energy Per Ton (USD)} \tag{4}$$

Where a is the annual household cooking energy demand in a region (tons) calculated from equation (3).

3. Results and discussion

3.1. *Factors that favor pellets production in Ghana*

3.1.1. *Biomass resources*

3.1.1.1. Wood waste. About 40% of Ghana's land is covered with forest and woodlands [45]. The timber processing sector [23], produces vast quantities of unused logging and sawmill residues [46,47], as shown in Fig. 1, and the proportion has not changed much over the years [48]. A recent study found that the timber processing sector generates about 495,000 tons of logging waste [49,50] from about 953,496 tons of biomass consumed annually. With the growing agricultural sector, wood waste in Ghana reached 3 million tons in 2020 [49]. The Ashanti, Bono, Ahafo, Western North, Western, and Eastern regions [23] are the densely forested regions in Ghana and generate lots of wood waste. The huge volume of wood waste generated by the timber processing sector can be attributed to the use of outmoded sawmilling equipment, inexperienced operators, administrative inadequacies, and no appropriate method of converting waste to valuable products [51,52].

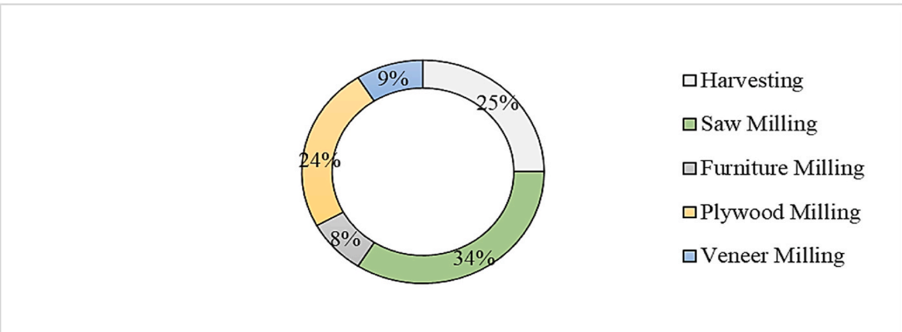

Fig. 1. Wood waste generated by the timber processing industry in Ghana [46,47].

Wood waste is burnt in open places, dumped into drainages and water bodies, or left to decay, causing significant environmental pollution [47]. A previous study placed wood waste's bioenergy potential at 39.5 PJ which can reduce household wood and charcoal demand [21]. A study in the Brong Ahafo region reported that sawmills and forest residues could yield 1064 tons of pellets and completely replace the region's cooking demands [45]. However, the disparities in tree species and their properties observed in Ghana's timber industry pose a challenge for pellet production [34,53]. Although many biomass can be compressed into pellets, the homogeneity of the feedstock is significant in producing good-quality pellets [16]. However, an assessment of six popular wood species in Ghana [54] reported good gross calorific value and ash contents suitable for pellet production according to Austria standards [55].

3.1.1.2. Crop residues. About two-thirds of Ghana's land area is used for agriculture, which employs many small-scale industries [46]. Table 1 shows the major crops grown in Ghana and their associated residue potential. This quantity of crop residue is projected to double by 2050 [56,57]. While the highest amount of crop residues is generated in the Eastern region of Ghana (2309 kt), the least is generated in Greater Accra region (50 kt) [31]. The highest potential of crop residues is from cassava, yam, plantain and maize. Seglah et al. [58] and Kemausuor et al. [51] reecho similar findings for the regional distribution of crop residues and the crops with the highest residue potential. Additionally, according to Mohammed et al. [59] also indicated that rice, maize and plantain residues made up majority of the agricultural residues generated. These residues have desirable properties [32] and can produce about 4.4 million tons of pellets to replace 54% of wood and charcoal demand in all regions (Fig. 2) [31]. Previous studies [22,27,32] found that cassava stalk, yam stalk and maize cob should be prioritized for pellet production in Ghana. Mohammed et al. [59] in their study did not prioritize all types of residues produced by maize (stalks, cobs, and husks) and rice (straw and husks). However, including various crop residues components when estimating residue and energy yield potential can significantly impact pellet production Seglah et al. [58]. Thus the residue-to-product ratio is a significant factor to consider when evaluating the residue potential of different crops [60]. In line with past results, the Ashanti, Eastern, Northern, Bono East and Bono regions show the most crop residue potential.

Crop residues in Ghana are fed to livestock, burnt in open fields [51] or burnt in traditional stoves, causing severe household and ambient air pollution, which deteriorates health, the environment and the climate [56]. For example, a study in the coast savannah zone of Ghana reported that open straw burning released 1446 kg of CO_2 for every hectare into the atmosphere [64]. Utilizing crop residues for pellets is desirable because they are affordable, renewable and environmentally friendly [22]. However, most crop residues require prior processing before compression into pellets because cultivation, storage, and harvesting practices may influence their physical properties [65,66]. Other studies in Hong Kong have also suggested hydrothermal carbonization as a means of efficiently utilizing crop residues for producing briquettes because it will eliminate the intensive drying of feedstock as a pre-requisite, save significant amount of energy, and produce hydrochar briquettes with high energy density to supplement energy demands [67,68]. Even though residential wood demand may remain high in Ghana [31], producing pellets from wood waste and crop residues may reduce more than half of the wood demand [22]. Recent studies reported that about 25% of Ghanaian households cook with LPG [7,

Table 1
Major crops grown in Ghana.

Index	Crop	Annual production (kt)[a]	Residue type	Residue to product ratio (RPR)[b]	Total residue produced (kt)	Lower heating value (MJ/kg)[c]	Residue energy potential (PJ)
1	Cassava	18,471	Stem/stalk	1.24	22,904.04	17.50	400.82
2	Cocoa, beans	884	Husk	1.00	884	15.48	13.68
3	Coconut	384	Husk/shell	0.54	207.36	18.62	3.05
4	Coffee, green	0.73	Husk	2.1	1.53	12.38	0.02
5	Groundnut	420	Husk/shell/ straw/stalk	2.08	873.6	17.58	15.29
6	Maize	1965	Husk/cob	0.63	1237.95	19.66	22.38
7	Millet	167	Stalk/husk	5.53	923.51	12.39	14.32
8	Oil palm fruit	2470	Kernel shell/ fiber	0.44	1086.80	18.33	16.55
9	Plantain	4051	Peels/stalk	0.50	2025.50	17.40	31.35
10	Rice, paddy	721	Straw/husk	3.28	2364.88	19.33	33.82
11	Sorghum	230	Stalk	4.75	1092.50	12.38	18.57
12	Sugarcane	152	Bagasse	0.2	30.4	18.10	0.41
13	Sweet potato	146	Straw	0.50	73	17.00	0.77
14	Cocoyam	1200	Straw	0.50	600	17.70	10.62
15	Yam	7953	Straw	0.50	3976.50	17.58	42.19
16	[d] Cowpea	–	Stalk	–	359.4	–	–
17	[d] Soybean	–	Stalk/husk	–	64.5	–	–
18	[d] Tomato	–	Stalk/leaves	–	6	–	–
19	[d] Other fruits and vegetables	–	Stalk	–	6.83	–	–
Total		39,215			38,718.30		623.84

[a] Annual crop production in 2017 in kilotons (kt) [61].
[b] Residue to product ratio (RPR) [62].
[c] Lower heating value [63].
[d] [31]; Residue energy potential in petajoules (PJ).

