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RESEARCH

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Assessment of agricultural residue potential for electrification of off-grid communities in the Sawla-Tuna-Kalba District of Ghana

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Abstract

Background There is a close link between the lack of electricity access and poverty indicators such as illiteracy, high infant mortality, lack of access to health care and malnutrition among others. Most rural farming communities in Ghana lack access to electricity due to the high cost of extending the grid to these communities. This lack of access tends to worsen the gap between urban and rural inhabitants regarding access to education, healthcare and development.

Methods This study assessed the technical and theoretical potential of agricultural residues in providing electricity to off-grid communities. The study used crop production figures of maize, cassava, millet and groundnut in the Soma and Goyiri farming communities in the Sawla-Tuna-Kalba District to conduct an assessment of the theoretical and technical potential of residues from the crops. The production figures of these crops were obtained from the District Office of the Ministry of Food and Agriculture. Expected electricity demand of households, schools and health centers in the study communities were collected and employed for the projected load demand estimates.

Results The study found that 312.23 MWh/day of electricity could be generated from the combined residues of maize, cassava, millet and groundnut from the two communities. This amount of electricity is capable of providing ~ 202 to 263 times the peak electricity demand of the studied communities. Out of the total electricity demand of the two communities, only about 91 kWh/day is needed for use in a school and Community Health Promotion and Services (CHPS) compound, implying that the electricity from crop residues can also help to improve education and health provision in the rural communities.

Conclusion It is concluded that the potential of crop residues in meeting the electricity demand of off-grid communities is enormous. Hence, it must be considered in Ghana's energy development plans to achieve universal electricity access.

Keywords Agricultural residue, Electricity access, Off-grid communities, Recovery factor, Technical assessment

Background

Access to energy is a key factor for socio-economic growth globally [1]. Almost all domestic, commercial and industrial activities rely on the quality and quantity of energy to thrive [2]. Energy access, especially access to electricity, contributes to good healthcare, education and green job creation globally [3]. According to Huttunen et al. [4], energy access must take into consideration the availability of affordable and reliable clean

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cooking facilities and electricity that can sufficiently provide basic energy services like powering light bulbs and radios, and charging basic domestic gadgets like mobile phones, rechargeable lamps, etc. All over the world, there has been a disparity between urban and rural electricity access rates [5].

Globally, 1.3 billion people, representing roughly 16% of the world's population, still lack access to electricity, and 85% of this population lives in rural communities [6]. Approximately 97% of people without access to electricity come from sub- Saharan African (SSA) countries [6, 7]. Furthermore, over 3 billion people globally still rely on fossil (coal, oil and gas) and wood fuels (firewood and charcoal) for their energy needs, with a majority of this population coming from SSA countries and South Asia [2]. These fuel sources affect climate change due to their heavy carbon emissions. The amount of greenhouse gases (GHGs) in the atmosphere today is 40% higher than pre-industrial levels [8]. According to the Intergovernmental Panel on Climate Change (IPCC), global average temperature rise must not exceed 2 °C higher than pre-industrial temperatures [8].This prevention of global temperature rise can be achieved by using more sustainable forms of energy with either fewer or no carbon emissions.

Ghana, like most SSA countries, lacks access to clean energy and relies heavily on fossil fuels to meet its energy demand, despite the country being rich in renewable energy sources like solar, biomass and wind, which have the capacity to exceed the country's energy demand [9] when fully harnessed. At the end of 2020, Ghana's total electricity generation was about 5488.82 MW, comprised three hydro generation plants which provide a total of 1584 MW (34.1%), fifteen thermal plants with a capacity of 3753 MW (65.3%) and thirteen renewable energy plants (nine on-grid, two off-grid and two mini-grid), totaling to roughly 119.865 MW (0.55%) [10].

The current electricity generation mix of Ghana shows a great increase in thermal-based generation, which depends on fossil fuels at the expense of hydro generation due to the growing electricity demand caused by increasing population growth, industrialization and decreasing levels of water as a result of climate change. There remains ~ 37% of the national population living in remote areas and island communities, who lack access to electricity due to the high cost of extending the national grid to those communities [11]. Access to reliable and affordable electricity is a very essential commodity for domestic, industrial and commercial activities [4]. There is a close link between the lack of electricity access and poverty indicators like illiteracy, high infant mortality, lack of access to health care and malnutrition among others [12].

It is important that the contribution of distributed energy generation using renewables ensures universal electricity access. Yet, renewables have not received the needed attention from most governments in SSA countries. In Ghana, only about 0.55% of the generation mix comes from solar and wind, which are considered the only renewable sources of energy in the generation mix [10]. Large hydro plants are excluded from being considered a renewable energy source in the electricity generation mix of Ghana [10]. This classification is due to the large hydro plants' potential to emit large amounts of GHGs and pose great negative social and ecological impacts [13]. Doe et al., [14] state that Ghana has the potential of meeting its electricity needs from biomass-based electricity generation using crop residues. In 2020, the total consumption of biomass was estimated to be 2977 ktoe, with the residential sector consuming roughly 2567 ktoe, the industrial sector consuming roughly 279 ktoe and the services sector consuming roughly 131 ktoe [14]. There are only four small-scale biomass-fired co-generation plants distributed amongst four palm oil production sites in Ghana, producing a combined total of 12.3 GWh annually [15], which could be replicated in many areas lacking electricity access. The high dependence of the country on the national grid is one major hampering factor to the access to electricity in rural communities. Furthermore, there are limited off-grid and stand-alone power generation systems, even though they can provide a key role in achieving universal access to electricity in Ghana's rural communities.

The main economic activity in most rural communities in Ghana is crops farming, which leads to the production of large quantities of agricultural residues. A small fraction of the residues is used for producing animal fodder and domestic heating, but the rest is either left on the farm to decompose or is burnt in open fires [15]. However, studies show that power generation from agricultural waste is feasible and it provides a great opportunity to meet energy demands of rural communities in Ghana [16, 17]. It is more environmentally, socially and economically sustainable to use the residues from agricultural activities for energy generation instead of importing fossil fuels or extending grid connection [18], which provides a huge potential in solving the country's current electricity access deficit, especially the rural access deficit. Besides agricultural waste in the rural communities, there is also abundant and readily available feedstock in several forms, including forestry residues, waste from agro-processing and the growing of energy crops for energy generation.

