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Environmental and socio-economic benefits of a circular economy for bioethanol production in the northern part of Ghana

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ABSTRACT

Sweet sorghum grains (SSG) cultivation are the primary source of income and subsistence for approximately 80% of poor smallholder farmers in the northern part of Ghana. Regrettably, sorghum prices in rural markets are constantly falling, resulting in a small income for smallholder farmers and a negative impact on their socio-economic lives. This study presents a shift towards a circular sweet sorghum supply chain in the northern part of Ghana through bioethanol production from excess sweet sorghum. The study looks at using excess red and white sweet sorghum grains (RSG and WSG) grown in northern Ghana to produce bioethanol. The SSG was pre-treated and fermented with *Saccharomyces cerevisiae* yeast to produce 87.6 g/L and 84.24 g/L of WSG and RSG bioethanol, respectively. This was equivalent to an estimated yield of 91.57% (WSG) and 89.24% (RSG). Likewise, the bioethanol volumetric production of SSG was between 3.50 g/h·L and 3.70 g/h·L, indicating that its production was efficient after 24 h of fermentation. The fuel properties of the bioethanol were also found to be acceptable for commercial use in bioethanol cookstoves, reducing the reliance on firewood in the northern part of Ghana. A sweet sorghum supply chain based on two different models was developed and could be implemented in the northern sector to benefit smallholder farmers and to save the environment.

1. Introduction

Agriculture is the economic mainstay in most rural areas of Ghana, contributing up to 64% of the total working force (Lamptey et al., 2014; Bawa, 2019). In most Ghanaian farming communities, farming depends entirely on the quality of the rainy season, a situation that makes Ghana particularly vulnerable to climate change. As lands become less productive under new climate conditions, people living there may be forced to migrate to urban areas, where infrastructure is already approaching its limits due to population pressure and a lack of resources (Dessus and Jackson, 2011). In Ghana, the northern part is the most vulnerable and exposed area to climate change and variability. At the receiving end of these consequences are the poor smallholder farmers, already impoverished, who strongly lean on agriculture for food and income (Dessus and Jackson, 2011; Bawa, 2019). The smallholder farmers rely solely on a single annual rainy season, implying that only a very small number of crops can withstand variable and erratic climate conditions in this region. In Ghana, there are multiple rainfall patterns in the eastern, central, and western regions, allowing smallholder farmers to grow cocoa, coconut, and other crops for processing into food, biofuels, vegetable oils, and other products. (Darfour and Rosentrater, 2016; Appiah et al., 2022; Tulashie et al., 2022; Dodoo et al., 2022). Therefore, research into crops that are productive and profitable in the northern part of Ghana, where there is only one rainy season per year, is crucial.

Sweet sorghum, *Sorghum bicolor*, ranks first among cereal crops grown in the northern part of Ghana in terms of drought resistance, low cultivation costs, ability to withstand high temperatures, and water requirements (Lamptey et al., 2014). Yet, the smallholder farmers face multiple challenges and distress in the markets due to sweet sorghum's price depreciation and market shocks. As a result, very little income is earned from the sales of sweet sorghum grown by smallholder farmers in rural communities, negatively affecting their socio-economic livelihoods. That points to the need to shift towards a circular sweet sorghum

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Acronyms

CO_2	Carbon Dioxide
GHG	Greenhouse Gas
SSG	Sweet Sorghum Grains
RSG	Red Sweet Sorghum Grains
WSG	White Sweet Sorghum Grains
RI	Refractive Index
KV	Kinematic Viscosities
ON	Octane Number
FP	Flashpoint
ITCZ	Inter-Tropical Convergence Zone
LPG	Liquefied Petroleum Gas
PAHs	Polycyclic Aromatic Hydrocarbons
CEIHD	Center for Entrepreneurship in International Health and Development

supply chain in which smallholder farmers not only supply sorghum but process the excess sweet sorghum into bioethanol to create additional income from their sales. Bioethanol production from sorghum is a simple procedure in which smallholder farmers can be trained within the shortest possible time (Quan et al., 2012). The bioethanol that is produced by smallholder farmers can be sold at rural and urban markets for the purpose of being used as fuel, and more specifically, in cookstoves. This alleviates the burden of collecting firewood and improves the health of women and children, who would otherwise be exposed to harmful air pollutants from burning firewood. In fact, creating bioethanol markets in rural communities is crucial due to the high cost of fuel and the continuous felling of trees for use as firewood, which greatly reduces the carbon sink. Burning non-renewable and eco-friendly energy sources contributes to carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions in the atmosphere, raising concerns about global climate change (Zainal et al., 2018). The consequences of this predicament would be an increase in climate change, which would have a negative impact on agricultural activities in the northern sector.

In order to reduce deforestation, poverty and promote prosperity among poor smallholder farmers in the northern part of Ghana, it is imperative for us to understand how the circular sweet sorghum supply chain contributes to this agenda. Hence, this research focuses on bioethanol production from excess sweet sorghum towards a circular sweet sorghum supply chain in the rural communities. In a circular economy, smallholder farmers can use extra sorghum that would otherwise be thrown away as biowaste to produce a valuable sorghum product. Therefore, the objectives of this study include: a) production of bioethanol from sweet sorghum cultivated in the northern part of Ghana; b) evaluation of the fuel properties of the bioethanol to assess their potential use in cookstoves in rural communities, and c) proposing an approach to increase the income of poor smallholder farmers in rural settings through the circular sweet sorghum supply chain. This research is expected to provide an efficient and sustainable way for poor smallholder farmers to improve their social-economic, and environmental wellbeing through a circular sweet sorghum supply chain in the northern part of Ghana.

2. Materials and method

Red sweet sorghum grains (RSG) and white sweet sorghum grains (WSG) were obtained from the Department of Crop Science at the University of Ghana (Legon, Ghana). The sweet sorghum grains (SSG) were whole grains from the species of *Sorghum bicolor*, deprived of unpleasant odours, living and dead insects, dirt, and plant debris such as sorghum seedcoats. The provider indicated that the SSG were cultivated and freshly harvested in the northern part of Ghana, devoid of heavy metals and pesticide residues, with tannin content below 0.5% on a dry matter basis. The supplied SSG was kept in a ventilated room in sealed clean plastic bags. The fermentative yeast, *Saccharomyces cerevisiae*, was purchased in an airtight and sealed plastic bag from a chemical shop at the Cape Coast supermarket (Cape Coast, Ghana), and obtained in powdery form.

2.1. Pre-treatment

Mechanical screeners and palm wood basket winnowing were used to remove any remaining debris, such as stones, sand particles, husks, and plant residues. A magnet was passed through the SSG to remove metallic and magnetic objects. 1200 g of SSG was weighed, cleaned, and sun-dried on metal plates (50 cm × 30 cm) for 12 days in a clean drying area to remove any remaining moisture and contaminants. To ensure that all grains were evenly and uniformly sun-dried, the SSG was occasionally rotated multiple times each day. The moisture content of RSG and WSG determined in triplicates was approximately 7.78 ± 0.12%. RSG and WSG were mechanically milled to a powdery form in order to obtain an appropriate mesh size of sieves. Thus, the RSG and WSG were sieved to a fine particle size of less than 10 mm using a vibrating mechanical sieve shaker with sieve sizes ranging from 0.1 to 10 mm for 10 min. The RSG and WSG aggregates retained on each sieve were recorded, and the mean particle size diameter was estimated by the Sauter mean diameter (mm) (Fiori et al., 2008), illustrated in equation (1). The powdered RSG and WSG were weighed and stored at room temperature in an air-ventilated room in airtight plastic bags.

$$Sauter\ mean\ diameter\ (mm) = \frac{1}{\sum_{j=1}^{N} \frac{\omega j}{d_{p,j}}} \tag{1}$$

where: N, represents the number of granulometric classes; j (subscript), signify the j-th granulometric class; ω_j, weight fraction; d_p, is the particle diameter (mm).