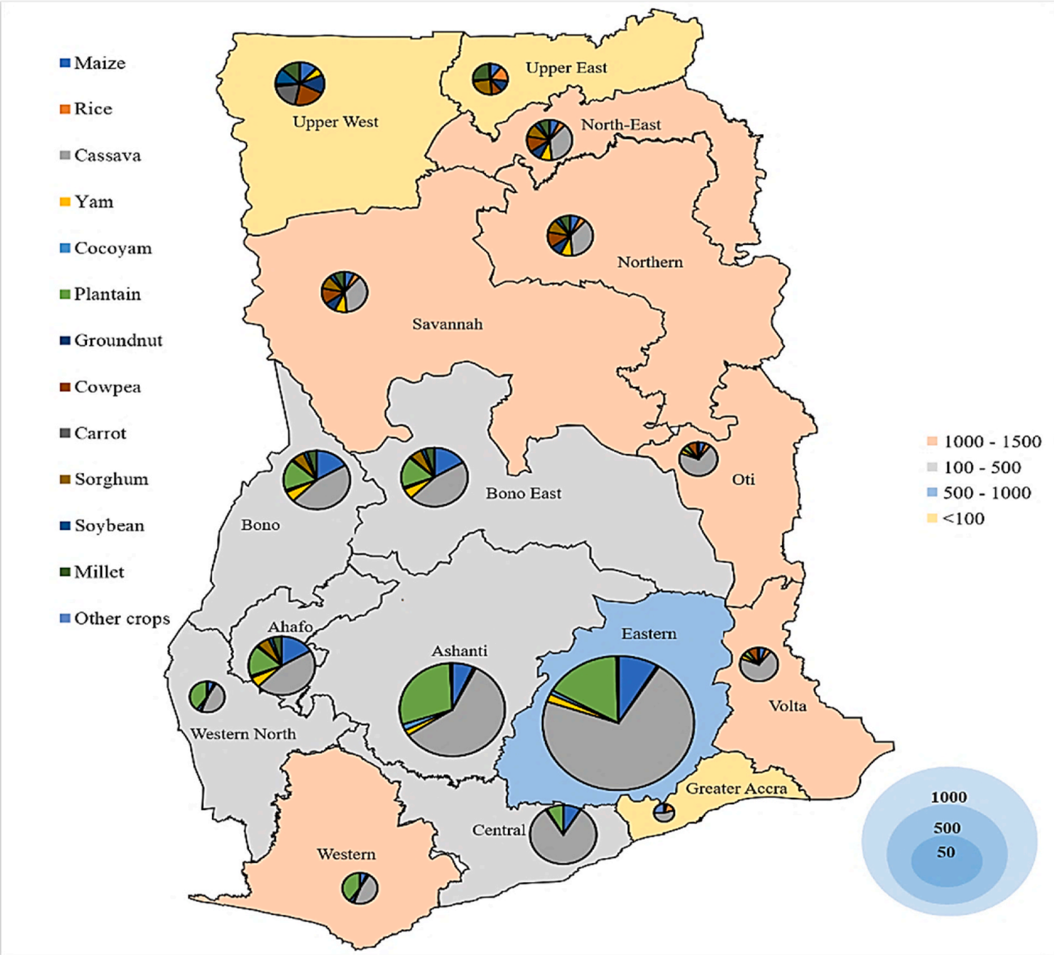

Fig. 2. Total amount and types of crop residues produced (kt, dry weight) and the associated pellets potential per the 16 regions of Ghana (kt) (adopted from Ref. [31]). The pie charts and the legend on the left show the types of crop residues produced (kt) in each region. The legend on the upper right corresponds with the crop residue pellet potential in each region of Ghana. The legend at the bottom right indicates the total amount of crop residues produced in each region, as shown by the size of the pie chart.

11]. The sustained use of these clean cooking fuels could significantly strengthen Ghana's commitment to United Nations SDGs 7 and 13 [31].

3.1.2. Market demand

A past assessment [69] found a high demand from potential users and the willingness to replace charcoal and wood with charcoal briquettes. Other studies [32,70–72] also emphasize Ghana's high commercial demand for pellets. A survey in the Ashanti region [69] shows 93% of the respondents were willing to use briquettes because they were easy to ignite and had higher heat input than wood or charcoal. A randomized trial of sawdust pellets [73] reported significantly reduced smoke compared with other biomass fuels.

3.1.3. Policies

The GoG formulated the strategic national energy plan (SNEP) in 2006 to comprehensively evaluate available energy sources and cost-effective means of harnessing them for sustainable energy growth by 2020 [28]. The SNEP also aimed at developing an efficient energy market for economic development by using RE sources, including biomass [74]. The energy for poverty reduction action plan of 2012 is another policy to maximize the provision of clean and affordable energy in at least 50% of all households, especially in rural areas [74].

The National Energy Policy (NEP) was formed in 2010 to develop RE sources [28] and emphasizes the promotion of refined wood and crop residues through monetary and technological incentives [74]. That same year, the bioenergy policy was formed to ensure food and energy security by promoting biofuels and improved stoves [29]. This policy has regulated the demand for biofuels through pricing mechanisms and attracted foreign investments to Ghana's RE sector [75]. Ghana's renewable energy Act, Act 832, was passed in 2011 to enable the government to issue legislative instruments that promote clean technology and control the use of biofuels [28, 76]. The complementary Feed-In-Tariff provided financial support for the Act to enable private sector participation in Ghana's RE sector [77]. The GoG developed the REMP to improve past energy policies [28], establish a long-term development strategy, and promote Ghana's RE source since most RE efforts were experimental programs or conducted on short-term planning cycles [78]. The

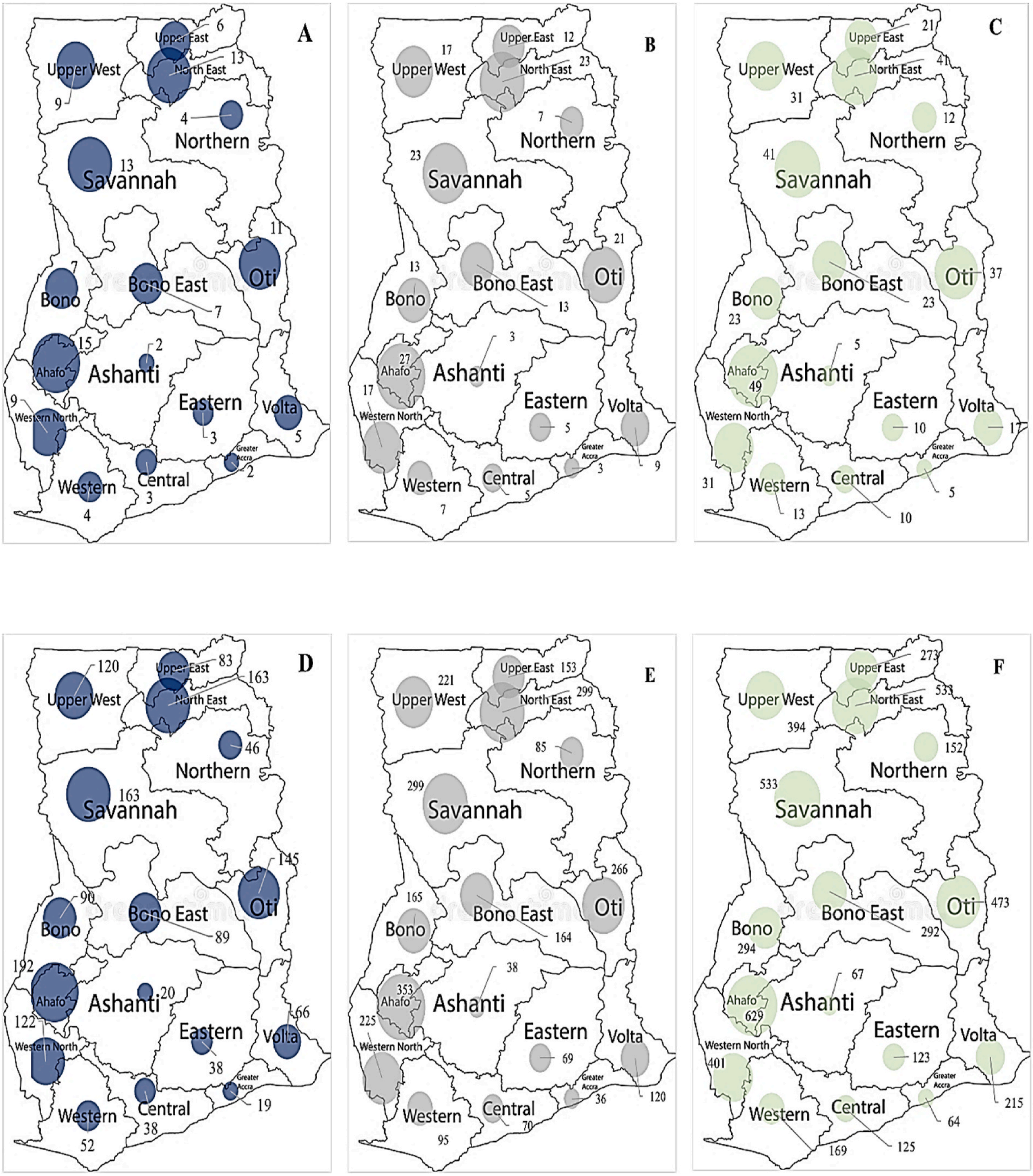

Fig. 3. Potential of pellets to replace annual regional household cooking energy demands. The size of the bullets corresponds with the number of times pellets can replace household cooking demand per region. The potential of wood pellets to replace wood, charcoal and LPG demand is represented by A, B, and C, respectively. The potential of crop residue pellets to replace wood, charcoal and LPG demand is denoted by D, E and F, respectively. The blue, ash and green colors indicate the potential of wood pellets (first row) and crop residue pellets (second row) to replace household wood, charcoal and LPG cooking demands, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

aims of the REMP include facilitating the adoption and use of 3 million advanced pellet stoves by 2030 and promoting the development and use of wood pellets by cultivating 430,000 ha of woodlots [29].