Several studies have investigated the potential of agricultural residues for energy application in Ghana and SSA at large [14, 19–25]. Doe et al. [14] estimate that about 91.2% of the total electricity demand of Ghana can be met through bioethanol-based electricity generation using crop residues, with regions like the Eastern, Bono, Ahafo, Bono East, Northern, Upper East and Upper West Regions having the potential to generate electricity in the range of 2 to 6 times higher than their current electricity demand. Arranz-Piera [18] argues that a cluster of ten farmlands with a size between 22–54 ha are capable of producing about 1000 kWe electricity from crop residues using a combined heat and power (CHP) plant, while 13–30 cluster farms of the same size are able to feed a 600 kWe CHP plant. These studies, however, fail to define the specific potential of each crop residue in meeting the energy needs of the people. Instead, they define a generalized potential of all the crops combined, which does not provide a clear picture for policy direction and investment. This information gap, i.e., a detailed analysis of the technical potential of different crop residues, is the focus of the present study.

Resource assessment for energy projects must be specific to a location in order to avoid a broad generalization that could lead to the failure of the project. Findings from this study will therefore help support precise investments and policy decision-making in the implementation of biomass energy projects. It is worth mentioning that most of the studies on biomass resource assessment have contributed to knowledge on the enormous potential that exists through recovering energy from waste for the achievement of universal access to electricity and carbon emissions reduction. The studies have also shown areas that policies must address in the renewable energy sector. These findings have resulted in the implementation of policies that promote waste-to-energy initiatives and the attraction of donors and investors to waste-to-energy projects [26, 27]. The enactment of the Ghana Renewable Energy Act of 2011 and its subsequent amendment in 2020 [28] can be traced to some of the studies conducted in the renewable energy sector on resources' potential for energy generation. Projects like the 400 kW Gyankobaa hybrid waste-to-energy power plant, the 900 kW Adieso fruit waste power plant, the 100 kW Ashaiman market and fecal waste power plant and the 2 MW oil palm power plant at Kwae are some projects implemented in Ghana [29, 30]. In these projects, a thorough resource assessment was completed and the potential of producing electricity from the resources was evaluated.

The government of Ghana created six new regions in addition to the already existing ten regions in 2018 [31]. Since then, there have been little or no known studies that have assessed the potential of electricity generation from biomass in most of these newly created regions. The Savannah Region is one of the newly created regions, where agriculture is the largest economic activity, with the majority of its population living in off-grid rural communities. Furthermore, this region, just like the other new regions, lacks studies on the region's produced agricultural residues and their potential for electricity generation that can form the basis for the implementation of renewable energy projects. The objective of this study, therefore, was to assess the technical and theoretical potential of agricultural residues in providing electricity to off-grid communities in the Sawla-Tuna-Kalba District in the Savannah Region of Ghana.

Methods

Description of study area

The study area of this research is the Sawla-Tuna-Kalba District in the Savannah Region of Ghana as shown in Fig. 1. The 2020 energy statistics of Ghana by the Energy Commission indicate that the Savannah Region has the lowest electricity access rate in both population and household access rates, namely, 60.1% and 59.5%, respectively [10]. Similar statistics by the Energy Commission also show that the Sawla-Tuna-Kalba District has the lowest residential electricity access rate (31%) in the Savannah Region as of 2020 [32]. However, about 58% of all the crop residues produced in the Savannah Region come from this district, which could be utilized for electricity generation to serve as a solution to the low electricity access rate in the region [33]. This insight provides the motivation for the present study in this area.

The Sawla-Tuna-Kalba District is located in the western part of the Savannah Region, between latitudes 8° 40′ and 9° 40′ North and longitudes 1° 50′ and 2° 45′ West. The district shares boundaries with Wa West District and Wa East of the Upper West Region to the North, Bole District to the South, West Gonja to the East and the Republics of La Cote d'Ivoire and Burkina Faso to the West. The district has a total land area of about 4173 km^2 [31]. The district's capital**,** Sawl, is about 66 km from the regional capital, Damongo. The total population of the district is estimated to be 112,664 [32]. The dominant economic activity in all communities in the district is agriculture. The people are mostly engaged in crop farming (97.1%) cultivating various varieties of cereals (such as maize, millet, sorghum), groundnuts, soya beans and tubers, as well as the rearing of livestock (64.4%). The private informal sector is the largest employer in the district, employing 96.9% of the population followed by the public sector with 2.0% [34].

Demographics and agricultural activities of study communities

Since the study assessed the potential of using agricultural residue for electricity generation, there was a need to know the various agricultural activities of the study area. The various agricultural activities and