2.2. Production of bioethanol

2.2.1. Hydrolysis

The WSG and RSG sorghum grains, milled to a mesh size of 0.5 mm, were suspended in five different volumes of water ranging from 3000 ml to 7000 ml. The hydrolysis was carried out with continuous stirring at a temperature of 50 °C for 72 h to liberate and convert starch into fermentable sugar. Throughout the hydrolysis period, the pH of the grain/water mixture was monitored to maintain a pH range of 5.91–5.98. After hydrolysis, the resulting mixture was cooled and separated by vacuum filtration with a mesh filter measuring 0.5 mm in diameter. Aliquots of the filtrate (hydrolysate) were taken to measure the amount of reduced sugar in the filtrate after the hydrolysis, employing a Brix refractometer (Mettler Toledo, Columbus, Ohio, USA) expressed in g/L. The total sugar generated and its productivity were calculated from equations (2) and (3).

$$Total\ sugar\ generated\ (\%) = \frac{Sugar\ conc.\ \ after\ hydrolysis\ (g/L)}{Amount\ of\ sorghum\ grains\ in\ water\ (g/L)} \times 100 \tag{2}$$

$$Total\ sugar\ productivity\ \left(\frac{g}{L \times hr}\right) = \frac{Total\ sugar\ generated\ \left(\frac{g}{L}\right)}{Hydrolysis\ time\ (hr)} \tag{3}$$

The hydrolysis process was repeated by maintaining the amounts of WSG and RSG (1000 g), while raising the initial volume (ml) of water from 4000 to 7000. The hydrolysis conversion efficiencies (HCE) of RSG and WSG into fermentable sugars were estimated from equation (4).

$$HCE\ (\%) = \frac{Sorghum\ grains\ in\ water\ \left(\frac{g}{L}\right) - Sugar\ content\ \ (g/L)}{Sorghum\ grains\ in\ water\ (g/L)} \times 100 \tag{4}$$

2.2.2. Fermentation

Yeast (*Saccharomyces cerevisiae*) was cultured aerobically in 100 ml of hydrolysate at a pH of 4.5 and a temperature of 37 °C for 6 h in order to activate and grow yeast cell population. Approximately 0.1 L of the filtrate (hydrolysate) was used to aerobically culture 7.5 g/L of the yeast (*Saccharomyces cerevisiae*) for 6 h at a pH of 5.75–5.95 and 37 °C to activate and grow the yeast cell population. The fermentations were performed in triplicate by transferring 500 mL of the hydrolysates (RSG and WSG) into 1000 mL Erlenmeyer flasks that were well-sealed to limit oxygen penetration. The hydrolysates (RSG and WSG) were mixed with 75 g/L each of yeast and stirred at 300 rpm to ensure that the yeast was evenly dispersed throughout the mixture. Throughout the fermentation period, the temperature and pH were monitored to maintain a temperature of 37 °C and a pH range of 5.05–5.95. After fermentation, the supernatant was filtered through a mesh filter with a 0.5 mm diameter for bioethanol and reducing sugar analysis. The fermentation conversion efficiencies (FCE) of hydrolysates (RSG and WSG) into bioethanol were estimated from equation (5).

$$FCE\ (\%) = \frac{Initial\ sugar\ conc.\ (g/L) - Sugar\ after\ fermentation\ (g/L)}{Initial\ sugar\ conc.\ (g/L)} \times 100 \tag{5}$$

The bioethanol's yield and volumetric productivity were estimated from equations (6) and (7).

$$Bioethanol\ yield\ (\%) = \frac{Actual\ bioethanol\ produced\ (g/L)}{Total\ converted\ sugar\ (g/L)} \times 100 \tag{6}$$

$$Bioethanol\ volumetric\ productivity\ \left(\frac{g}{L \times hr}\right) = \frac{Produced\ bioethanol\ \left(\frac{g}{L}\right)}{Fermantation\ time\ (hr)} \tag{7}$$

2.2.3. Distillation

The fermented hydrolysates (RSG and WSG) were distilled by employing a simple distillation set-up at a temperature of 78–81 °C. After heating the fermented hydrolysates (RSG and WSG) at 78–81 °C for 4 h, the bioethanol vapour that exited from the mixture was captured, cooled, and condensed into bioethanol. The yield of the condensed bioethanol were estimated using equation (8).

$$Distillated\ bioethanol\ yield\ (\%) = \frac{Actual\ bioethanol\ yield\ (ml)}{Theoritical\ bioethanol\ yield\ (ml)} \times 100 \tag{8}$$

The concentration of bioethanol that can likely transform into energy was estimated by equation (9) proposed by Manmai et al. (2020), where it is assumed that 1 g of bioethanol can release an energy of approximately 30 kJ.

$$Transformable\ energy\ of\ bioethanol\ (kJ\ /\ L) = Bioethanol\ \left(\frac{g}{L}\right) \times 30 \tag{9}$$

2.2.4. Unit operation process

In Fig. 1, the water (ml) and pre-treated sorghum grains (g) in a ratio of 3:1 were charged into the hydrolysis reactor. The samples were heated under continuous stirring at a temperature of 50 °C for 72 h at a pH of about 5.91–5.98. After the hydrolysis reaction, the grain-water mixture was filtered using a 0.5 mm diameter mesh filter. Approximately 0.1 L of the filtrate (hydrolysate) was used to aerobically culture 7.5 g/L of yeast (*Saccharomyces cerevisiae*) at a pH of about 5.75–5.95 and a temperature of 37 °C to activate and grow the yeast cell population for 6 h. The remaining hydrolysate and the pre-cultured yeast were charged into the fermentation reactor. The conversion of fermentable sugar into bioethanol and CO_2 took place at a temperature of 37 °C and a pH of 5.05–5.95, anaerobically. After fermentation, the spent yeast was filtered off, and the filtrate (bioethanol) was distilled at 78 °C to 81 °C for 4 h to separate the ethanol from the water, producing pure bioethanol.

2.3. GC-MS analysis

The presence of ethanol in the produced bioethanol was detected, qualitatively and quantitatively by the use of a Perkin Elmer gas chromatograph (Clarus 580, USA) coupled with a mass spectrometer (Clarus SQ 8 S), GC-MS. The separation was achieved with Elite-5MS (5% diphenyl–95% dimethylpolysiloxane) connected to a capillary (30 × 0.25 μm ID × 0.25 μm DF) and an oven temperature programmed from 80 °C to 250 °C. The Turbo-Mass (version 6.1.0) was employed as the mass detector to portray the mass spectra and chromatograms. For mass spectrometric detection, an electron ionisation system was operated in an electron impact mode with an ionisation energy of 70 eV. Helium gas (99.999%) was used as a carrier gas, and an injection volume of 1 μl was employed. The injector temperature was kept at 250 °C, while the ion-

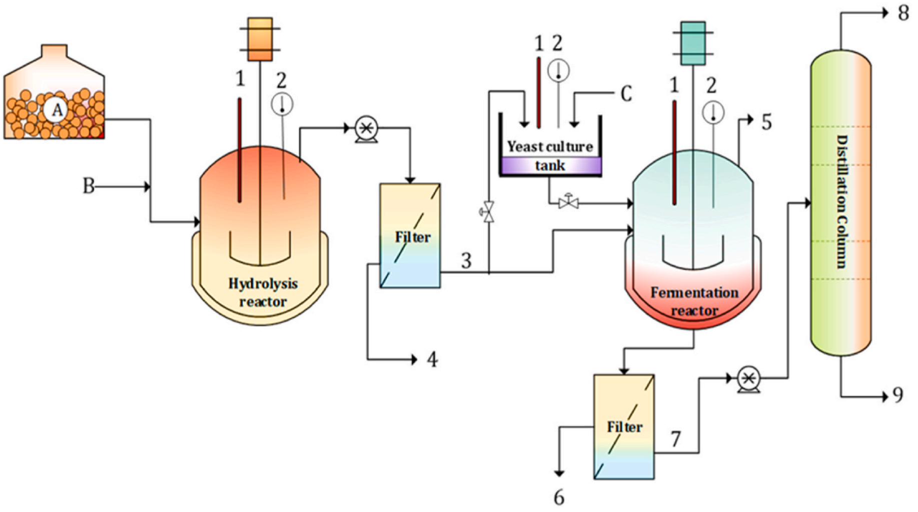

Fig. 1. Process flow diagram for the production of bioethanol from sweet sorghum grains. Variables: (**A**) Pre-treated sweet sorghum grains; (**B**) Water; (**C**)Yeast (*Saccharomyces cerevisiae*); (**1**) pH meter, (**2**) Thermometer, (**3**) Hydrolysate; (**4**) Spent grains (filter cake); (**5**) Carbon dioxide; (**6**) Spent yeast cells; (**7**) Broth; (**8**) Ethanol + relatively small amount of water; (**9**) Water + relatively small amount of ethanol.

source temperature was kept at 150 °C. The mass spectra were taken at 70 eV, a scan-interval of 0.5 s, and fragments from 45 to 425 Da. The solvent delay was 0–3 min, and the total GC–MS running time was 48 min. The interpretation of mass spectral GC–MS was done using the database of the National Institute of Standards and Technology (NIST), which has more than 62,000 patterns.

2.4. Fuel properties evaluation

The moisture content (%), density (g/cm^3) at 15 °C, refractive index, octane number, kinematic viscosity at 40 °C (mm^{2}s^{-1}), flash point (°C),.... and pH were used to assess the properties, quality, and performance of the bioethanol. The methods and their corresponding protocol are summarised in Table 1.