3.2. *Potential of pellets to replace annual cooking energy demands*

Fig. 3 shows the potential of wood pellets and crop residue pellets to replace annual regional household cooking demands for wood, charcoal, and LPG. Fig. 3A, B and 3C denote the potential of wood pellets to replace household cooking demand for wood, charcoal and LPG, respectively, in Ghana. The potential of crop residue pellets to replace household cooking demand for wood, charcoal and LPG is also shown by Fig. 3D, E, and 3F, respectively. More details can be found in Section S4 of the SI. The estimates agree with projections in the SNEP [44]. Our estimates show that pellets (2.7 million tons) produced from wood waste in Ghana can completely replace annual regional cooking energy demand in decreasing order LPG > charcoal > wood. A similar trend but with a higher substitution potential was found for crop residue pellets (34.85 million tons). Studies in Kenya [79], Chile [80] and China [81] also reported the non-viability of biomass pellets to replace LPG demand in homes in the short-term due to the higher energy content of the latter. Past studies in China [82] and Norway [83] have also reported the high potential for straw to yield pellets compared to wood waste. However, the type of pellets produced is influenced by geography, the available raw materials and the end-use of the fuel [84] Across all the regions in Ghana, the potential for pellets from wood waste and crop residue to replace annual household cooking energy demands was highest in the North East, Savannah, Oti, and Ahafo regions. These regions are moderately populated and have lower cooking energy demands [85]. Other studies [31,32,86] corroborate the high potential of pellets to replace household cooking energy demand in these regions. However, the lowest potential to replace annual household cooking energy demands was found for the Greater Accra region because it is densely populated, and residents require more energy for household cooking [37]. On a national basis, the potential of wood waste pellets to replace annual national household cooking energy demands increased from wood (0.27 times) < charcoal (0.5 times) < LPG

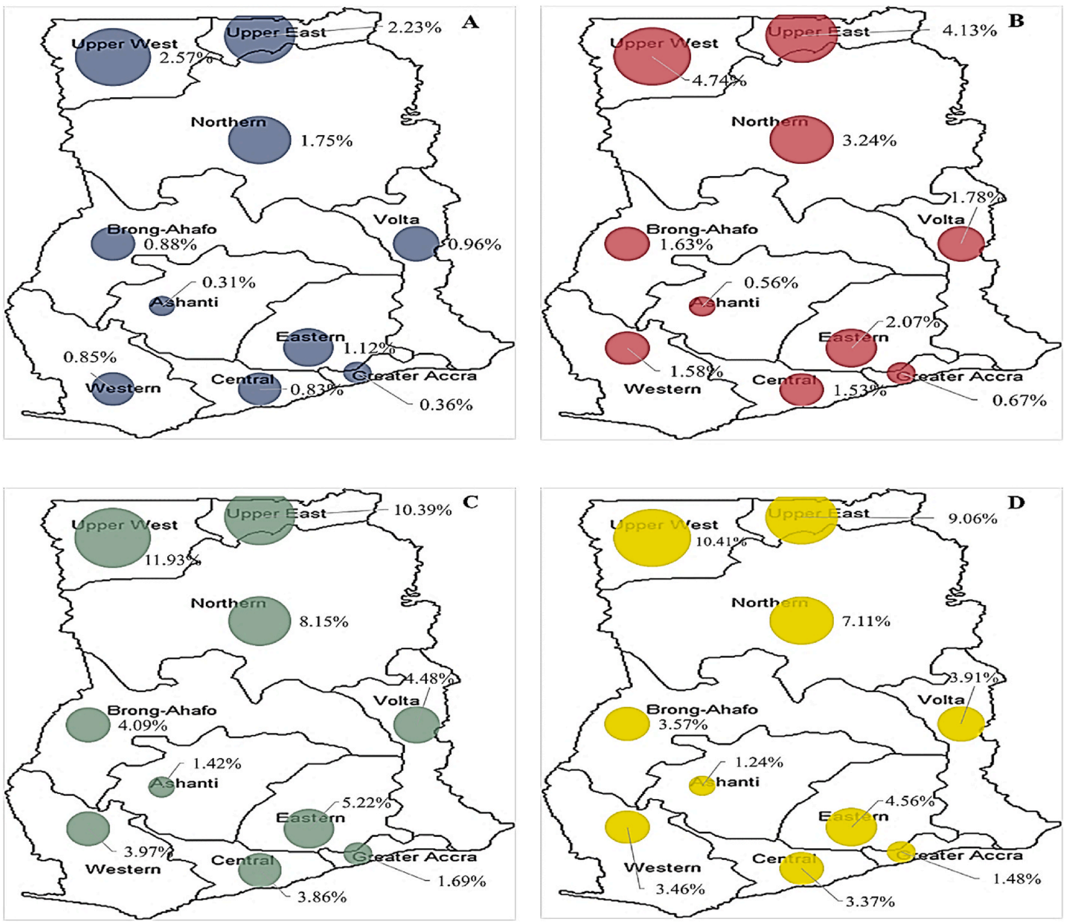

Fig. 4. The percentage of annual regional average household income spent on annual regional household cooking energy. The size of the bullets corresponds with the percentage of annual average household income spent on annual household cooking energy demand. The percentages of annual average household income spent on wood, charcoal, LPG, and pellets are represented by A, B, C and D, respectively. The blue, red, green, and yellow bullets indicate the percentages of annual regional household income spent on household wood, charcoal, LPG and pellet cooking demands, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(0.89 times). The same trend but a higher capacity was found for pellets from crop residues; wood (3.5 times) < charcoal (6.46 times) < LPG (11.51 times). Among the two types of pellets, crop residue pellets showed the highest potential of replacing the total national annual household cooking energy demand (by up to 1.9 times).

3.3. Impact of cooking energy cost on annual household income

The estimated impact of the cost of annual household cooking energy demand on annual household income is shown in Fig. 4. More details are shown in Section S5 of the SI. The price per ton of household cooking energy in Ghana is; LPG (USD 317.51), Pellets (USD 99.79), charcoal (USD 70.76), and wood (USD 20.87) [42–44]. Among the cooking energy demands, a considerable percentage of the annual average household income will be spent on LPG (Fig. 4C), and the least percentage will be spent on household wood demand (Fig. 4A). However, the percentage of annual average household income that will be spent on pellet demand (Fig. 4D) exceeds that of wood and charcoal (Fig. 4B). Generally, a small percentage of annual average household income will cater for annual household cooking energy expenditure in the Greater Accra and Ashanti regions, and the converse is found for the Upper West, Upper East and Northern regions (Fig. 4). This is expected since the average household income in Greater Accra and Ashanti regions are higher than in other regions [41].

In terms of locality, the rural areas in Ghana will spend a significant part of their annual average household income on cooking energy demand than the urban areas (Table S8). More specifically, rural areas will spend 4.22%–9.27% of their annual average household income on household pellet consumption, with rural savannah areas spending the highest (9.27%). Past studies in China show that rural households spend 9%–17% of their annual income on pellets [5,87]. A past study also reported that rural Indian households spend 11–13% of their monthly on clean cooking fuels, as opposed to 6–8% by urban households [5,88]. The higher cost of clean fuels hinders their adoption, especially in rural households [30]. Poverty is ubiquitous in Ghana's rural areas; thus, the residents rely solely on traditional biomass fuels [89]. The production and sale of wood and charcoal in these areas are critical to meeting household energy needs and livelihood support [90]. Though pellet production and use may reduce HAP, these residents may not be able to afford clean energy [91] and will continue to use charcoal and wood. The indigenous nature of charcoal production to meet household cooking energy requirements has resulted in huge vegetation loss in these regions [92]. Table S9 shows that annual national household pellet consumption will require 2.67% of the annual national average household income. About 43% of the average Ghanaian household income is spent on food [37]. With the high cost of cooking energy demand, income will play a significant role in household cooking energy choices. Since urban households in Ghana are more responsive to price changes in cooking energy than rural households [11], the introduction of pellets without proper pricing mechanisms may increase the use of wood and charcoal in urban areas, increase the financial burden of rural dwellers who adopt pellets and intensify deforestation in Ghana [22]. Thus, practical efforts are needed to enable the production, adoption and sustained use of biomass pellets in Ghana.