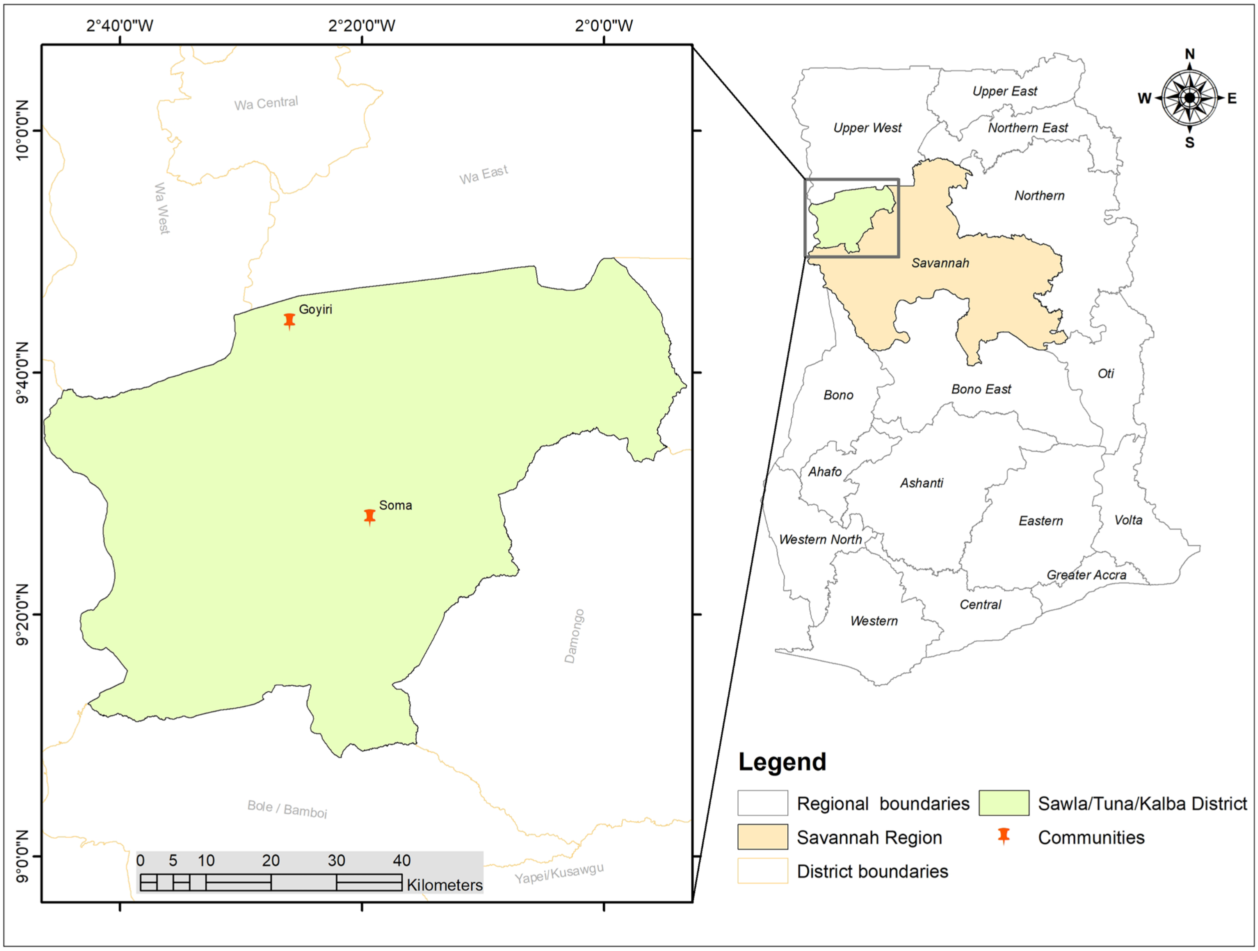

Fig. 1 A map of Sawla-Tuna-Kalba District with communities where the studies were conducted

demographics of the study area were determined using a survey questionnaire. Two farming communities, namely, Goyiri and Soma, were selected from the Sawla-Tuna-Kalba District for the study. The criteria for selecting mini-grid and off-grid power project sites were considered in the community selection, namely, distance from the closest grid-connected community, population and settlement and the availability of raw materials [34, 35]. Soma and Goyiri were selected for meeting these criteria. For crop production, the two communities were ranked among the highest crop production communities in the district according to the Department of Food and Agriculture (MOFA). A sample size of 100 households was used, which was obtained using the equation by Anabire et al. [36] as illustrated in Eq. (1):

$$SS = \frac{\mathrm{HP}}{[1 + \mathrm{HP}(e)^2]}, \tag{1}$$

where SS is the sample size; HP is the household population and e is the error margin. The error margin was set to be 10% as used by Anabire et al. [36] and a household population of 22,678 obtained from the 2021 PHC [32] was used. The sample size was distributed among the two communities based on the population of the communities. For each of the communities, the survey was conducted using a random sampling method based on the household head's willingness to participate in the survey. The survey questionnaire sought to obtain data on the types of crops cultivated by the farmers, land size and yield. These data were employed to select the major crops for analysis.

Data for cropland size, average yield and crop production for the district was obtained from the Ministry of Food and Agriculture (MOFA) for the period of 2017–2021, which was used to determine the average crop yield of the district using Eq. (3):

Table 1 Demographic characteristics of study communities

Characteristics of study communities	Goyiri	Soma
Estimated population (field data)	1010	1680
GPS coordinates	Lat: 9.736101; Long: − 2.451932	Lat: 9.463611; Long: − 2.310833
Electrification	Off-grid	Off-grid

$$aYi = \frac{\sum_1^n Yi}{n}, \tag{3}$$

where aYi is the average yield of crop i; Yi is the yield of a crop i for a particular year and n is the number of years.

The two communities where the study was conducted were both off-grid communities, whose energy demand is met by wood fuel for domestic heating and dry cells, solar cells and fossil fuel (mainly diesel) in generators. Soma has an estimated population of about 2680 while the population of Goyiri is estimated to be roughly 1010. Aside from being off-grid communities, Soma and Goyiri were also selected because they are predominantly farming communities and are situated remotely from the nearest grid-connected community [35]. The major crops both communities farm are maize, cassava, millet and groundnut. The communities had similar demographic characteristics for household population, major economic activities, educational level of household heads, etc. The demographic features of both communities are presented in Table 1.

Agricultural activities of study communities

The number of farmers cultivating a particular crop

i. Legume farmers

According to the survey, groundnut, cowpea and soya beans were found to be the leguminous crops cultivated by farmers. Analysis showed that groundnut was the leguminous crop planted by most of the farmers in the study communities in the district. The percentage share of groundnut per legume farmers is 56% as shown in Fig. 2. This indicates that most of the legume farmers in the communities cultivate groundnut, hence groundnut was selected as one of the crops for this study. About 29% of farmers in the selected communities cultivate cowpeas, while only 15% cultivate soybeans. Cowpea and soybean were not considered as potential crops for energy generation.

ii. Cereal farmers

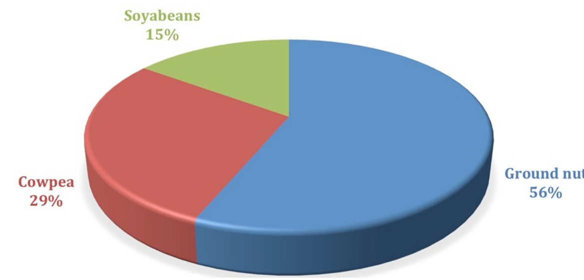

Fig. 2 Percentage share of legume farmers in Soma and Goyiri

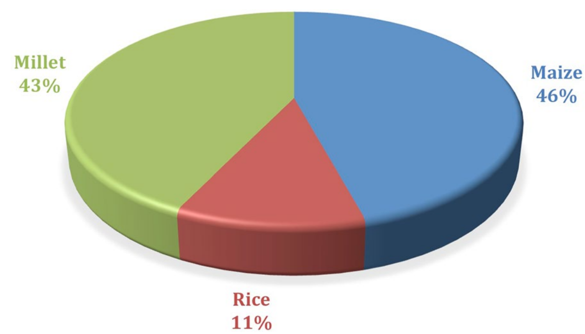

Fig. 3 Percentage share of cereal farmers

Maize, millet and rice are the major cereals that are cultivated in the district. For cereals, 46% of farmers cultivate maize, 43% cultivate millet and only 11% cultivate rice as shown in Fig. 3. Millet and maize were selected for energy production in this study due to their high percentage of production.

iii. Tuber farmers

Cassava and yam were the tuber crops cultivated in the selected communities. According to the survey, 92% of farmers cultivate cassava and only 8% cultivate yam (Fig. 4). Cassava was therefore considered for the analysis since it is the dominant crop cultivated by most of the farmers in the communities.