2.5. Statistical analysis

Statistical analysis was performed with OriginPro (version 2020, Northampton, MA, USA) and Microsoft Excel®. Each sample was repeated three times, and the mean values were presented to guarantee reproducibility. Each replicate was expressed as the mean ± SD and the one-way analysis of variance (ANOVA) was to compare the mean values. The significant difference was defined by the Duncan test ($p < 0.05$).

3. Results and discussion

3.1. Effects of water-grain ratio

The potential use of RSG and WSG for bioethanol production in the northern part of Ghana was investigated in this study. The sweet sorghum grains were milled down to 0.5 mm particle size, and the optimal amount of water needed to convert the starch into fermentable sugars was determined. The hydrolysis of a varied amount of water content (3000–7000 ml) into fermentable sugars and spent grains at a constant sweet sorghum content (1000 g) is shown in Fig. 2. The northern part of Ghana experiences high temperatures, low annual precipitation, intermittent periodic rainfall patterns, and a single rainy season, so an investigation was carried out to vary the water-grain ratio. This was necessary to assess the amount of water required to produce bioethanol to demonstrate that less water is required for bioethanol production. For smallholder farmers in northern Ghana, where there is only one rainy season per year, the production of bioethanol using a minimal amount of water will be more efficient and profitable.

The sugar content (filtrate) generated by varying the amount of water content during hydrolysis was measured and presented in Fig. 3. It was found that when water content was increased from 3000 ml to 7000 ml, hydrolysis increased, but the reduced sugars decreased. With 1000 g of SSG and 7000 ml of water, high hydrolysis conversion efficiencies of 90.45 ± 0.11 (WSG) and 89.67 ± 0.16 (RSG) were observed. These high conversion efficiencies suggest that 7000 ml of water can hydrolyse and produce a substantial quantity of fermentable sugars. However, a different result was observed with the water-grain ratio of 3000 ml-1000 g, which had the lowest hydrolysis conversion efficiencies (%) of 90.45 ± 0.11 (WSG) and 89.67 ± 0.16 (RSG) and produced the highest sugar content (%) of 95.53 ± 0.33 (WSG) and 94.27 ± 0.36 (RSG). This challenge can be effectively resolved by increasing the SSG weights proportionally to the increase in reactor water volume. Even so, the low water demand for bioethanol production is particularly desirable in the northern part of Ghana, where water scarcity is prevalent. For this reason, 1000 g of SSG in 3000 ml of water was chosen as the best condition for bioethanol production in the northern part of Ghana with the highest sugar concentration.

Table 1
Standard ASTM methods for fuel properties measurements.

Fuel property	Unit	ASTM Method
Refractive index	–	D1747-09
Octane number	–	D2700
pH	–	–
Moisture content	%	D6980
Flash point	^{0}C	D93
Density at 15 °C	g/cm^3	D1298
Kinematic viscosity at 40 °C	mm^{2}s^{-1}	D44504e

3.2. Bioethanol production

Table 2 presents a detailed summary of the results obtained from the production of bioethanol. After 72 h of SSG hydrolysis with conversion efficiencies (%) of 90.45 ± 0.11 (WSG) and 89.67 ± 0.16 (RSG), a sugar content (%) of about 95.53 ± 0.33 (WSG) and 94.27 ± 0.36 (RSG) was produced. The WSG recorded a higher amount of sugar content (%), conceivably owing to its higher starch levels than the RSG, as reported by Shalsh et al. (2021). As a result, the majority of the fermentable sugar in WSG was converted into bioethanol with a conversion efficiency (%) of 95.48 ± 0.16. This yielded about 91.57 ± 0.17% bioethanol after 24 h of fermentation, while the yield of RSG was approximately 89.24 ± 0.19%. Likewise, the bioethanol volumetric production was around 3.65 ± 0.15 g/h·L (WSG) and 3.51 ± 0.14 g/h·L (RSG), suggesting that the bioethanol production from WSG would be more efficient. The fermented bioethanol was then distilled to remove moisture while increasing the ethanol content. The yield of pure WSG bioethanol after a simple distillation was 81.25 ± 0.15% with a moisture content of about 8.91 ± 0.26%. This was a better result than the RSG bioethanol, which had a yield of 78.69 ± 0.12% with a moisture content of 10.18 ± 0.21%. According to Manmai et al. (2020), it could be presumed that 1 g bioethanol could release energy of approximately 30 kJ. In this study, it was found that WSG bioethanol can release 249.80 ± 0.23 kJ/L of energy, whereas RSG bioethanol can release 237.72 ± 0.25 kJ/L. From this, it follows that the WSG bioethanol has a greater chance of giving off more energy when it is used than the RSG bioethanol. In summary, the results (Table 2) obtained from the hydrolysis and fermentation of the sweet sorghum were similar to those of Basavaraj et al. (2013) and Manmai et al. (2020), who also found that bioethanol can be made from sweet sorghum with high bioethanol yields and volumetric productivities.

3.3. Distillation curve for bioethanol

The bioethanol was distilled at a temperature of 78 °C for 5 h to reduce its water content while increasing the its purity. The distillation curve in Fig. 4 shows a typical sigmoid plot expected to separate ethanol from water. The bioethanol distillation occurred at a reasonably stable temperature of about 78 °C until about 60 ml of bioethanol was distilled at 79 °C. The temperature ranges from 78 °C represent the boiling point of the lower-boiling liquid component (ethanol), which is approximately 78.32 °C. About 60 ml of pure bioethanol was obtained at this temperature and transferred into a separate flask. Further increases in the temperature produced a plateau at about 98–100 °C and advanced from 80 ml until distillation ended at 120 ml. The second boiling point plateau, at 100 °C, is assigned to the second, higher-boiling component (water). All in all, the stable distillation curve signifies a well-defined water separation from the bioethanol (WSG and RSG) after the fermentation of 60 °C.

3.4. GC-MS analysis of bioethanol

The GC results of the bioethanol produced from WSG and RSG are shown in Fig. 5(a) & (b). From Fig. 5(a) & (b), the two distinct components detected at retention times (min) of 3.97 ± 0.15 and 7.68 ± 0.10 correspond to the presence of ethanol and water (Tulashie et al., 2021; Quan et al., 2012). In Fig. 5(a), the amount of ethanol produced from the WSG contains about 80 ± 2.50% purity with 16 ± 2.40% of water. The RSG had less ethanol, with nearly 78 ± 1.80% purity with 17

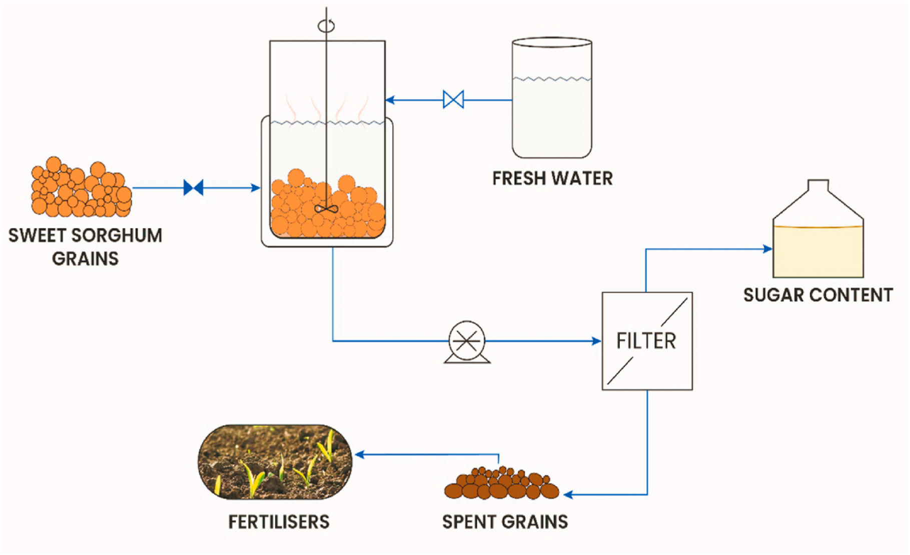

Fig. 2. Hydrolysis of varied amount of water content (3000–7000 ml) into fermentable sugars and spent grains at constant sweet sorghum content (1000 g).

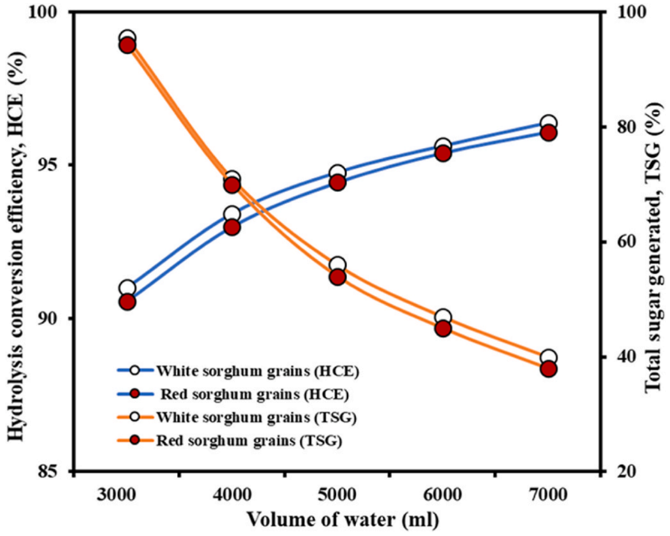

Fig. 3. Effects of increasing water content at fixed sweet sorghum weight (1000 g) on the hydrolysis conversion efficiencies and total sugar generated.