3.4. Barriers to the production and use of pellets in Ghana

3.4.1. The cost of pellets and gasifier stoves

The cost of pellets exceeds that of other solid household cooking fuels in Ghana [42,43]. The payment of Value Added Tax (VAT) on local pellet sales and the low market penetration of gasifier stoves influences pellet use [93]. A study [86] in the Bono, Bono East and Ahafo regions reported that although a ton of pellets should be sold at USD 225.22 for a 10% marginal profit, most respondents were willing to pay only USD 180.18. In rural Shandong and Heilongjiang provinces, the price of biomass pellets (USD 73–175) and heating stoves (USD 437–727) burden households, despite the significant government subsidies [5,94]. A report by the Ghana Energy Commission shows that aside from the <0.003% market penetration of pellet stoves, they are only provided to a handful of company-related customers [93]. More than 2.2 million Ghanaians use charcoal for cooking and heating [90]. Popular charcoal stoves in Ghana include the Ahibenso, Toyola and local coal-pot charcoal stoves, with the Gyapa charcoal stove having about 66% market penetration [93]. Gyapa charcoal stoves projects are carbon financed and are marketed at an affordable price (USD 2 per stove) due to the readily available local materials for production [37,95]. In addition to weak market regulations, charcoal stoves manufacturers use attractive incentives and advertisements to buoy the sale of their products [95]. The majority of respondents (59%) in a recent survey [95] were not willing to purchase a stove for more than USD 5. Also, the high duty and VAT on imports make clean energy stoves like gasifier stoves uncompetitive in the Ghanaian market [95]. The cost of clean household energy influences consumer preference and is a significant challenge to adoption in Ghana [95]. If practical fiscal measures are not put in place, the sustained production and use of pellets may not be successfully achieved in Ghana since 47% of Ghanaians, who are eligible consumers, are multidimensionally poor and would relish affordable energy for household cooking [89,96,97].

3.4.2. Limited research on biomass pellets

Past studies have highlighted the importance of assessing the pollutant emission characteristics, health and climate benefits of pellet combustion [98,99]. However, to date, only a few laboratory studies [71,73,100–105] and one field study [86] have been found that assess the properties, test emissions and cost analysis of producing pellets and using them in Ghana. There has been no pellet demonstration project in Ghana, as witnessed in other developing countries like China [5], Malawi [106], Rwanda [98], and Zambia [107]. This can be attributed to the lack of skilled personnel to conduct technical and feasibility studies [108]. Other reports on the benefits of pellets were based on projections rather than empirical assessments [31,32,109]. Previous field investigations reported no significant difference in emissions between traditional fuels and clean fuels [110,111]. There is still a lack of accurate data on pellet production and trade in Europe, thus affecting pellet markets' development and future trends [112]. In China, household heating with biomass pellets is limited due to the lack of convincing data on the environmental performance and benefits of these clean fuels [113]. Other studies in Rwanda [98] and Malawi [106] also report the uncertainty surrounding the use of biomass pellets due to the limited number of investigations being conducted. Thus further in-depth evaluation and comparison of emissions from pellet combustion with those of other solid fuel/stove combinations in Ghana is warranted. Apart from that, there is a dearth of information on the factors that impact pellets production and use, and require future assessments.

3.4.3. Lack of infrastructure

There is no primary pellet-producing factory in Ghana. Only recently, Abellon Clean Energy Limited and Philips Stove Company Limited started small-scale pellet production that serves a handful of business-related customers in Ghana [114]. Also, a robust collection system for raw materials has not been established since little is done to add value to biomass wastes in Ghana [86]. Past studies from China [82] and Norway [83] also reveal that the lack of an efficient feedstock collection system impacts the supply chain by increasing costs, limiting fuel production and the promotion of biomass pellets. This lack of infrastructure has contributed to the non-inclusion of pellets in Ghana's energy mix. Similarly, there is no evidence of the production of gasifier stoves for pellet combustion [7]. Improved biomass stoves manufactured in Ghana are only charcoal and wood-burning stoves and form only 25% of stoves used in Ghanaian households [25,115]. Although sawdust briquette could replace household wood and charcoal combustion [116], its large-scale production was suddenly halted in 1984 due to operational challenges and the breakdown of manufacturing plants [69]. Also, finding a suitable stove for sawdust briquette combustion remains challenging [117,118].

3.4.4. Inadequate financial support

The major problem confronting pellet production in Ghana is inadequate funding for research and development (R&D) [21,76]. Out of the USD 480 billion budget for clean energy, only 9% has been allocated to the R&D of pellets and other renewables [119] due to misuse. The estimated investment required for pellet production in the REMP is USD 304,500, of which the government expects 80% to be provided by the private sector [120]. However, little monetary contribution has been received from private investors because of the uncertainty of returns on investment and productivity [121]. Although from 2016 to present, the Chinese government makes annual investments on the order of USD 16 million to support biomass pellets production in Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shanxi, Shandong, Henan, Jiangsu, Anhui, Shaanxi and Sichuan provinces, biomass pellets projects have achieved modest success due to the lack of funding [122]. The current progress of the REMP implementation suggests that its goals may not be attained if more private investment is not obtained [120]. Of the ~3.5% of the REMP achieved so far (which is 10.5% less than the expected achievement), over 90% is from private investors, which signals the importance of the private sector to the attainment of pellet production and other targets of the REMP [120]. Also, the approved total budgetary support for R&D for the RE sector of Ghana is 0.25% compared to over 4% in Israel and South Korea [118].

The high cost of capital [7] is also a significant bottleneck to pellet development. Most bioenergy projects in Ghana use debt – either at the project level or on corporate balance sheets - to reduce financing costs [121]. These costs accrue high-interest rates and affect business growth [123]. Bergman et al. [124] reported that the high cost of labor and equipment impacted the production of wood pellets in the United States. A past study in Northeast Argentina revealed that the high cost of dryers (770,000 €) and other production factors increased annual energy consumption (194 GJ/year), and affected pellet production [125] Also, Ghana's reputation as having one of the highest global lending interest rates hinders the development of pellets [121]. This high lending interest rates increases the cost of borrowing for bioenergy companies and limits their operations. A study on low-carbon supply projects indicated that lower lending rates significantly impacted decision-making of firms, increased profit returns, and consequently reduced carbon emissions due to investment in efficient technologies [126]. The reduction in carbon emissions and promotion of carbon-reducing technologies have become an intrinsic part of the United Nations sustainable development goals [105]. To achieve SDGs, interest rates for short- and long-term borrowing need to decrease, especially for developing countries [127]. Also the Ghanaian cedi exchange rate volatility between other international currencies, particularly the United States dollar, remains a significant concern to most Ghanaian businesses and industries [121].

3.4.5. Social issues

A past study [128] stated that the social perspective is the primary issue influencing the acceptance of bioenergy energy projects in Ghana. The inability to develop pellets is due to the mismatch between the perspective of local communities and the country's vision regarding why they should be promoted [128]. Previous studies [129,130] reveal that weak social support for cultivating different feedstock due to the centralized approach stifles broader community participation. The lack of public participation in biofuel projects contributes to Ghana's inability to develop and use pellets [131]. For example, limited public participation contributed to the failure of Ghana's Jatropha sector [130]. Farmers affected by Ghana's Atuabo gas project and traditional rulers were not involved in discussions about compensation for farmlands loss [132]. In rural Heilongjiang, residents did not entirely accept biomass pellets due to their high cost, and their non-inclusion in planning the biomass pellet heating projects [94].

Aside from the issues with land availability and rights [133], there is no long-term guarantee for a continuous land supply due to the negative impacts of shifting cultivation and the shortening fallow period [128]. The livelihood uncertainty deters local people from committing their land to cultivating bioenergy crops [134]. For example, farmers in Brazil are often pushed to the peripheral in the modern bioenergy sector, and thus multinational companies exploit them leasing to their overall unwillingness to participate in clean energy projects [135]. The current legislation on compensation for loss of land in Ghana only mandates payment for land acquisition by the state through its eminent domain, for which replacement with equivalent land or the payment of the market value of the land and cost of disturbance is compulsory [136]. There is no provision for other land acquisitions, hence the widespread violation of peasant farmers' land rights [136]. Farmers and other landowners have high levels of insecurity and uncertainty due to the possibility of losing their lands to project investors or selfish chiefs [50].