Estimation of theoretical potential of crop residue

The assessment of the availability of resources is an important step in the study of biomass-to-energy projects. In this study, the residue-to-product ratio (RPR) of cassava, which was the only crop found on the field at the time of the survey, was determined experimentally on the field at the time of the survey, while that of maize, millet and groundnut were obtained from literature [36, 37]. RPR is the ratio of the waste or by-products produced from a particular crop to the actual yield of the product [37]. RPR is used to assess the theoretical potential of residue that can be available for energy generation. RPR can

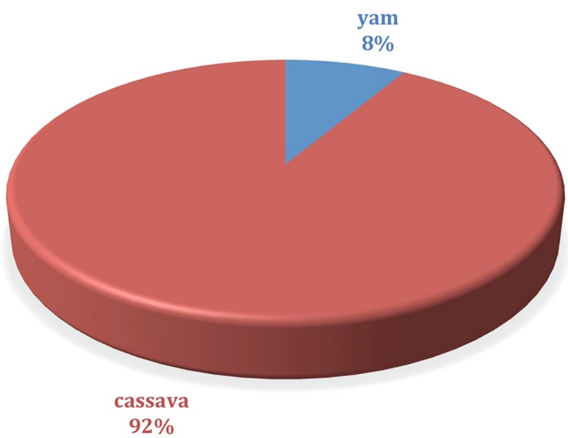

Fig. 4 Percentage share of tuber farmers

be estimated using Eq. (4) as used by Anabire et al. [36]. It is important to note that the RPR is a ratio and, therefore, has no unit.

$$\mathrm{RPR} = \frac{\text{Crop sample residue weight}}{\text{crop sample weight}}. \tag{4}$$

The RPR was used to estimate the theoretical residue generation from the selected crops using Eq. (5). This potential gives an idea of the total amount of residue that is produced from the selected crops, even though they might not be available for energy production due to other competing uses.

$$\mathrm{Rg}i = \sum aYi \times \mathrm{RPR}i, \tag{5}$$

where Rgi is the theoretical residue generation potential of a crop i, aYi is the average annual yield of a crop i and RPRi is the RPR of a crop i.

Estimation of the technical potential of crop residue

The technical potential of crop residues was estimated for maize, millet, groundnut and cassava. The technical potential was estimated using the recoverability fraction (RF). The RF takes into consideration technical factors like the competing use of crop residue for other equally important purposes like mulching, animal feeding, housing and industrial use, which are not considered during the estimation of theoretical potential. This was estimated with the relation used by [13] as shown in Eq. (6);

$$Tp = Rgi \times Ri, \tag{6}$$

where T_{p} is the technical potential of a crop i.

Determination of lower heating values of crop residues

The Lower Heating Values (LHV) of dried samples of crop residues were obtained through laboratory analysis. This was done to estimate the energy content of the selected residues of crops from the study area. Samples of the selected crop residues were collected and dried in an oven for analysis. The percentage content of carbon, hydrogen, sulphur and oxygen of the samples was determined and the LHV was estimated using Eq. (7) adopted from Ioelovich [38]:

$$\mathrm{LHV}\ (\mathrm{MJ/kg}) = 0.339\ \mathrm{C} + 1.029\ \mathrm{H} + 0.109\ \mathrm{S} - 0.109\ \mathrm{O}, \tag{7}$$

where C, H, S, and O are the percentages of organic carbon, hydrogen, sulphur and oxygen in samples.

Estimation of electricity generation potential from crop residues

Gasification technology is deemed more suitable for rural energy applications due to the small energy needs of rural areas and the flexibility in generation capacity of the technology [39, 40]. Among gasification systems, both a fixed bed and a downdraft gasifier (DG) coupled with a gas engine alternator are considered the most ideal for power generation in the range of biomass crop residues. The following reasons were elaborated on the benefits of the technological systems:

i. To produce syngas of low tar rate (<3 mg/Nm^3) [41, 42].
ii. High tolerance for moisture.
iii. Suited for small-scale applications [41].
iv. Ability to operate on biomass at a flow rate of 100 kg/h, while producing producer gas and releasing tar contents of between 300 and 400 mg/m^3 with moisture tolerance of 40% [42].

Equation (8) adopted from Ibikunle et al. [43] was modified and used to estimate the electricity generation potential from crop residues.

$$E_{\text{potential}} = \mathrm{LHV}_{\mathrm{CR}} \times \frac{W_{\mathrm{CR}}}{3.6 \times 365} \times \mathrm{Eff}_{\mathrm{PP}}(\mathrm{MWh/day}), \tag{8}$$

where $E_{\text{potential}}$ is the daily electricity generation potential of crop residues in MWh/day, $\mathrm{LHV}_{\mathrm{CR}}$ is the lower heating value of crop residue in MJ/kg, W_{CR} is the weight of crop residue in kg and $\mathrm{Eff}_{\mathrm{PP}}$ is the conversion efficiency of the power plant. Power plant efficiency is considered to be between 30% and 40%. The power plant efficiency in this study is taken to be 30% [42].