± 3.10% of water (Fig. 5(b)). These findings further reinforced the notion that bioethanol production from WSG would be more efficient and profitable on a large scale than RSG production. Nevertheless, the unidentified component detected at the retention time of 9.24 ± 0.10 min was identified as uncalibrated peaks, which was undetected by the GC (Fig. 5(a) and (b)). This could be due to impurities lowering the purity of the bioethanol obtained, as previously observed in a study (Tulashie et al., 2021).

3.5. Fuel properties of bioethanol

The use of bioethanol in cookstoves in the northern part of Ghana is highly dependent on how well its fuel properties match those of commercial fuels. It was therefore necessary to assess the bioethanol's fuel properties against those of commercial fuels and standard ethanol to ensure that they met regulatory standards. As shown in Table 3, the fuel properties of bioethanol were similar to those of standard ethanol and commercial fuels.

Table 2
Parameters for the hydrolysis, fermentation and distillation of sweet sorghum into fermentable sugars, bioethanol and pure distilled bioethanol, respectively.

Parameter(s)	White sorghum grains	Red sorghum grains
(I) Hydrolysis		
Time (hr)	72	72
pH	5.96 ± 0.12	5.94 ± 0.15
Total sugar generated (%)	95.53 ± 0.33	94.27 ± 0.36
Total sugar productivity (g/hr·L)	3.98 ± 0.25	3.93 ± 0.19
Hydrolysis conversion efficiencies (%)	90.45 ± 0.11	89.67 ± 0.16
(II) Fermentation		
Time (hr)	24	24
pH	5.84 ± 0.14	5.10 ± 0.11
Sugar after fermentation (%)	4.32 ± 0.32	5.68 ± 0.38
Bioethanol yield (%)	91.57 ± 0.17	89.24 ± 0.19
Mass of bioethanol produced (g)	87.42 ± 0.13	87.44 ± 0.10
Bioethanol volumetric productivity (g/hr·L)	3.65 ± 0.15	3.51 ± 0.14
Fermentation conversion efficiencies (%)	95.48 ± 0.16	93.98 ± 0.18
(III) Distillation		
Time (hr)	4	4
pH	6.97 ± 0.14	6.93 ± 0.11
Mass of bioethanol distillate (g)	8.32 ± 0.15	7.92 ± 0.14
Density of bioethanol distillate (g/cm^3)	0.82 ± 0.17	0.83 ± 0.13
Percent (%) yield of bioethanol distillate	81.25 ± 0.15	78.69 ± 0.12
Moisture content (%)	8.91 ± 0.25	10.18 ± 0.21
Transformable energy of bioethanol (kJ·/L)	249.80 ± 0.23	237.72 ± 0.25

Within the pH range of 6.92–6.98, bioethanol (WSG and RSG) was found to be in the same range as standard ethanol and commercial fuels, which range from 6 to 8. This suggests that bioethanol has a lower acidic component than fuels derived from crude oil. Bioethanol production is an eco-friendly process that produces a negligible amount of acidic compounds, making bioethanol less susceptible to corrosion during use, transportation, and storage. In Table 3, the densities of the WSG (0.83 ± 0.06 g/cm^3) and RSG (0.83 ± 0.11 g/cm^3) bioethanol matched well with those of commercial diesel. Fuel densities are used to assess the purity and concentration of fuels for specific applications. Therefore, the excellent similarity between bioethanol and conventional fuels suggests that the bioethanol produced was of standard quality.

The refractive index (RI) is a further criterion that can be used to

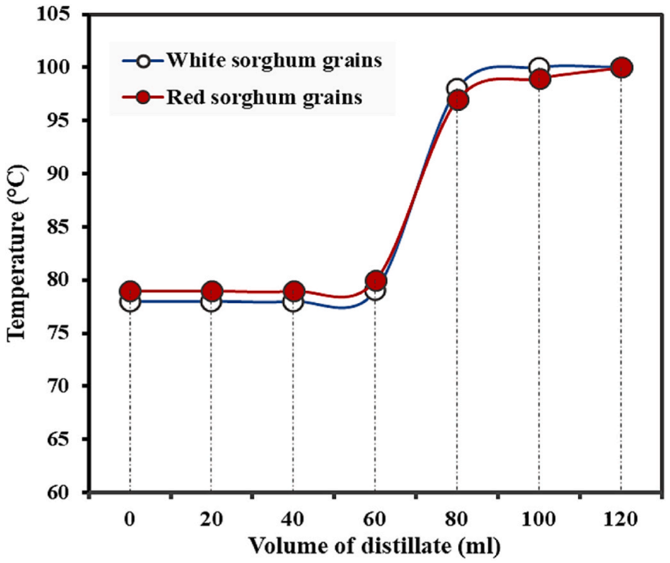

Fig. 4. Distillation curve for bioethanol produced from white and red sweet sorghum grains. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

evaluate the overall quality of bioethanol. Both WSG and RSG bioethanol met the prescribed RI ranges of 1.43–1.46 for commercial fuels and 1.35–1.37 for standard ethanol. According to Sarıkoç (2020), fuels with unsuitable RI values likely contain impurities, rendering them unfit for commercial applications. In this regard, the suitable RI of bioethanol indicates that its production is efficient and sustainable, resulting in minimal impurities in the fuels. The kinematic viscosities (KV) of fuels are the next most important factor in determining the best storage, handling, and operational conditions. A suitable KV demonstrates good performance in commercial and industrial applications and could be used in cookstoves. As shown in Table 3, the KVs of both WSG and RSG bioethanol were close to those of commercial fuels.

Similarly, the octane number (ON) of the bioethanol also determines its high performance for commercial uses. The bioethanol recorded a lower ON of about 76–79, insinuating that the bioethanol could ignite efficiently and quickly when used in cookstoves. To demonstrate this, a combustion test was conducted by igniting bioethanol distillate, which produced a light blue, soot-free flame. Finally, the flashpoint (FP) measured for the bioethanol (WSG and RSG) was identical to that of the standard ethanol and was easily volatilized in a flammability test. The observations made from these results point to high-quality bioethanol that could be used to cook and light lanterns in rural areas. This means that the bioethanol is of high quality and could perform well when it is sold commercially.

3.6. *Production of bioethanol towards a circular economy in Ghana*

3.6.1. *Case study in the northern part of Ghana*

The study was conducted in Ghana, a West African country located near the Gulf of Guinea and a few degrees north of the equator (Ghana Statistical Service, 2021). It lies between the latitudes of 4°45′N and 11°N and the longitudes of 1°15′E and 3°15′W (Ghana Statistical Service, 2021). In 2020, 16 administrative regions in Ghana were formed, with the northern part of the country covering about 41% of Ghana's total land area of 238,535 km^2 (Fig. 6) (Ghana Statistical Service, 2021). The northern part of Ghana is made up of the Northern, North East, Upper East, Upper West, and Savannah regions, which are more vulnerable to climate change and fluctuation than the southern parts of Ghana. The average monthly temperature ranges between 27 °C and 36 °C, and the various areas in these regions generally receive less rainfall due to their proximity to the Sahel (Abdul-Razak and Kruse, 2017; Incoom et al., 2020). This is because rainfall and duration depend significantly on the Inter-Tropical Convergence Zone (ITCZ), which moves across these areas annually (Abdul-Razak and Kruse, 2017; Incoom et al., 2020). It stays nearer to the equator for the rest of the year, restricting the amount of rainfall in the northern part of Ghana. As a result, the northern part of Ghana experiences high temperatures, low annual rainfall, periodic intermittent rainfall patterns, and a single rainy season.

Despite the unfavourable climatic conditions and erratic rainfall patterns in the northern part of Ghana, agriculture remains the predominant land-use activity in most areas (Abdul-Razak and Kruse, 2017). The majority of the agricultural activities are subsistence, rain-fed farming, and as a result, most farming activities are bound mainly to the rainy season, with little-to-no effective farming activities occurring during the dry season (Bawa, 2019). Therefore, the northern part of Ghana has traditionally been home to small grain cereals that can withstand variable and inconsistent climate conditions. A few of the main crops grown include sorghum (*Sorghum bicolor*), millet (*Panicum miliaceum*), maize (*Zea mays*), and rice (*Oryza sativa*) (Bawa, 2019 & Abdul-Razak and Kruse, 2017). Among these crops, sorghum is the most drought-tolerant and is mostly grown in the northern part of Ghana. One principal advantage over other cereal crops in the northern part of Ghana is its low water requirement of about 500 ± 100 m^3 (Lamptey et al., 2014).