Also, due to the lack of necessary institutional arrangements and infrastructure support for commercial-scale bioenergy generation [128], technology and market barriers in Ghana are not developed to support pellet production [108]. Though a million hectares of land is dedicated to producing biofuel feedstock crops, Ghana has no domestic use of biofuel. In the United States, the lack of public awareness and skilled personnel, along with economic, technological, and regulatory barriers, remain significant to bioenergy projects including pellets production [137].

Another major bottleneck to pellet production and use is the lack of public awareness [120]. While most Ghanaians still lack clean fuel awareness, others perceive it to be costly [138]. In Indonesia, the lack of public education has caused biomass pellets to not become common in rural communities [139]. A previous investigation [140] reported that household family size, income, and household head's employment status influenced the adoption of clean fuels. The conservativeness of users in terms of food tastes, cooking habits, and fuel availability has also limited the demand for clean fuels [7,30]. A study in Shaanxi also reported that household fuel choices were influenced by housing characteristics, cooking and heating habits and stove use patterns [9]. The unavailability of pellet fuels in Yangxin county is a significant limitation to household heating with biomass pellets [5]. The Gyapa charcoal stove market is Ghana's only formalized market [115]. Although it does not have significant emission reductions [110], its existence significantly limits consumer choice and the preference for other stoves and fuel types [141]. Currently, only 22% of Ghanaians have access to clean cooking fuels [85], and 22 million still rely on wood and charcoal for household energy [142]. Recent reports also state that although studies have quantified the socioeconomic factors that limit clean energy transitions, little attention has been paid to the impact of peers, although that matters in household fuel choices and is critical in the cultural context of developing countries [143,144].

3.4.6. Policy issues

Despite the growing political acceptance of clean energy, there is a lack of governmental commitment to take decisive actions to promote pellets [78]. The high dependency on fossil fuels for economic development restricts the penetration of RE sources [145]. Past studies also echo the insufficient capacity of current government policy frameworks to promote clean energy transitions [28]. For example, despite the wide recognition of biomass pellets by the Chinese government, the medium and long-term development plan for bioenergy does not have clear targets and strategies for including biomass pellets in development planning, nor does it stipulate the functions of the different departments concerned with the development and planning of biomass pellets heating to enhance efficiency [146]. Ghana is no different as it is far behind its REMP targets, especially in producing and using pellets, since this project relies heavily on electricity, whose supply is erratic in Ghana [120]. The low coordination among stakeholders in renewable energy planning accounts for their non-commitment to the REMP [78]. Ghanaians have yet to feel the impacts of the REMP in leveraging macro-environmental forces and encouraging indigenous investment in RE technologies [147] since most actors are oblivious to the entire plan [78]. Apart from the modest 3.5% target achievement of the REMP, there is no access to pellets [7,120].

Several sections of the SNEP are yet to be executed due to challenges in legislation, monitoring and compliance obligation by the Ghana Energy Commission [76]. Investors are deterred from financing biofuel projects in Ghana because most policies lack effective implementation strategies and do not state specific time frames for achieving their targets [148]. In Brazil, the development of biofuel projects is still nascent due to the instability of policies and their influence on foreign investment [149]. Apart from the ambiguity of Ghana's RE Act, it remains disintegrated in its planning and implementation and lacks supervisory authorities to enforce and review its mandates [150]. A recent study [151] found that poor business planning, institutional barriers, and policy inadequacies have resulted in the closure of 12 of 17 Jatropha plantations in Ghana. In Rwanda, inadequate government policies to promote biomass pellets also influence public awareness and the failure with households transitioning to clean household energy [152]. The failure of the GoG to assume responsibility for unrealized targets of biofuel projects, coupled with the lack of implementation of regulatory policies, significantly impacts the promotion of pellets [151]. The significant impact of the Feed-In-Tariff (FIT) on the RE sector is not realized because of the ineffectiveness of the renewable energy fund [76,153].

Most of the challenges confronting pellet production in Ghana are tied to political regimes [154]. Most policies are subject to change in the ruling government in Ghana; thus, there is no stability in investment in the RE sector [147]. For example, the solar photovoltaic and wind energy projects suspended license issuance in 2017 from the GoG and failed to experience a successful penetration into the energy mix [154]. Due to a lack of policy instruments and the appetite for borrowing to finance RE projects, the GoG is compelled to enforce neoliberal policies dictated by donors, not in agreement with national statutes [150]. For example, the Ghana Ministry of Energy unwillingly failed to publish the government's guarantees to support RE projects but instead sought the assistance of the World Bank and the African Development Bank for partial risk guarantees [150]. Implementing these neoliberal policies has often been disadvantageous to Ghana and presents uncertainties about GoG seeking donor support for RE projects [150]. Aside from the institutions responsible for promoting and developing pellets and other renewable energy not being adequately furnished with the necessary resources and personnel to carry out their duties, there is a lack of coordination among them [145].

3.5. The implication of pellet production and use in Ghana

3.5.1. Socioeconomic implications

Pellet production is projected to create 4,570 jobs [118], reducing Ghana's high unemployment rate [155]. The biofuel industry is also proposed to create 25,000 jobs in Ghana through feedstock cultivation, processing, and factory work [46]. Feedstock supply through sustainable agricultural practices will add USD 400 to the per-capita income of Ghanaian farmers [156], thereby alleviating poverty and empowering rural dwellers [157]. A previous cost-benefit analysis reported that groundnut production in Ghana would reduce extreme poverty by 3.6% by enhancing energy production and access to international markets [158]. Past studies on hydrochar briquettes production from biomass feedstock in China report on the favorable energy density (23 MJ/kg) of the fuels, and the potential to replace energy demands from fossil fuel [67,68]. Using pellets can ensure power generation, safe household cooking and enhance the delivery of small-scale industry services [7,159–161]. The energy from pellets could power medical refrigeration facilities and enable access to potable drinking water for rural households in Ghana [50].

In Ghanaian households, women and children spend an average of 1.6 h every day searching for wood for cooking [162]. This act exposes them to dangers like physical and sexual abuse, long-term physical damage from strenuous work, and loss of school time [163]. A previous evaluation of how solid fuel use affects early child development in Ghana [164] found that 85% of children, especially girls, were more likely to suffer from cognition, numeracy, and social, emotional and physical impairments. Thus, access to pellets would allow women to engage in proper child care and complete other household tasks. Children, especially girls, would have good development and enough time to pursue an education or engage in any means of livelihood [30]. The production of pellets would attract over USD 306 million in investment to enable economic growth [120]. A past study [165] found that Ghana suffers a daily loss of USD 2.1 million in productivity due to the 50% increase in energy demand and its consequent energy distribution problems. A recent review [166] stresses the need for more sustainable energy alternatives to reduce the effects of future energy crises and buoy economic growth. Thus, past studies suggest that pellets would contribute to over 54% and 91% of the national household cooking wood and electricity demand [22,31,32,167].

However, other studies suggest that supplanting charcoal production and use with pellets may impact the livelihood of different categories of people involved in the charcoal commodity chain and, consequently, the national economy [90]. There are no clear national policy guidelines regulating charcoal production; thus, the market penetration of biomass pellet and gasifier stoves may remain challenging due to an already-established consumer preference for local stoves [90]. The deforestation rate in Ghana [24], coupled with ineffective regulation in the timber processing sector [23], threatens the raw material supply for wood pellet production. A past study [160] projected that biofuels will negatively affect food prices and imports in Ghana by 2030. Already, about 15 million Ghanaians are multidimensionally insecure [96]. Thus with the considerable cost associated with household pellet consumption, many households may not be able to afford this clean energy and would continue to use wood and charcoal [89]. Also, future pellets production may lead to land availability issues for plantation-based projects and land-use conflicts [153,168], threatening low-income households without legal land rights [151]. A past study [169] reported that many families in Ghana's Brong Ahafo and Ashanti regions were coerced into relinquishing landholdings to develop biofuel plantations without compensation, which directly affected their livelihood. Defragmentation and loss of land could stir insurgencies and threaten a community's sovereignty [157]. Lastly, the high capital cost associated with fuel pricing and feedstock and equipment procurement threatens the development and use of pellets in Ghana [170]. Other studies [171] suggest that an increase in feedstock production will lead to cheap labor and, consequently, low-income levels/unemployment in Ghana.