Table 2 Household electric appliances and their hours of usage

Appliance	Power rating (W)	Number of consumer class			Hours/day	Period of use
		Lower-class	Middle-class	Upper-class		
Bulb	15	3	4	5	12	6 pm to 6 am
Radio	20	1	1	1	4	7 pm to 11 pm
Mobile phone	10	3	3	3	3	4 pm to 7 pm
Television	250	–	1	1	3	7 pm to 10 pm
Fan	75	–	1	2	8	8 pm to 4 am
Refrigerator	440	–	–	1	24	6 am to 6 am
Decoder	45	–	1	1	3	7 pm to 10 pm

Electricity demand forecasting of study communities

The energy demand assessment was categorized into households, education, health and commercial loads since they were the energy consumption sectors for the communities covered in the study. A 12-unit classroom block was considered for the education section, while a community health planning and services (CHPS) compound was also considered for the health section since they were identified in the study communities. The demand of the two communities was averaged and used for the estimations. Households were categorized into lower-class, medium-class and higher-class consumers, based on patterns discovered in the study and a similar method used by Yeboah et al. [44].

Household energy demand

The expected household appliance and their expected daily usage hours were divided into lower-class, medium-class and upper-class consumers [44, 45]. During the survey, respondents were asked to indicate the electrical appliances they will use or acquire after they are provided with electricity and when they intend to use them.

i. Lower-class users (low life-line end-users): these end-users are considered to be respondents who indicated they will only use basic appliances like light bulbs, radios and mobile phones. The quantity of appliances was also determined by using data such as the number of rooms, the number of people in households and the willingness of household heads to purchase an item [44].
ii. Middle-class (average income rural end-users): the medium-class users are those who will use television, a decoder and fans in addition to the appliances used by the lower-class users. The quantity of light bulbs also increased from three to four from lower-class users to middle-class users.
iii. Upper-class end-users: these end-users are consumers who will use a refrigerator and a decoder in addition to the appliances used by middle-class users. The upper-class end-users do not form the majority in most rural areas.

The household end-users and the appliances described are summarized in Table 2.

Table 3 Electric appliances and their hours of usage for CHPS compound

Appliance	Power rating (W)	Quantity	Hours/day	Period of use
Indoor bulbs	15	10	18	6 pm to 12 pm
Radio	20	1	4	7 pm to 11 pm
Television	250	5	12	10 am to 10 pm
Mobile phone	10	12	3	6 pm to 9 pm
Fan	75	6	18	6 am to 12 am
Iron	1100	1	0.5	7 pm to 8 pm
Computer	350	2	9	8 am to 5 pm
Outdoor bulbs	15	6	12	6 pm to 6 am
Refrigerator	440	3	24	6 am to 6 am
Water pump	1500	1	2	9 am to 11 am

Table 4 Electric appliances and their hours of usage of a 12-unit classroom block

Appliance	Power rating (W)	Quantity	Hours/day	Period of use
Bulb	15	10	12	6 pm to 6 am
Fridge	265	1	8	7 am to 3 pm
Television	250	4	5	10 am to 3 pm
Mobile phone	10	20	2	10 am to 12 pm
Fan	75	4	6	9 am to 3 pm
Computer	350	40	5	8 am to 1 pm

Table 5 Daily unit energy consumption by end-users of study communities

End-users	Total daily energy consumption (kWh)	Number of prospective end-users	
		Goyiri	Soma
Lower-class household	0.710	59	126
Middle-class household	2.240	27	36
Upper class household	13.115	10	15
School	68.850	1	1
CHPS compound	22.240	1	1

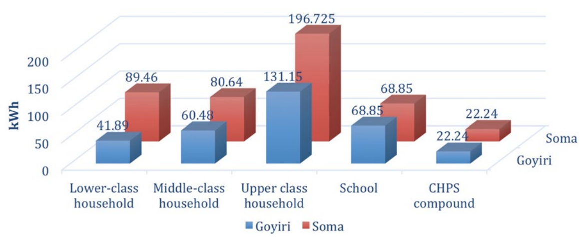

Fig. 5 Total daily expected electricity consumption by end-users of the study communities

Energy demand of CHPS compound

The major appliances envisaged to be used by this category of consumers consist of appliances used by the upper-class category of household consumers with other appliances like computers, water pumps and electric irons (Table 3).

Energy demand of schools

As shown in Table 4, the major appliances to be used by this category of consumers are similar to the appliances used by upper-class households, with computers being additional appliances.

Results

Energy demand and load profile of study communities

The daily electricity consumption per consumer for the different household classes in the two study communities is presented in Table 5 and the total daily expected electricity consumption is presented in Fig. 5. The daily energy consumption per household for the lower-class (life-line) consumers was estimated, based on Table 2, to be 0.71 kWh. This category of consumers falls under the consumption bracket for life-line consumers under the Public Utilities Regulatory Commission (PURC) energy consumption structure [46]. From the survey, life-line consumers constituted the majority of residential consumers, as was the case in Asuamah's et al. study [44]. The total daily energy consumption per household for middle-class consumers was estimated to be 2.24 kWh. Middle-class consumers were found to be the second largest group of residential consumers after the life-line consumers. The total daily energy consumption per household for the upper-class household category of residential consumers is 13.115 kWh. This category of consumers constituted a small fraction of the residential consumers in the study areas. The total energy consumption at the12-unit classroom block is estimated to be 68.85 kWh, while that of a CHPS compound is estimated to be 22.24 kWh.

Daily load profiles were generated from the energy consumption of the two study communities using the demand forecasting data presented in Tables 2, 3 and 4. This is presented in Fig. 6. The peak loads for the two communities were estimated to be 49.46 kW and 64.30 kW for Goyiri and Soma, respectively.

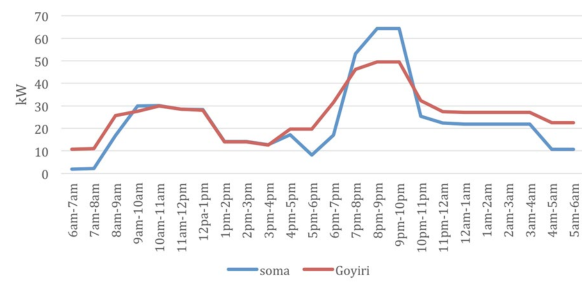

Fig. 6 Daily load profile of the study communities

Table 6 The RPR and RF of selected crops

Crop	Residue type	RPR	RF
Maize	Cob	0.57[a]	0.35
	Husk	0.23[a]	0.8
	Stalk	1.15[a]	0.2
Cassava	Peels	0.2	0.06
	Stem	0.8	0.25
Millet	Stalk	5.53[b]	0.8
	Cob	0.29[b]	0.6
Groundnut	Stem	1.75[b]	0.9
	Shell	0.35[b]	0.9