3.6.2. *Traditional sweet sorghum supply chain*

Sweet sorghum has remained a vital cereal than other cereals in the northern part of Ghana for a variety of reasons, including (a) adaptation to various soil conditions, (b) higher agronomical resilience to temperature instabilities, (c) lower water requirement, (d) excellent drought tolerance, (e) shorter crop duration of about 4 months, and (f) lower cultivation cost (Isaac et al., 2012; Atokple et al., 2014; Bawa, 2019). It is also reported in the literature that the cost of cultivation ranges between 200 USD/ha and 450 USD/ha (Ahmed et al., 2000; Atokple et al., 2014; Reddy et al., 2010). This is lower than the costs for sugarcane and maize, which were reported to be around 995 USD/ha and 273 USD/ha, respectively (Ahmed et al., 2000; Atokple et al., 2014; Reddy et al., 2010). A variety of sorghum cultivars are grown by smallholder farmers in the north, where rural residents start farming on a small plot of land for sweet sorghum (Atokple et al., 2014; Abdul-Razak and Kruse, 2017). A significant number of smallholder farmers grow sweet sorghum for consumption and utilisation within households while earning some income from their supply in rural and urban markets (Atokple et al., 2014; Abdul-Razak and Kruse, 2017). A survey conducted by several researchers (Isaac et al., 2012; Mustapha, 2017; Bawa, 2019) revealed that most smallholder farmers in the north follow a traditional sweet sorghum supply chain concept illustrated in Fig. 7. The initial phase of sorghum production is depicted in Fig. 7 as the post-harvesting of sorghum plants, during which the grains and stalks are pre-treated, packaged, and stored prior to their use. Due to high levels of poverty and unemployment in the northern part of Ghana, some smallholder farmers may seek to produce sweet sorghum, primarily as food and fuel for their various households, in order to improve their quality of life (Bawa, 2019). Thus, impoverished smallholder farmers who may not be fully integrated into rural and urban markets choose to produce sweet sorghum solely for their families. The cultivated sweet sorghums are supplied to smallholder farmers' households for fresh consumption and utilisation. The grains are ground into flour and consumed as food, whereas the stalks of the sorghum plant are put to use as a source of fuel for the kitchens of various homes. In order to generate some income for the family, majority of smallholder farmers supplied the sweet sorghum to the local and commercial traders in the rural and urban markets. In the rural markets, traders sell the farmer's produce to food processors, who process the SSG into finished products, distribute them to wholesalers or retailers, and ultimately sell them to rural end-users (Isaac et al., 2012; Mustapha, 2017). In Ghana, sweet sorghums supplied by

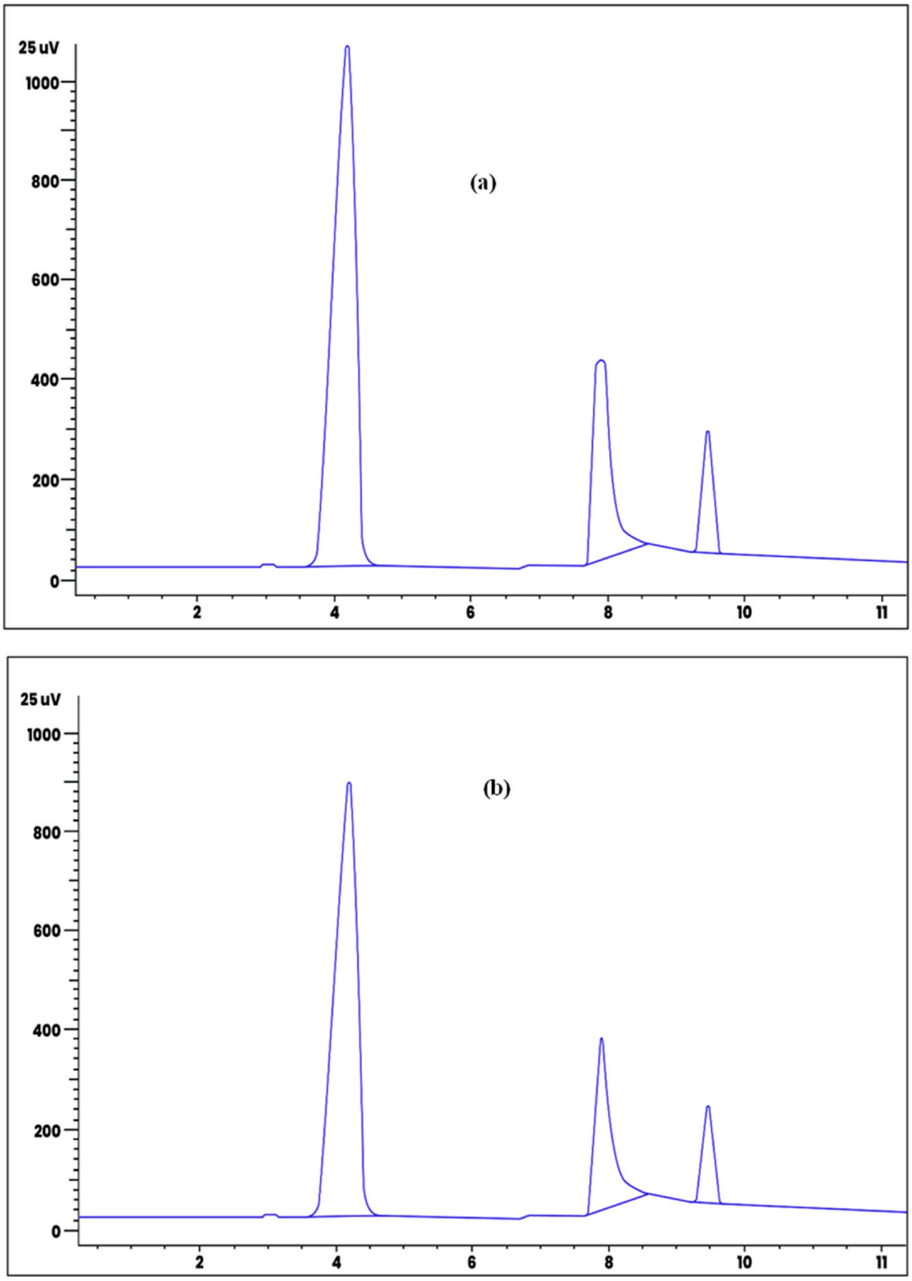

Fig. 5. Chromatograph of bioethanol produced from **(a)** white and **(b)** red sweet sorghum grains. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Fuel properties of the bioethanol from sweet sorghum and its comparison with commercial fuel and ethanol[a].

Fuel Properties	Bioethanol[b]		Standard[c]	Commercial fuels[d]		
	WSG	RSG	Ethanol	Diesel	Kerosene	Gasoline
pH	6.97 ± 0.16	6.93 ± 0.14	6.15–7.45	6–8	6–8	6–8
Refractive index	1.37 ± 0.08	1.38 ± 0.13	1.35–1.37	1.46	1.44	1.43
Density @ 15 °C (g/cm^3)	0.83 ± 0.06	0.83 ± 0.11	0.78–0.81	0.83–0.89	0.78–0.82	0.70–0.77
Flashpoint (°C)	18.92 ± 0.14	17.63 ± 0.15	12–20	≥50	≥32	≥37
Octane Number	76.14 ± 0.17	79.53 ± 0.28	81–89	–	20–49	70–100
Kinematic viscosity @ 40 °C (mm^{2}s^{-1})	1.34 ± 0.12	1.32 ± 0.21	1.20–1.58	2–5	1–2.50	3–5

[a] Data are given as mean values ± SD, n = 3.

[b] Bioethanol produced from white and red sweet sorghum grains (WSG and RSG), whereas, the.

[c] Standard ethanol and

[d] Commercial fuels values were taken from the literature (Sarıkoç, 2020; Şahin and Aydın, 2018; Nwufo et al., 2016).