3.5.2. Health implications

Most households in Ghana, especially in rural areas, are exposed to high levels of HAP due to the burning of wood and charcoal [164]. HAP accounts for the loss of 502,000 disability-adjusted life years (DALYs), 18,000 premature deaths per year, and 2.2% of Ghana's national burden of disease related to solid fuel use [172]. Recent studies [21,109,173] project that the household demand for wood and charcoal will increase and constitute about a third of the total energy demand by 2030. Thus, practical solutions are required to alleviate the health issues linked with the surging dependence on traditional biomass fuels for household cooking. A past study reported that sawdust pellets burned with no smoke compared with other biomass fuels [73]. Mawusi et al. [105] found that the range for emission factors based on useful energy delivered of CO and $PM_{2.5}$ were 2.12–3.51 and 0.23–0.26 g/MJdelivered, respectively, for wood stoves; 4.45–4.82 and 0.04–0.05 g/MJdelivered for charcoal stoves; and 0.51–0.82 and 0.04–0.06 g/MJdelivered for pellet stoves. A field test in Rwanda also reported that $PM_{2.5}$ and CO emission factors from the Mimi Moto pellet stove, three-stone fire, and Jiko charcoal stove were 0.2 ± 10 and 20 ± 40 g/kg, respectively; 18 ± 35 and 110 ± 95 g/kg, respectively; and 0.7 ± 38 and 320 ± 210 g/kg, respectively [98]. A previous study [7] showed that transitioning to clean fuels offered the most significant health benefit by reducing the cost of monthly household medical bills by USD 0.95 compared to charcoal (USD 0.66). Aside from the harmful effects of wood combustion in Ghana, improved stoves, including the Gyapa, do not have significant emission reductions [110,111]. The low HAP from pellet combustion will reduce medical bills, illnesses and deaths associated with HAP [105,173]. Another study [12] revealed that clean cooking increased the share of healthy household members by 19.11%, of which the majority are women and children. A laboratory modelling analysis [105] revealed that replacing wood burning in three-stone fires, and charcoal stoves with the adoption of pellet stoves in a million Ghanaian homes would avert about 24,994 and 1482 disability-adjusted life years, and 592 and 36 deaths every year, with majority of the health benefits being reductions in acute lower respiratory infections in children below 4 years. A field test in Rwanda reported the estimated adjusted relative risk for cardiopulmonary and cardiovascular disease associated with household using three-stone fires, charcoal stoves, and pellet stoves were 2.1, 1.45 and 1.4, respectively [98]. Studies on sustainable development [167] and crop residue pellets [31] in Ghana stated that significant household health benefits of pellets outweigh that of LPG because of the gas leakages, cylinder explosions and surmised accidents associated with LPG acquisition.

However, further analysis into the socioeconomic, health and climate co-benefits of pellets is suggested, with priority to the sensitivity of fuel production cost, supply chain factors, and environmental benefits. This will enable policymakers make informed decisions about the impact of the production, adoption and sustained use of biomass pellets in Ghana. Despite the increased household adoption of clean energy like LPG in most urban areas, the reliance on wood and charcoal for household cooking remains high [11,111]. Hence the capacity to replace cooking demands with pellets as time passes may be low. The evidence of stove stacking in urban areas, especially in Accra, has been documented in past studies [174–176] and attributed to fuel availability issues and ease of access [7]. Apart from gasifier stoves producing high ultrafine particles [177], the quality of pellets, especially crop residue pellets, influences particulate matter emissions [5]. Past studies [111,178,179] indicate that post-intervention household exposures still exceeded health-relevant targets for many clean cooking technologies in Ghana. Thus, practical measures are required to salvage this situation due to the influence of traditional biomass fuel combustion on HAP in Ghana [179]. Again, the intense use of agrochemicals for crop production raises public health concerns associated with water pollution [29]. The surmised food insecurity [160] associated with pellet production could heighten cumulative hunger, malnutrition, developmental defects in children, and susceptibility to infectious diseases [127,180,181] among rural households in Ghana.

3.5.3. Environmental implications

Producing pellets from crop residues and wood waste would reduce open burning [51] and may restore ambient air quality in Ghana [182]. The circular economy associated with pellet production will provide an environmentally safe waste management procedure [170]. Morelli, Cashman, Rodgers and Thorneloe [40] revealed that the cumulative cooking energy demand for wood pellets in Ghana (4350 MJ) is lower than those of charcoal (15700 MJ) and firewood (9200 MJ), and would significantly reduce the high household demand for wood and charcoal and quell the alarming deforestation rate caused by charcoal and wood fuel production. Other studies in Ghana also reecho how biomass pellets would reduce household consumption of wood and charcoal [7,31,32]. The near-term global warming contributions from household cooking with biomass pellets, wood, and charcoal in Ghana were 3200, 4300 and 3800 kg-CO_2e/year/household [105]. A past life-cycle study on cooking fuels in Ghana reported that the global warming contribution and particulate matter formation potential for wood, charcoal and biomass pellets were 228 kg-CO_2e and 15.5 kgPM_{10}e respectively, 712 kg-CO_2e and 10.2 kgPM_{10}e respectively, and 152 kg-CO_2e and 0.162 kgPM_{10}e respectively [40]. Seglah et al. [58] reported that electricity potential from crop residue biofuels like pellets (~3100 GWh) could offset about 16% of electricity consumption and 2,507.35 kt CO_2 eq of GHGs in Ghana, with Ashanti (478 GWh), Eastern (430 GWh), Bono East (319 GWh) and Northern (314 GWh) regions demonstrating highest electricity potential. Kuamoah [183] and Azasi et al. [31] also reported that using pellets for electricity would reduce greenhouse gas emissions (GHGs). In India, electricity generation potential from biomass pellets (229 TWh) is predicted to increase to 244 TWh by 2030, The associated CO_2 mitigation potential through the substitution of coal is estimated to rise from 192 MtCO_2e in 2020 to 205 MtCO_2e by 2030 [184]. Electricity generation from wood pellets in Canada reduced GHG emissions by 91% and 78% relative to coal and natural gas systems, respectively. Compared to coal, wood pellets reduced NO_X emissions by 40–47% and SO_x emissions by 76–81% [185]. Previous assessments of Ghana's carbon emissions [166] also show that the use of pellets would reduce atmospheric CO_2 emissions, with significant reductions (about 12%) observed in the residential sector [109]. A past assessment of straw utilization for energy [186] found that straw residue had carbon emission factors of 0.09–0.18 kg (CO_2 eq per 1 MJ), and presented a net carbon emissions reduction of 0.03–0.15 kg (CO_2 eq per 1 MJ) compared with the convectional electricity or petrol. According to Tauro, García, Skutsch and Masera [187], the market energy potential for pellets from agricultural and forest residues in Mexico (131 and 233 PJ/yr, respectively), could offset 73% of LPG and natural gas demand for heating, and mitigate 18% of GHGs from electricity production.

However, the life cycle of pellet production is linked to severe air pollution, adverse climate impacts and intense land changes [188]. A comparison of the environmental effects of cooking fuels in Ghana reported that the production of biomass pellets was associated with the highest upstream emissions (7.82%) as opposed to charcoal (5.7%) and wood production (~0%) [105]. The production of pellets would increase GHG emissions and impact biodiversity due to the conversion of natural ecosystems for crops and wood plantations [50,189]. Intense farming practices and agrochemical products to ensure crop residue supply may result in water stress, soil and water pollution and loss of biodiversity [29]. The uncontrolled use of agrochemicals has resulted in severe pesticide levels in fish [190] and pollution of primary water sources like the Densu and Pra river basins [191–193]. Unsustainable agricultural practices in Ghana have resulted in an elevated level of Nitrates [194,195] and fluoride [196,197] in surface and groundwater. Morelli et al. [40] found that the fossil fuel depletion and water depletion potentials associated with producing cooking fuels in Ghana were 0.007 kg-oil eq and 8.16×10^{-5} m^3 respectively for wood, 10.6 kg-oil eq and 0.135 m^3 respectively for charcoal and 21.2 kg-oil eq and 0.868 m^3 respectively for wood pellet fuels. Studies in Thailand [188] Canada [198] and China [199] have also reported significant environmental pollution due to pellets production. A lifecycle assessment of wood pellets from agro-forest species in Pakistan reported that the intense fossil fuel consumption associated with fuel production was the largest contributory factor to significant environmental impacts; acidification (0.006 kg SO2 eq/kg pellets), abiotic depletion (0.018 kg Sb eq/kg pellets), marine aquatic ecotoxicity (417.803 kg 1,4-DB eq/kg pellets), human toxicity (1.107 kg 1,4-DB eq/kg pellets), freshwater aquatic ecotoxicity (0.191 kg 1,4-DB eq/kg pellets), eutrophication (0.001 kg PO4 eq/kg pellets), global warming (0.802 kg CO2 eq/kg pellets), and terrestrial ecotoxicity (0.008 kg 1,4-DB eq/kg pellets) [200].