[a] [21]
[b] [36]

RPR and RF of selected crop residues

The RPR and the RF of the residues from maize, cassava, millet and groundnut are presented in Table 6. The RPR obtained for cassava is similar to the one presented by

Nelson et al. [37]. The RF values are also conform with the ones presented by Ayamga et al. [36]. From the results of this study, residues like maize husk, cassava peel and groundnut shell have the lowest RPR values of 0.23, 0.20 and 0.35, respectively. These residues will have a low theoretical and technical potential because RPR has a direct relation with residue yield [24]. Maize cob and cassava stem had RPRs of 0.53 and 0.80, respectively, while maize stalk and millet stalk had relatively higher RPRs of 1.15 and 5.53, respectively. It is worth noting that factors like rainfall pattern, fertilizer application and farming practice, which affect crop yield, also impact RPR [36]. The RPR of millet shows a very high value, which implies that millet produces high quantities of residues. Considering the RF, cassava peels have the lowest RF (0.06).

The low RF of cassava peels can be attributed to their high usage in feeding animals, since roughly only 6% of the theoretical potential of cassava peels can be technically available for energy generation. Groundnut stem, groundnut shell, millet stalk and maize husk show high RFs of 0.9, 0.9, 0.8 and 0.8, respectively, which implies that about 80% and 90% of the theoretical potential of these residues can be technically available for usage since they are usually left on the farm fields to decompose or burnt on the field in land preparation for the next planting season. Maize cob, maize stalk and cassava stem also had moderately low RF values of 0.35, 0.2 and 0.25, respectively, implying that only 20% to 35% of the theoretical potential of these crops can be available for energy generation. Maize cob and stalk are used as sources of energy for domestic heating in the district, while cassava stems are used for replanting.

Theoretical and technical potential of crop residues

The theoretical and technical residue generation of the crop residues studied are represented in Table 7 and Fig. 7. From the results, millet stalk has the largest residue generation of 51,358.61 MT representing 58.84% of the total residue generated from the district. This is more than half of the total residue generated in the district from the four selected crops. This can be attributed to the high RPR and RF of millet stalk and also the high production levels of millet stalk in the district. Groundnut stem forms the next highest residue-generating crop producing about 20,646.84 MT of residue per annum, which represents about 23.66% of total residue generation. The remaining residues, which are maize stalk, maize cob, maize husk, cassava peels, cassava stem, millet cob and groundnut shell each had their percentage share of residue yield less than 10%. These residues have their combined percentage share of residue generation from the

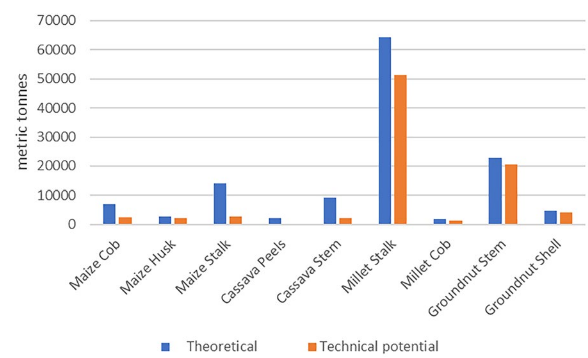

Fig. 7 Theoretical and technical potential of crop residue

Table 7 Theoretical and technical potential of crop residues

Crop	Yield (MT/year)	Residue type	Theoretical potential[a] (MT/year)	Technical potential[a] (MT/year)	% Share of total technical potential
Maize	12,183.43	Cob	6944.56	2430.59	2.79
		Husk	2802.19	2241.75	2.57
		Stalk	14,010.94	2802.19	3.21
Cassava	11,609.09	Peels	2321.82	139.31	0.16
		Stem	9287.27	2321.82	2.66
Millet	6917.10	Stalk	64,198.27	51,358.61	58.85
		Cob	2005.96	1203.58	1.38
Groundnut	13,109.11	Stem	22,940.94	20,646.85	23.66
		Shell	4588.19	4129.37	4.73
	Total		129,100.10	87,274.07	100

[a] The potentials of crop residues are estimated on dry basis

Table 8 Daily electricity generation potential from crop residues

Crop	Residue type	LHV (MJ/kg)	Daily epotential (MWh/day)
Maize	Cob	19.80	10.96
	Husk	15.34	9.23
	Stalk	20.84	13.30
Cassava	Peels	18.53	0.59
	Stem	19.59	10.36
Millet	Stalk	14.91	174.35
	Cob	14.84	4.07
Groundnut	Stem	16.28	76.53
	Shell	13.67	12.85
Total daily electricity potential			312.23

four crops at 17.5%. Even though these crops are produced in larger quantities than millet as seen in Table 7 and Fig. 7, millet residue generation potential is seen to be very high as a result of its higher RPR. This implies that even though a crop may be produced in high quantities, it might not be suitable for energy generation purposes if it has low RPR and RF values. Therefore, it is very crucial to determine the RPR and RF of a particular crop before considering it for energy generation purpose. It is also worth noting that it is not enough to consider only the theoretical potential of crop residue when embarking on resource assessment for energy generation. Crops with high RF should have their theoretical residue generation potential close to their technical. However, this is not usually the case due to other competing uses of crop residues such as mulching, animal feeding and shelter [24].

The LHV of samples were estimated using Eq. (7). The results show high LHV (between 18 MJ/kg and 21 MJ/kg) for maize and cassava residues, while the LHV of residues of millet and groundnut are relatively low (between 13 MJ/kg and 16.5 MJ/kg). The groundnut