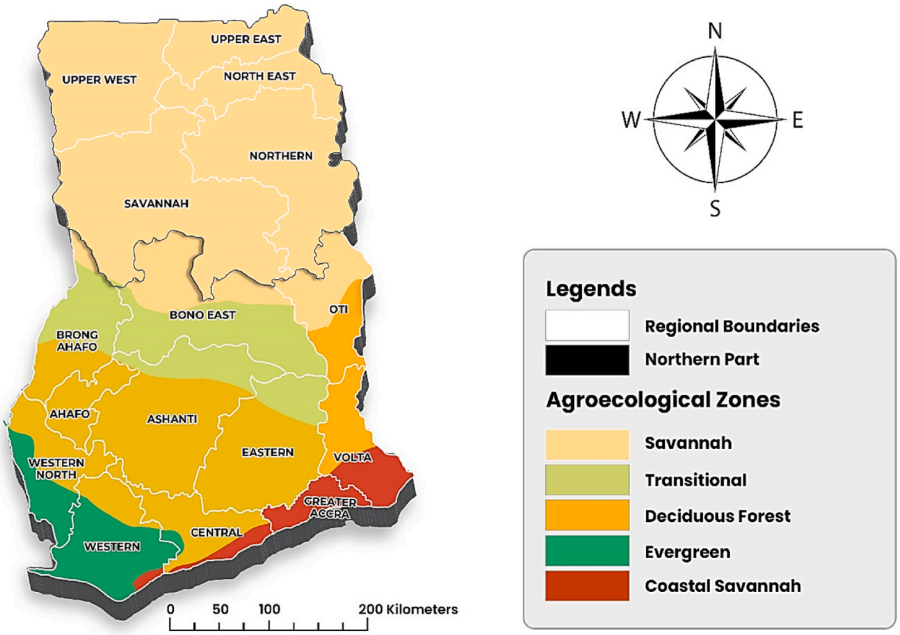

Fig. 6. Map of Ghana showing various respective regions and highlighting the northern part of Ghana.

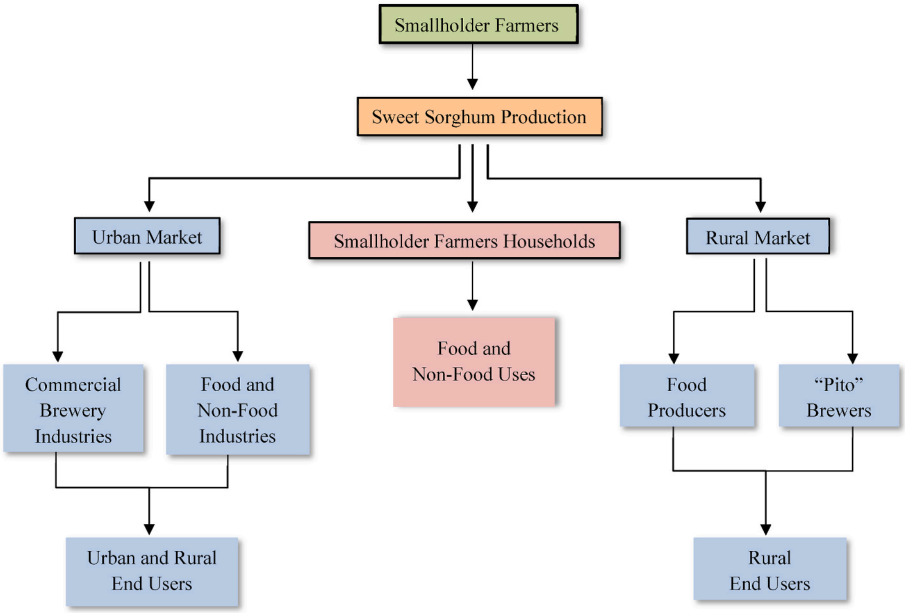

Fig. 7. Traditional sweet sorghum supply chain adopted by smallholder farmers.

rural traders to local producers are often used to prepare bread, syrup, and porridge (Isaac et al., 2012; Mustapha, 2017). Some local breweries also produce traditional sorghum beer, known as "pito," made by boiling fermented milled sorghum grains soaked in water using indigenous approaches (Isaac et al., 2012 & Zaukuu et al., 2016). A section of the sorghum produced is also supplied to the urban markets, where commercial traders supply it to commercial breweries and the food and non-food industries. In spite of this, the linear supply chain has failed to improve the economic and social conditions of smallholder farmers as a result of highly unstable sweet sorghum market prices. Sweet sorghum prices in rural and urban markets are strongly influenced by the current seasons in the region, political unrest in the communities, interest rates, and exchange rate fluctuations, among other factors (Isaac et al., 2012; Mustapha, 2017).

3.6.3. *Circular sweet sorghum supply chain*

The linear sweet sorghum supply chain, which involves the distribution of sweet sorghum to traders in rural and urban markets, provides insufficient income for smallholder farmers and their families. Due to the depreciation of sweet sorghum prices and market shocks, smallholder farmers face numerous challenges and distress in the markets (Isaac et al., 2012; Mustapha, 2017). As a direct consequence of this, the smallholder farmers in the northern sector are unable to generate a significant income from the sale of their sweet sorghum in the various markets in that region. The circular economy appears to be the best and most promising way for them to increase their income and improve their standard of living by utilising surplus sorghum from a bumper harvest. After a bumper harvest, only a small amount of sweet sorghum is consumed in the northern part of Ghana, and the excess is stored in a warehouse, where it is eventually discarded after a lengthy storage period (Isaac et al., 2012; Mustapha, 2017). Burning this excess sorghum results in the production of greenhouse gases, which have a negative impact on the environment. In addition to this, it causes financial losses for the smallholder farmers, which has a negative impact on their socioeconomic status. Along these lines, the excess sorghum stored in traditional storerooms during the dry season is affected by high temperature fluctuations, insects, and pest attacks that reduce the quality of the product and contribute to financial losses for the smallholder farmers (Isaac et al., 2012; Mustapha, 2017). However, in a circular economy, the excess sorghum, which might otherwise be discarded as biowaste, may instead be put to use by smallholder farmers to produce a valuable product. Hence, this study suggests moving toward a circular supply chain for sweet sorghum, in which smallholder farmers not only supply sorghum but also process the excess sweet sorghum into valuable products, thereby enhancing both their economic and social wellbeing. This is based on the fact that this strategy enables smallholder farmers to serve as both producers and suppliers of sweet sorghum. A circular supply chain could be seen as a business strategy and a multifaceted approach to sustainability and social impact.

In this approach, smallholder farmers could follow a simplistic procedure to convert the surplus of sweet sorghum into bioethanol. This study showed that sweet sorghum bioethanol production requires less than 3000 ml of water for hydrolysis and low-cost fermentable yeast (*Saccharomyces cerevisiae*), which can be easily found in rural and urban markets for the fermentation process. Bioethanol volumetric productions were found to be around 3.65 ± 1.15 g/h·L (Table 2), suggesting that growing WSG and RSG for bioethanol would be a highly efficient and productive venture in the northern part of Ghana. There was also a substantial difference in the amount of energy that could be released if WSG or RSG bioethanol were used. According to our findings, the expected amount of energy that could be released by WSG and RSG bioethanol was roughly about 249.80 ± 0.23 kJ/L and 237.72 ± 0.25 kJ/L, respectively. Thus, for 1 L of bioethanol used, the combustion of the bioethanol could release energy of about 230–250 kJ. This was closer to commercial gasoline and kerosene, which could release about 397 ± 2.3 kJ and 380 ± 1.5 kJ of energy, respectively (U.S Department of Energy, 2014 & Garrett-Peltier, 2017). Therefore, when bioethanol is used as a fuel, it has a greater chance of generating energy comparable to that of gasoline and kerosene, which are commonly used in the northern part of Ghana. This has the potential to replace the use of kerosene and gasoline, both of which are prohibitively expensive in the northern sector and are occasionally becoming scarce due to demand outstripping supply. In addition to our findings, Table 4 provides a concise estimate of the profit that can be anticipated from the production of bioethanol using sweet sorghum. It is important to note that the estimation was performed using the information obtained from this study and the models reported by Basavaraj et al. (2013). Future research could examine the profitability analysis on a larger scale, taking into account additional variables. Nevertheless, the minimum quantity of raw material (sweet sorghum grain) used for estimation was 0.1 kg. The expected profit from the production of bioethanol was 0.8 USD/liter, using a standard selling price of 1.4 USD/liter as the basis. Basavaraj et al. (2013) predicted a profit of 0.2 USD/liter with a selling price of 0.5 USD/liter for the production of bioethanol from sweet sorghum.

Table 4
Expected estimated profit for bioethanol production from sweet sorghum.

Parameters	[a]Present study	[b]Basavaraj et al.
[c]Cost of raw material, USD/tonne	16.6	13.1
Cost of feedstock, USD/liter	0.8	0.3
Cost of processing, USD/tonne	9.9	7.2
Total cost of ethanol production, USD/tonne	26.6	20.5
Selling price of bioethanol, USD/liter	1.4	0.5
Profit of bioethanol, USD/liter	0.8	0.2

[a] Estimates were made using data from the current study that was conducted in 2020 with an exchange rate of 5.8 GHC to 1 USD as of that year.

[b] Similar to the current study, a previous study reported by Basavaraj et al. (2013) was used for comparison, and the exchange rate from RS (rupee) to USD as of 2012, when the work was conducted, was 53.44 RS to 1 USD (BookMyForex, 2013).