3.6. Lessons learned from global biomass pellets production

Europe is the world's largest pellets producer, and its countries have collectively implemented a common pellet quality standard (EN 14961-2) [201]. However, the rapid establishment of pellet plants in most parts of Europe has resulted in uneven market characteristics and pricing, poorly developed pellet markets, and high costs of raw materials [202]. There is still a lack of accurate statistics on pellet production and trade [112], affecting pellet markets' development and future trends.

Pellet production in China has increased significantly and has been ranked the highest globally for the past five years [203]. Aside from increasing the share of biomass fuels in the national energy mix, China has also formulated relevant standards for biofuels, including pellets [5]. Over 200 pellet-producing factories in 5 provinces, each producing 100,000–300,000 tons of pellets annually

[204]. Yet China's pellet industry's development is still comparatively slow [199]. Past studies [205] report that large amounts of straw are wasted because its collection, transportation, and preservation are labor-intensive and costly. Also, most of the pellets produced do not meet the national standard requirements due to the dispersed nature of pellet production [5]. A recent study reported high emission concentrations from straw pellet combustion [94]. The Chinese pellet standard does not cover other industry sections such as collecting, storing and transporting raw materials, fuel marketing, and environmental protection [204]. Furthermore, due to a lack of mandatory development goals, policies to incentivize the use of pellets have not made a significant impact [204].

In Rwanda, pellets and gasifier stoves were promoted through the Inyenyeri enterprise and the Emerging Cooking Solution program [98,206]. Measures to develop pellets production include a constant feedstock supply from rural customers and government-owned biomass plantations [206]. The Inyenyeri enterprise has also subjected its marketing model to various tests to understand Rwanda's socioeconomic and technical barriers to clean cooking [207]. The pellets were sold to households monthly at a relatively lower price than charcoal [208] to ensure affordability. Apart from centralized pellet production, there was an exploitation of the economy of scales and the inability to establish essential distribution facilities [206]. This situation has resulted in a disagreement between scale-up and finding the required capital to create a pellet supply chain [208]. Though rich in forest materials and labor, all four pellet factories in South Africa were closed after a few years of operation due to the unavailability of raw materials, costly logistics, lack of skilled personnel to run factories and the increase in the cost of feedstock treatment due to contamination [16,209]. Other African countries such as Malawi [210] and Uganda [211] have conducted feasibility studies on how to increase the share of biomass pellets in their energy mix. Thus, the production and use of biomass pellets in Ghana can be achieved through the formulation of effective policies and financing schemes, implementation of relevant fuel quality and industry standards, building a robust supply chain and solving other technical that limit pellet development.

3.7. Pellet development route for Ghana

Though a nascent technology [206], the successful production of pellets relies on building a comprehensive network that involves the supply of raw materials, the availability of skilled labor, the capacity to adapt to new technology, an adequate market demand, and efficient policies that attract investments and strengthens clean energy commitments [201]. The suggested route for the effective production and use of pellets in Ghana is shown in Fig. 5.

3.7.1. Establishment of a robust supply chain

Recent reviews on clean energy transitions [30,208] state that attention is not paid to the significant impact of the supply chain.

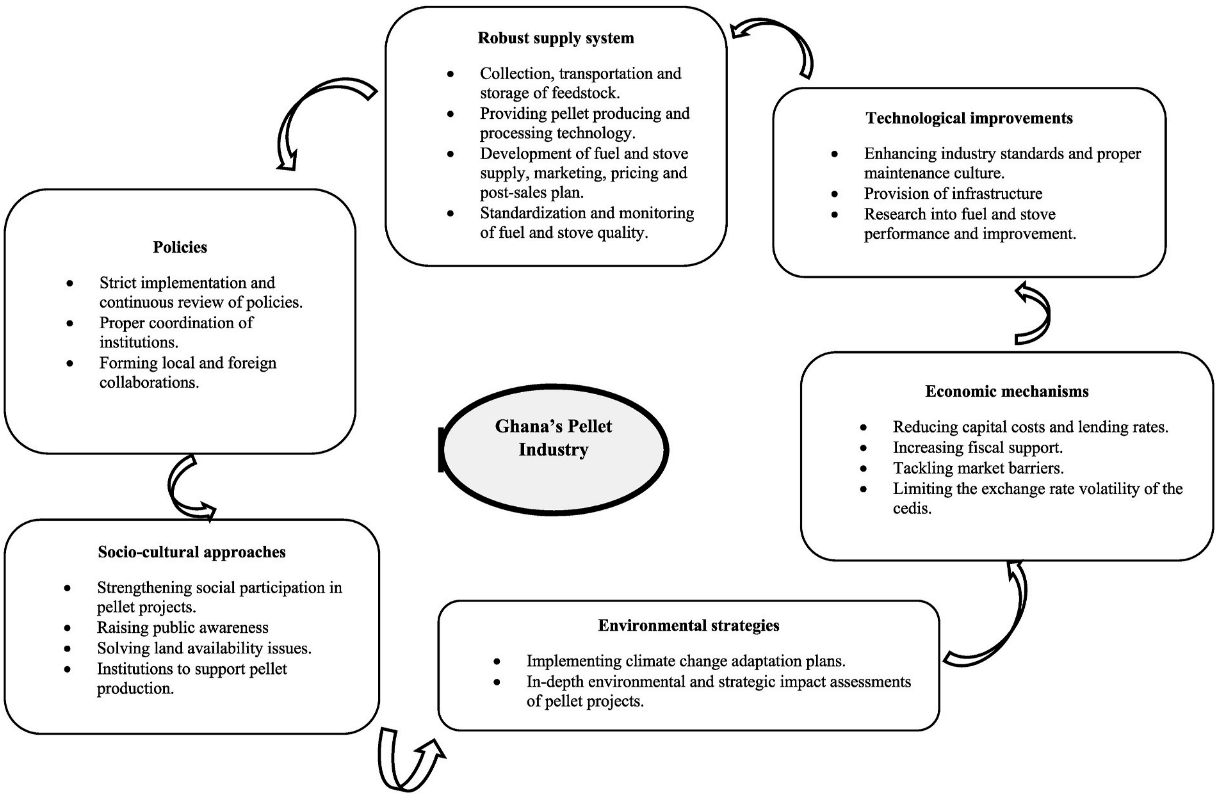

Fig. 5. The suggested route for pellet production and use in Ghana.

The upstream of a pellet supply chain (harvesting, transportation, storage and treatment of feedstock) is vital to promoting biomass pellets in Ghana [212]. Feedstock availability ensures an uninterrupted supply of end products so that a particular supply network can respond to market demands [213]. In Ghana, a robust feedstock supply system can be achieved by optimizing and coordinating the collection of crop residues and wood waste from the sectors that generate huge volumes of waste for pellet factories. China produced 30 million tons of pellets in 2020, compared to 9.6 million tons in 2016, by increasing the feedstock supply [203]. Sourcing feedstock from large providers will cut costs and time for collection and transportation to factories [214] and maximize production.

Since energy consumption is integral to the supply chain, improper transportation management from fields to factories can reduce overall efficiency and economics [215]. Thus, pellet factories should be sited at optimal locations to ensure lower transportation, capital and operating costs [216]. Ghana can ensure constant pellet production by spreading out or localizing factories, as seen in Europe [201] and China [199]. Mid-South and Northern Ghana could be optimal sites for pellet processing facilities as copious amounts of crop residue, and wood waste are generated in these areas [27,31]. The Ghana Ministry of Transport and other stakeholders must tackle issues with poor road networks [217] and transport mediums to ameliorate transportation's associated inconveniences and dangers. Problems with feedstock storage and treatment are not adequately understood within the pellet industry. For example, improper biomass storage in Malaysia during the lockdown from March to April 2020 caused the closure of many factories and affected energy generation in South Korea and Japan [212]. The varying properties of biomass feedstocks influence their heating value, combustion temperature and efficiency [218]. The choice of feedstock pretreatment and pelletization process can significantly impact pellet production [219,220]. However, treatment methods require using state-of-the-art technology to produce good quality pellets [19], which is capital intensive [221].

Though not prevalent in Africa, regions like Europe and China [146,201] have pellet standards [5]. To enhance fuel and stove quality, the GoG must develop standards in conjunction with yet-to-be-developed pellet firms. The GoG can employ International Organization for Standardization pellet fuel and stove standards as done in countries like Malawi and Rwanda [208]. Because high prices deter low-income households from adopting clean energies, the GoG and pellet-producing factories must make pellet and gasifier stoves affordable [199]. Pellet-producing firms in Ghana can provide fuel directly to homes or depots, as done in India and China [199,222], by liaising with local sales and advertisement enterprises. Finally, pellet businesses should develop strong business models that cater for the warranty on purchased products and use labor from local areas [30] to guarantee the success of pellet production and use in Ghana.