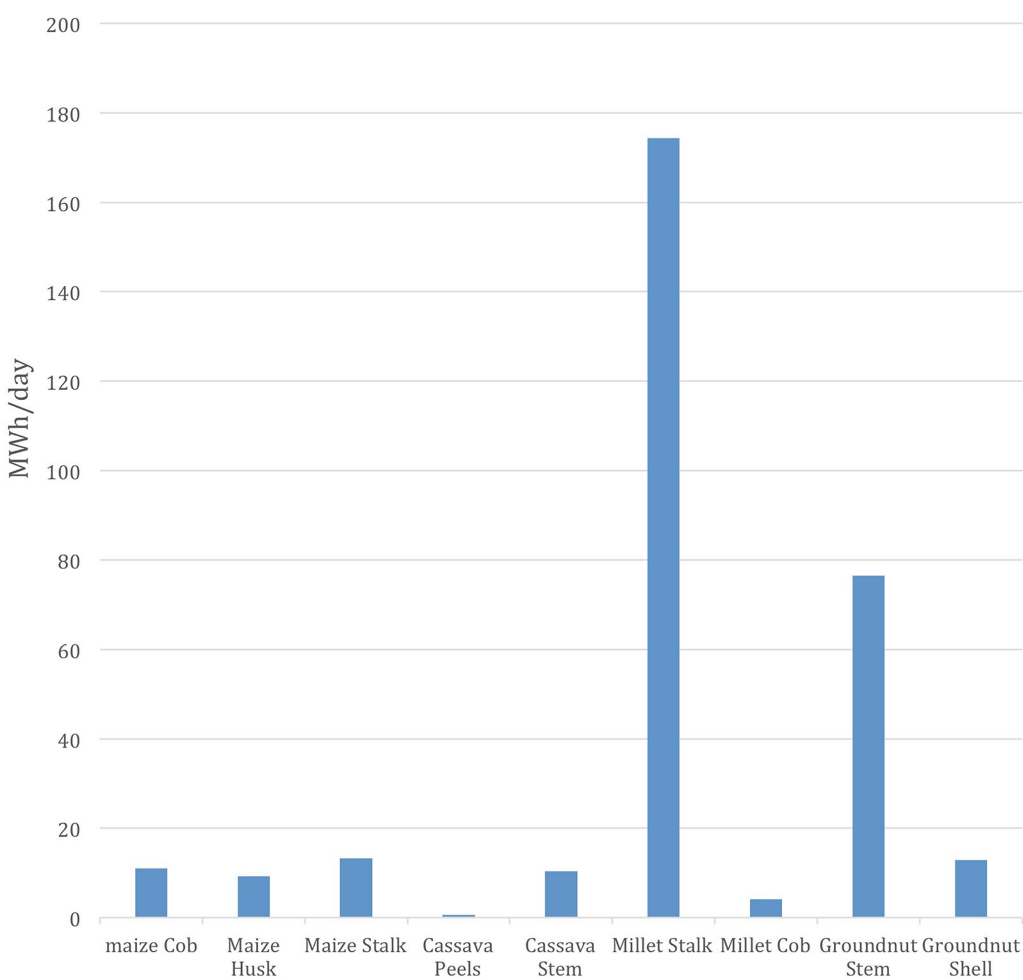

Fig. 8 Energy generation potentials of crop residues

pod is found to have the lowest LHV (13.67 MJ/kg), while maize stem is found to have the highest LHV (20.84 MJ/kg).

The energy potential of crop residues presented in Table 8 was estimated using Eq. (8). The results show energy potential to be in the range of 0.59 and 174 MWh/day and the total residue potential is estimated to be 312.23 MWh/day. Millet stalk produced the highest potential (174.35 MWh/day), while cassava peels produced the lowest potential (0.59 MWh/day). Groundnut stem, maize stalk, groundnut shell, cassava stem, maize cob, maize husk and millet cob occupy the 2nd, 3rd 4th, 5th, 6th and 7th positions, respectively, regarding their energy generation (see Fig. 8).

Discussion

Energy demand

From Fig. 6, the load profiles indicate that the two communities have their peak energy demand around 8–9 pm, which is similar to the load profile presented by Yeboah et al. and Rushman et al. [44, 45] for rural communities. This profile indicates that most of the energy is consumed by residential consumers, which does not support the productive use of electricity [45]. In the study of Yeboah et al. [44], the daily peak load was estimated to be 30.77 kW, which is less than the peak load of the two study communities, even though all communities of their study are off-grid communities. This can be attributed to the low population of their study community, which is nearly half the population of the study communities considered in this study. The electricity generation potential indicates that a total of 312.23 MWh/day equivalent of electricity can be generated from maize, cassava, millet and groundnut as indicated in Table 8.This has the potential to provide 263 times the peak load in Soma and almost 202 times the peak in Goyiri. This same amount of electricity can supply about 4,534 and 14,039 CHPS compounds and schools respectively with similar energy demand as Soma and Goyiri. The enormous potential that these crop residues provide is clear evidence that crop residues can play a key role in achieving the United Nations (UN), Sustainable Development Goal Seven (SDG7—Access to Affordable and Clean Energy) and subsequently goals three (SDG3—Good Health and Well-being) and four (SDG4—Access to Quality Education). From the results (see Fig. 8), millet stalk ranked highest in energy generation potential followed by groundnut stem with their daily electricity generation rated at 174.35 MWh/day and 76.53MWh/day, respectively. Similar studies by Yorke et al. [26], Duku et al. [37], Mohammed et al. [46] and Nelson et al. [47] estimated an annual energy potential of (401 PJ/yr), 75.20 PJ/yr, 91.60 PJ/yr, and 623.84PJ/yr, respectively from crop residues in Ghana, all of which greatly differ from the energy potential from this study, i.e., an annual potential of about 1.14 PJ/yr (3121.23 MWh/day). This difference can be attributed to the difference in the number of crops, LHV and the geographical coverage of each study [26].

As shown in Table 8, millet stalk forms about 56% of total electricity generation potential from crop residue, while groundnut stem forms about 25% of total electricity generation from crop residues. Maize stalk, groundnut shell, maize husk, maize cob, cassava stem, millet cob, and cassava peels occupied the 3rd to the 9th positions respectively for electricity generation potential. These crops have a combined total share of electricity generation potential from crop residues at 19%. A similar study by Mabuza [48] in Botswana shows that maize has the greatest energy potential, while a study by Odoi-Yorke et al. [26] in Ghana indicates that cassava residues have the highest energy potential, which is about 50% of the total energy potential with maize occupying the second place for energy generation potential, taking about 22% of total generation. The results further show that crop residue potential varies across different geographical

Table 9 Percentage of elemental constituents and LHV of samples

Sample	C (%)	H (%)	N (%)	S (%)	O (%)	LHV[a] (MJ/kg)
Millet cob	34.45	8.85	1.91	0.11	54.69	14.84
Millet stalk	34.18	9.18	0.25	0.06	56.33	14.91
Groundnut stem	36.71	9.24	1.83	0.08	52.13	16.28
Groundnut stem	34.85	8.46	3.49	0.10	53.11	14.74
Groundnut pod	32.59	8.63	1.24	0.07	57.47	13.67
Cassava stem	35.38	12.69	1.76	0.04	50.13	19.59
Cassava peels	34.98	11.97	1.10	0.09	51.86	18.53
Maize stem	33.92	14.42	1.02	0.12	50.53	20.84
Maize cobs	35.38	12.86	1.66	0.15	49.95	19.80

[a] LHV are estimated on dry basis

locations, hence the need for location-specific assessment of crops for energy potential for energy projects.