[c] The price of sweet sorghum in Ghana from the farm gate in 2020 was about 96.02 GHC/tonne (FxExchangeRate.com, 2010; Wamucii, 2015; FAO, 2013).

A further benefit of bioethanol production by smallholder farmers is that the process demonstrated in this study is a sustainable and efficient method that requires fewer materials and simple resources. An average smallholder farmer could complete the entire process of producing sweet sorghum into bioethanol after completing a simple rural community training programme. In addition, some smallholder farmers in rural communities are expert “pito” brewers (Isaac et al., 2012 & Zaukuu et al., 2016); thus, such traditional experience and knowledge could be utilised and exploited in bioethanol production.

In the first stage of the current circular sweet sorghum supply chain that this study is based on (Fig. 8(a)), smallholder farmers could grow sweet sorghum through cooperative or individual farming, and the extra sorghum could be used to make bioethanol. After extracting the juice from the sorghum stalks, the sorghum bagasse could be used as heat for the hydrolysis and distillation. The smallholder farmers could increase the yield of the sorghum crop by using the spent grains that were produced after the production process as fertilisers (Reddy et al., 2010; Bawa, 2019). Approximately 90% of the bioethanol produced could be used as fuel in cookstoves, with the remainder being used in lanterns for children to study at night. The excess quantity has the potential to be put to use in the production of disinfectants that will protect against the COVID-19 viral infection. Overall, the quality and quantity of bioethanol produced could determine whether it should be used exclusively in the households of smallholder farmers or distributed to rural and urban markets. Bioethanol sold in rural and urban markets has the potential to generate income and improve the financial situation of smallholder farmers. Creating a new bioethanol market in rural areas will encourage many poor smallholder farmers to become future entrepreneurs, exploring various ways to use sweet sorghum as raw materials in their communities. For the future circular sweet sorghum supply chain model depicted in Fig. 8(b), the sorghum stalks produced from the cultivation of sweet sorghum could replace the excess sorghum used in the current model (Fig. 8(a)). A similar circular value chain model was illustrated by Schmidt et al. (2021) in the conversion of rural wastes into valuable products. Thus, to creatively and sustainably improve the socio-economic livelihoods of smallholder farmers who rely entirely on sweet sorghum as their primary food source, the current model should be optimised to include potential alternatives for producing bioethanol from a sustainable source. In this future scenario, the sorghum stalks, which are generally regarded as sorghum by-products and are either burned or used as sources of fuel, could be utilised in a future circular sweet sorghum supply chain. Due to their high fermentable sugar content, sorghum stalks are a low-cost and easily accessible source of bioethanol substrate (Shalsh et al., 2021 & Khalil et al., 2015). According to studies reported in the literature, bioethanol derived from stalks produces higher yields of about 1000 l/ha to 1500 l/ha than that derived from grains of about 700 l/h to 1000 l/h. This renders their production costs effective and efficient.

After the sorghum production (Fig. 8(b)), the sorghum stalks are isolated from the excess sweet sorghum as the raw material for bioethanol production. As part of this model, it is essential that the sorghum stalks from smallholder farmers be thoroughly analysed to determine if they are suitable for use. There are several factors to consider when evaluating the sorghum stalks from smallholder farmers, including their source, quantity, quality, and the sorghum cultivar they come from. If the sorghum stalks are of suitable quality, they follow the exact subsequent pattern and finally generate income for smallholder farmers. This future model increases smallholder farmers’ income while reducing the emissions of greenhouse gases from the incinerating of sorghum stalks,

Fig. 8. A circular sweet sorghum supply chain current **(a)** and future **(b)** models.

which contribute to climate instability in various regions. Bioethanol production from sorghum stalks using *Saccharomyces cerevisiae* and a 48-h fermentation period was also investigated by Manmai et al. (2020). According to their findings, 1 L of bioethanol produced from sorghum stalks could produce 250 ± 54.40 kJ of energy. This suggests that sorghum stalks may contain a high amount of energy, allowing for more efficient and productive production, as originally described in the future model.

3.6.4. *Beneficiaries of circular sweet sorghum supply chain*

The main beneficiaries of a circular sweet sorghum supply chain are the vulnerable people in rural communities, which form about 60% of smallholder farmers in the northern part of Ghana (M. et al., 2013; Abdul-Razak and Kruse, 2017; Bawa, 2019). Vulnerable people are those who are at risk of harm or abuse due to differences in gender, ethnicity, and age, as well as physical, mental, and financial problems. In the northern part of Ghana, the vulnerable population consists of low-income youth, the elderly, migrants, single parents, the disabled, orphans, and widows whose spouses were lost as a result of ethnic and internal community conflicts (Dessus and Jackson, 2011; Bawa, 2019). A survey by other authors (Dessus and Jackson, 2011; Bawa, 2019) revealed that about 70% of unemployed individuals in the northern part of Ghana are vulnerable people in many communities. The high unemployment rate has been the primary impetus for the majority of vulnerable people to engage in small-scale sweet sorghum farming; the sales of sweet sorghum barely support their livelihoods (Dessus and Jackson, 2011 & Tackie et al., 2020). In a circular sweet sorghum supply chain, the smallholder farmers identified themselves as bioethanol producers who earn additional income beyond sweet sorghum sales to improve their standard of living and reduce poverty. Through cooperative farming, vulnerable individuals are able to pool their resources, thereby increasing bioethanol production and improving their market opportunities. Gathering sorghum stalks for use in bioethanol production is a potential area in which the smallholder farmers may be able to provide employment to more vulnerable people in the rural communities.

Rural areas in the northern part of Ghana that lack access to electricity could use bioethanol-powered lanterns to allow low-income students to study at night. An important benefit of using bioethanol instead of traditional fossil fuels is the availability of a fuel that is both inexpensive and environmentally friendly for use in a cookstove. This is due to the high cost of liquefied petroleum gas (LPG) in the northern part of Ghana, which forces many rural residents to seek alternative fuel sources (Tackie et al., 2020). Because firewood is the only fuel that is readily available, easily accessible, and within their financial means, vulnerable people are forced to cut down trees for their domestic cooking needs. As a result, many vulnerable people are prime collectors in many rural areas where firewood is primarily used, travelling long distances to fetch firewood, consuming massive amounts of time smallholder farmers at could be spent increasing farming activities (Hussein et al., 2021). The high reliance on firewood in rural communities in the northern part of Ghana has raised concerns about environmental issues such as soil erosion, deforestation, and the negative health effects of exposure to harmful air pollution. Children and women are frequently the most vulnerable groups whose health is harmed as a result of repeated inhalation of toxic air pollutants such as particulate matter, soot, and organic compounds such as acrolein and polycyclic aromatic hydrocarbons (PAHs) (Hussein et al., 2021). In addition to health concerns, the combustion of firewood emits greenhouse gases, leading to climate change affecting annual sweet sorghum productivity.

A cookstove powered primarily by bioethanol produced by smallholder farmers was proposed in this research as a solution. This will benefit the vulnerable population, particularly the majority of those who cannot afford LPG. According to the fuel properties data in Table 3, bioethanol is of high quality and has the potential to deliver excellent performance when commercially used in cookstoves. Similarly, the probable GHG emissions per liter of sorghum-derived bioethanol have been reported by Nasidi et al. (2010) to be less than 1 kg CO_2 eq. per liter. This value was lower than sugarcane-derived bioethanol, which Nasidi et al. (2010) found to be about 2.42 kg CO_2 eq. per liter.

In this study, the bioethanol had a lower octane number of 76–79, indicating that it could be ignited rapidly and effectively. As a result, cooking with bioethanol could become easier and less time-consuming. The bioethanol cookstove could alleviate the burden of collecting firewood, improve the health of women and children, and help preserve and protect the environment. The design of a possible bioethanol cookstove that could be put to use in the northern part of Ghana is depicted in Fig. 9. According to Fig. 9, the bioethanol cookstove has a fuel tank that can hold 1.7 L of bioethanol and is adequately covered with a fuel cap. Using a funnel that flows through the fuel pipeline, a suitable amount of bioethanol could be charged into the tank. The flow rate into the combustion chamber can be adjusted by turning the knob. To create the fire that exists through the holes around the rim of the cookstove, vapours from the bioethanol in the combustion chamber mix with surrounding oxygen and are ignited with either a long lighter or a matchstick. The knob controls the intensity and heat power of the fire. In this case, a pot containing the food to be cooked could be placed directly on the cookstove. The components of the proposed bioethanol and its function are detailed in Table 5 and Fig. 10. Instruction on the use of bioethanol cookstoves, instruction on their safe operation could be provided in the form of training for the rural households.