3.7.2. Technological advancement

Pellet production involves infrastructure and sophisticated technology [66,212,220]. The GoG and other RE research institutions must facilitate research into various pelletization technologies [220] and appropriate combustion devices to ascertain which applies to the Ghanaian setting and would provide the surmised benefits. The existing pelletization methods include hot press pelletizing, cold press pelletizing and charring pelletizing [223]. Currently, the primary biomass molding equipment are ring molding roller forming machine, flat embossing roll forming machine, roll extrusion molding machine, mechanical piston molding machine, hydraulic piston molding machine and spiral hot press molding machine [223]. The molding of pellets is impacted by the types, particle size, moisture content of the feedstock, molding pressure, and heating temperature [224,225] and requires further investigation and understanding to enable the development of pellets in Ghana. The lifecycle of pellet production generates high upstream emissions due to the intense use of fossil fuel during production [105, 226]. Thus, the production of pellets should employ practical measures of lowering energy consumption and climate-altering emissions.

RE transition in Ghana is also influenced by a lack of skilled personnel and knowledge on developing, operating, and maintaining renewable energy systems [78]. Other studies highlight the decadence in maintenance culture [121, 227], especially in the public sector of Ghana. Pellet-producing factories and equipment require regular upkeep to ensure their continuous function. Thus, the GoG and other regulatory bodies must provide clear industry standards to protect equipment and personnel and prevent mishaps [228]. Training should be provided to equip personnel with skills for operating and maintaining Ghana's pellet industry and its processes. Lastly, further investigations must be conducted [98] to assess the socioeconomic, climate and health benefits of pellets production.

3.7.3. Economic mechanisms

The GoG can attract investments from state-owned institutions like the Ghana Commercial Bank, the Bank of Ghana and other private investors and donors to enable the development of the pellet industry. Apart from this, the GoG must create conditions for establishing green banks where RE projects can acquire lower-interest loans [229]. Subsidizing pellets would contribute significantly to their production and sustained use in homes and industries [230]. For example, pellet-producing companies in China receive more than 80% subsidy in operating costs from the government and other financial institutions [231]. Investment, subsidies and other national incentives on household levels in Europe have been the driving forces for developing domestic pellet markets [201]. The GoG and pellet factories should develop a robust business model to cater to diverse customers and various monetization schemes [227]. The high cost of capital for pellet production can be reduced through tax exemptions or reductions and tax rebates [7]. Other indirect support programs to attract investment, enhance the competitiveness of pellets against conventional fuels, remove market barriers and help include pellets in the energy mix are essential [218].

3.7.4. Environmental strategies

Though the benefits of pellets outweigh that of LPG, the life cycle of pellet production causes severe environmental issues like increased air pollution and intense land changes [188]. However, the evaluation of pellet production cost considers only internal costs of materials, labor, energy and equipment and leaves environmental externalities to be borne by third parties in the form of medical expenses, accident compensation and poor environmental quality [232]. The GoG and the Ghana environmental protection agency must ensure that environmental impact assessments of pellet projects are carried out per the environmental statutes of Ghana [233]. Regular environmental audits must be carried out to ensure industry compliance and assess the impact of pellet projects. For example, China conducts regular audits to assess how pellet production influences carbon emissions, the economy and health [199]. This monitoring role will help ameliorate the negative environmental and social impact of biofuel generation already prevalent in Ghana [234].

3.7.5. Sociocultural dynamics

The sustained production of pellets in Ghana can be realized by correcting the mismatch between local community perspectives and the country's vision regarding clean fuels [128]. Rigorous efforts should be made towards pellet demonstrations and promotion programs to conscientize citizens [176] since most Ghanaians are oblivious to pellets [7]. The public can be sensitized through social media, other media avenues and campaigns conducted in local dialects. Involving communities in pellet projects will pique their interest and address socio-cultural issues affecting production and adoption [30]. Aside from this, the GoG should provide attractive compensations to reduce livelihood uncertainty that deters local people from committing their land to bioenergy projects [134].

Because Ghana's large-scale development of bioenergy sources occurred devoid of the necessary institutional arrangements and infrastructure to support it [151], technology and domestic market barriers are not developed to support clean fuels like pellets [128]. Ghana has no domestic use of biofuels, even though over two million acres of land have been delineated for cultivating feedstock crops [128]. To achieve the targets of the REMP, Ghana's RE sector must be strengthened to resolve the fragility of the network between the various stakeholders due to conventionalized and bureaucratic institutionalized systems [78]. Also, the capacity of the stakeholders, NGOs and private institutions within the RE sector must be built to enable proper institutional arrangements and the provision of infrastructure to support pellet production and remove market barriers [108]. The Lands Commission of Ghana and the Ministry of Agriculture should intensify the ongoing planting for food and jobs program [134, 235] as a panacea to resolve land rights and availability issues related to commercial biofuel projects [133] since there is no long-term guarantee for a continuous land supply due to the negative impacts of shifting cultivation and the shortening fallow period in Ghana [128].

3.7.6. Policy reforms

Political and regulatory barriers are critical to RE development in Ghana [236]. The production and sustained use of pellets can be achieved by stabilizing the political environment. The energy policy instruments in Ghana should be devoid of ambiguities on specific timeframes for achieving targets [183]. The GoG can devise incentive packages to attract private sector investment for its REMP. When backed by a well-justified reason, such an incentive receives public backing, signals strong policy directions and is not affected by changes in political regimes [120].

The GoG should address issues with policy support instruments like the FIT and RE fund to help grow the renewable energy sector and reduce borrowing [108]. This is vital since investors compare the capital cost of renewable energy projects to conventional energy and their rate of return [119]. To increase acceptance and awareness of pellets, relevant stakeholders should be consulted during energy policy formulation [78]. Coordination between relevant energy experts and institutions should be devoid of conflict and political biases to help develop clean fuels such as pellets. Strict policies and supervisory authorities should be employed in the RE sector to reduce nepotism, corruption and the circumvention of appropriate procedures in favor of partners since it deters investment and limits the sector's development [236, 237]. Because low-income households struggle to adopt clean fuels, the GoG should provide subsidies and enforce practical rules to phase out wood and charcoal, as seen in countries like China [238] and Indonesia [139]. Providing attractive incentives to households, especially in the savannah zone, will discourage the use of wood and charcoal and enable the adoption of pellets. This is important since the forest stock per hectare is very low in these areas [239]. Also, the rural LPG program should be intensified to increase the share of LPG use in rural Ghanaian households [240]. Lastly, RE policies must be constantly reviewed to make them effective and create accessible economic avenues for developing biomass pellets [119].

4. Conclusion

Apart from the substantial available biomass resources, Ghana has high market demand and policies to enable the production and use of biomass pellets. However, access to pellets has not been attained due to ambiguity in renewable energy policies, including the Renewable Energy Master Plan, and the lack of coordination amongst energy experts and institutions. This observation has resulted in limited research, infrastructure, and private sector participation in pellets production. Other issues such as the huge capital cost of businesses, dissenting perspectives between the populace and government about the importance of clean fuels, and limited necessary institutional support arrangements remain bottlenecks to the production, adoption and sustained use of pellets in Ghana. Our estimates also show that when pellets are produced, significant portions of average household incomes will be spent on household pellet demand compared to other solid fuels. To achieve the production and sustained use of pellets, the government of Ghana must show commitment to renewable energy development through policy reviews. This will attract foreign investment to fund pellet production and strengthen the regulatory capacities of the renewable energy sector. Attention should be paid to providing infrastructure and equipment for feedstock collection, processing and pelletization. An enabling environment for the pellet industry can be created by raising public and industry awareness, providing fiscal incentives and encouraging community and private sector participation in pellet projects. Also, thorough impact assessments addressing the climate, health and socioeconomic issues related to pellet production are essential.

This review does not replace the thorough investigations required to establish national energy priorities or the social and political considerations necessary to execute substantial public health, energy and climate interventions. However, it gives an evidence-based assessment and framework for comparing Ghana's current clean technology and policies on health and climate and assessing whether the current efforts are on track to meet the sustainable development goals. The recommendations can inform policymaking and help build a robust model for developing and upscaling biomass pellets and other renewable energy sources in Ghana.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data associated with this study has been deposited at

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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