Potential of maize residues in meeting electricity demand

The results presented in Table 9 show that residues from maize alone have the potential to generate 33.48 MWh/day of electrical energy. This amount of electricity can meet about 28 times the peak electricity demand of Soma and 22 times the peak demand of Goyiri. This implies that only maize residues can provide electricity to about 28 communities with similar demographics and electricity demand as Soma and about 22 communities with similar demographics and electricity demand as Goyiri. For utilizing the electricity for health and education purposes, the electricity generated from maize residues is able to provide electricity to about 486 CHPS compounds and 1,505 schools with the same electricity as the demand of Goyiri.

Potential of cassava residues in meeting electricity demand

Cassava generates about 0.59 MWh/day of electrical energy. The potential electricity generation from cassava is able to meet about 9 times the peak electricity demand of Soma and 7 times the peak electricity demand of Goyiri. The potential of electricity supply from cassava residues is low compared to other residues. This low potential is due to cassava stems being used for replanting, while cassava peels are usually used for feeding animals as indicated by Kemausuor et al. [24]. Even though the potential of cassava appears to be relatively small, it is able to supply power to about 26 CHPS compounds and about 8 schools with demand equivalent to that of Soma and Goyiri.

Potential of millet residues in meeting electricity demand

Millet presents the highest potential for electricity generation, amounting to about 178.42 MWh/day. This is able to meet about 150 times the total electricity demand of Soma and 115 times the total electricity demand of Goyiri. Also, the residues have the potential to supply electricity to about 2585 schools and 8003 CHPS compounds of similar energy demand as that of the study communities.

Potential of groundnut residues in meeting electricity demand

From the results, groundnut also presents a high potential for electricity generation, amounting to about 89 MWh/day. This generation is able to meet about 75 times the total electricity demand of Soma and 58 times the total electricity demand of Goyiri. The electricity from groundnut residues is also able to supply energy to about 4001 CHPS compounds and 1292 schools with similar demand as the study communities.

Studies on the usage of crop residues for energy generation in Ghana usually have maize and cassava occupying the highest potential as indicated in the studies of Kemausour et al. [24], Nelson et al. [47] and Yorke et al. [26]. However, the findings of these studies show a different outcome where millet and groundnut have high energy generation potential among the four selected crops. This difference is a result of the high production yield of these two crops in the study area and the availability of their residues for energy generation. The outcome of this study reiterates the need for location-specific resource assessment since different locations may show different resource potential, which might conform to or deviate from the national or regional scenario.

Conclusions

The study sought to investigate the technical potential of using crop residues for electricity generation in the Sawla-Tuna-Kalba District of the Savanna Region in Ghana. Findings reveal that a total of 312.23 MWh/day of electricity could be generated from the four selected crops (maize, cassava, millet and groundnut) residues. Residues from these crops are able to supply electricity to about 202 to 263 times the peak electricity demand of the study communities. This suggests that crop residue use for electricity generation in rural off-grid communities can solve or complement the electricity deficit of rural communities in Ghana. Providing electricity to rural communities, considering the various loads from schools, health centers, households and commercial activities will go a long way to improve people's standard of living and access to quality education and health services in those communities.

The study brings to light the enormous potential that exists in utilizing energy from crop waste to provide electricity for rural dwellers. This potential must be considered as part of Ghana's vision to achieve universal access to electricity by 2030. Currently, rural communities in Ghana are mainly supplied with electricity from the national grid, which is most often very challenging due to their remote locations and sparse distribution of the residential, commercial and service facilities. Since there is proven potential for generating electricity from crop residues, they can be good substitutes for dealing with the challenge of connecting rural communities to the national grid. Nevertheless, to ensure the sustainability of projects intended to utilize crop residue for electricity generation, it is recommended that residue generation assessment be done in the local context, taking into consideration economic, social and cultural variations. Since this study has shown that there is great potential in using second generation crop residues for energy generation, there is a need for policies that favor the use of second-generational energy crops for energy generation to avoid the competing use of land for planting first general energy crops which can lead to food shortage in the future.

Regarding the technology, based on the discussion in Sect. "Estimation of electricity generation potential from crop residues", gasification technology is recommended as the most suitable for electricity generation from the crop residues studied. It is recommended that economic analysis (such as net present cost, levelized cost of energy, internal rate of return, return on investment and discounted payback time) is performed in future studies to assess the sustainability of agricultural residue energy production projects. Future studies could also consider comparing the cost–benefit analysis between using the crop residues for electricity generation and as a soil amendment for agricultural activities.

Abbreviations

CHPS	Community Health Planning and Services
kWh	Kilowatt-hour
kW	Kilowatt
kg	Kilogram
Ktoe	Kilo tonne equivalent
LHV	Lower heating value
LHV_{CR}	Lower heating value of crop residue
MOFA	Ministry of Food and Agriculture
MT	Metric tonnes
RPR	Residue to product ratio
RF	Recovery factor
SSA	Sub-Saharan Africa
W_{CR}	Weight of crop residue

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Author contributions
The conceptualization of the research was done by Edward A. Awafo (E. A. A.) and Gilbert A. Akolgo (G. A. A.). Augustine Awaafo (A. A.) conducted the field data collection, theoretical calculations and drafted the manuscript under the supervision of E. A. A. and G. A. A. The final draft was edited by E. A. A and G. A. A. E.A.A. secured funding for the study. All authors have read and agreed to the published version of the manuscript.

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Availability of supporting data
Not applicable.

Declarations

Ethics approval and consent to participate
The submitted paper has not been published previously and it is not under consideration for publication elsewhere. The publication of it is approved by all authors.

Consent for publication
This manuscript, if accepted for publication, will not be published elsewhere in the same form, in English or any other language, including electronically without the written consent of the copyright holder.

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The authors declare no competing interests.

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