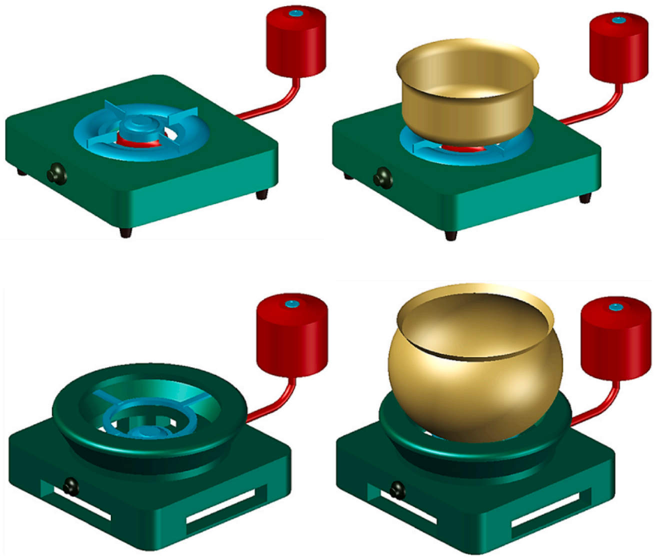

Fig. 9. The design of a potential bioethanol cookstove for use in the northern part of Ghana.

There is already some operational data and information demonstrating the use, safety, and evaluation of bioethanol cookstoves in some areas and countries where they have been implemented. For example, the Center for Entrepreneurship in International Health and Development (CEIHD) conducted a field performance evaluation on a cookstove pilot in several households in Kebribeyah, Bonga, and Addis Ababa before and after using the cookstove in specific households (Benka-Coker et al., 2018). According to the findings, the average level of kitchen particulate matter and carbon monoxide decreased by 84% and 74%, respectively, after the clean cookstove field trial was completed (Benka-Coker et al., 2018). The safety of bioethanol cookstoves under real-world conditions has also been examined in studies from several countries, with little to no explosions, fires, burns, injuries, and accidents reported (Johnson and Bryden, 2015; Kimemia and Van Niekerk, 2017).

Ultimately, the bioethanol is intended to be used for cooking stoves, lanterns, and the production of COVID-19 sanitisers, but the excess could end up being consumed as alcoholic beverages. This could have an adverse effect on the social and economic well-being of the people living in the northern part of Ghana. In order to address this, a training programme for smallholder farmers on bioethanol production could include information on the harmful effects of bioethanol consumption. Bioethanol is primarily produced through fermentation and simple distillation, but there is evidence to suggest that it may contain traces of methanol and other potentially harmful components (Tulashie et al., 2017 & Manning and Kowalska, 2021). For instance, both ethanol and methanol are produced during the distillation process and have similar physical and chemical properties (Tulashie et al., 2017). Methanol consumption has been linked to sudden onset headaches, vomiting, blurred vision, and loss of consciousness, all of which can lead to death (Doreen et al., 2020 & Manning and Kowalska, 2021). In addition, excessive or frequent consumption of bioethanol can lead to: (a) physical and sexual violence; (b) increased risk of suicide and homicide; (c) alcohol-related motor vehicle crashes; and (d) other unintentional injuries, such as burns, falls, and drowning (Khaderi, 2019 & Tulashie et al., 2017). Therefore, bioethanol produced by smallholder farmers

Table 5
Components of bioethanol cookstoves and their functions.

Label	Component	Function(s)
a	Fuel tank	• Holds and releases ethanol to be burnt in the combustion chamber
b	Fuel Cover/Cap	• Prevents fuel contamination and protect the fuel tank • Prevents the volatile fuel from evaporating
c	Fuel pipeline	• Serves as the channel through which the fuel is transported to the combustion chamber
d	Combustion chamber	• An area within the stove where the fuel injected is ignited to produce energy for cooking
e	Knob	• Controls the flowrate of the fuel to be burnt in the combustion chamber

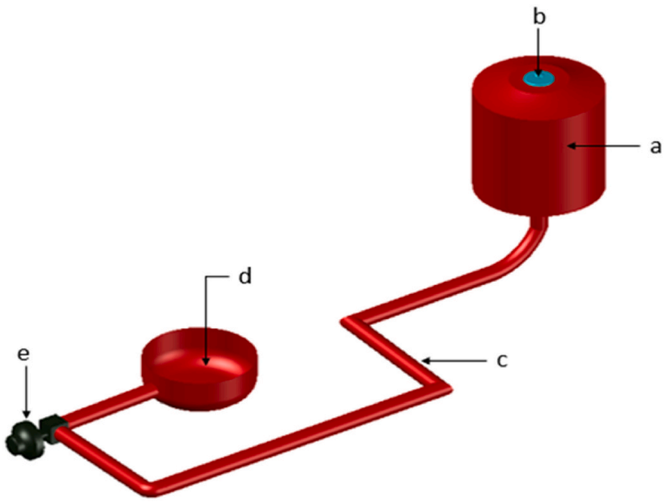

Fig. 10. Components of the bioethanol cookstove. This includes the fuel tank (a), fuel cover/cap (b), fuel pipeline (c), combustion chamber (d), and regulator (e).

should only be used as a fuel and not be consumed as this would be detrimental to the health of consumers. To ensure that the bioethanol produced is not misused, mass media health campaigns about the effects of consuming bioethanol could be conducted as part of the circular sweet sorghum supply chain model. Extensive public awareness and education could be conducted to inform and dissuade the people of the rural communities in the northern part of Ghana about the negative effects of bioethanol consumption. It is estimated that 75% of the people in the northern part of Ghana are illiterate as a result of (a) economic disparities, (b) gender discrimination, (c) poor education infrastructure and facilities, (d) fewer schools, and (e) technological barriers (Dessus and Jackson, 2011 & Tackie et al., 2020). There is therefore a lack of knowledge about both alcohol and methanol's negative effects on health among the general populace. As a result, public awareness and education will play a positive long-term role in the various communities, potentially limiting the use of bioethanol as an alcoholic beverage. This will be the case if the general public is educated about the negative health effects of bioethanol consumption.

A second issue with this model that could be remedied by raising awareness and educating the public concerns the production of bioethanol from consumption-fit material rather than surplus sweet sorghum. Some smallholder farmers may therefore choose to use the primary sweet sorghum in bioethanol production rather than consume the surplus sorghum. Hence, the public will be extensively educated on the topic of bioethanol production using only surplus sweet sorghum to lessen the likelihood of this happening. To ensure that bioethanol is obtained only from excess sorghum, the entire community, from small-scale farmers to community chiefs, would be involved. Likewise, the public will be made aware of the consequences of using consumption-fit materials, as well as the drawbacks of doing so. Cooperative farming will be suggested as a way for smallholder farmers without a surplus of sweet sorghum to increase their profits and reduce their reliance on consumption-fit products. Finally, future research will demonstrate how to use sorghum stalk as a feedstock for bioethanol production, providing smallholder farmers with additional options for producing bioethanol from sweet sorghum waste stalk.

4. Conclusions

Unemployment in the northern part of Ghana has been the primary driving force behind the majority of vulnerable people taking up small-scale sweet sorghum farming. For years, the linear sweet sorghum supply chain, which consisted solely of sweet sorghum grains (SSG) sales in rural and urban markets, provided insufficient income to smallholder farmers and their families. This necessitates the transition to a circular supply chain for sweet sorghum, which could increase the income of smallholder farmers through bioethanol sales. To accomplish this, the production of bioethanol from excess sweet sorghum in the northern part of Ghana was evaluated. Using white and red sweet sorghum grown in the northern part of Ghana for bioethanol production, the fermentation of SSG produced 87.6 g/L and 84.24 g/L of WSG and RSG bioethanol, respectively. Likewise, the bioethanol volumetric production of SSG was between 3.50 g/h·L to 3.70 g/h·L, indicating that its production was efficient after 24 h of fermentation. The fuel properties of the bioethanol indicated that they were of good quality and suitable for use in rural cookstoves, which could reduce the need for trees to be cut down for firewood and concerns about the health and environmental impact of this practise. As a matter of policy, the northern part of Ghana could benefit from a circular economy based on excess sweet sorghum by funding and enforcing training and education programmes for making bioethanol.

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CRediT authorship contribution statement

Samuel K. Tulashie: Conceptualization, Project administration, Supervision, Investigation, Methodology, Resources, Writing – review & editing, Formal analysis, Validation. **Daniel Dodoo:** Methodology, Software, Investigation, Visualization, Validation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Emmanuel Ketu:** Methodology, Software, Data curation, Investigation. **Samuel G.K. Adiku:** Conceptualization, Investigation, Resources, Writing – review & editing. **Michael K. Miyittah:** Formal analysis, Writing – review & editing. **Edem Forfoe:** Methodology, Investigation. **Ebenezer Arthur:** Methodology, Investigation.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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