Research article

Received: 1 February 2021 Revised: 7 April 2021 Accepted: 19 May 2021 Published online in Wiley Online Library: 6 June 2021

(wileyonlinelibrary.com) DOI 10.1002/jib.661

Screening of Ghanaian sorghum varieties for lager style brewing

Gregory A. Komlaga,[1]* Caleb M. Agbale,[2] Thomas Najah[1] and Solomon Dowuona[1]

Although sorghum is widely cultivated in Africa, its utilisation for the production of lager type beer by breweries is relatively limited. Sorghum is used unmalted as a brewing adjunct, in limited quantities, with barley and commercial exogenous enzymes for lager type beer production. The use of sorghum malt as the sole raw material in brewing lager type beers is generally limited because of its low diastatic power and high tannin content among other factors. The objective of this study is to identify sorghum varieties that could be malted and used as the sole (100%) brewing material for lager beer production. Twenty-six sorghum varieties cultivated in Ghana were screened for malting and brewing potential based on germinative energy, green malt hydration, gelatinisation temperature, extract yield, limit attenuation, free amino nitrogen and diastatic power. Five of the varieties; *Kadaga, Nakpaji, Kazea Nanga, Global 2000* and *Kyere,* of the twenty-six evaluated were found to have desirable characteristics for producing quality malt for lager beer production without the need for supplementary enzymes. Pilot scale malting and brewing trials are recommended to validate these findings.

Keywords: Sorghum malt; wort characteristics; screening; lager beer; brewing potential

Introduction

Sorghum (*Sorghum bicolor* (L) Moench) is an indigenous African cereal produced mainly in the savannah and grassland regions. The grain is grown mainly in the semi-arid regions of the tropics and sub-tropics. Sorghum is rich in carbohydrates (60-70%), proteins (8-12%), oil (2.8-3.6%), fibre (ca. 8%), ash (1-2%), vitamins and phytochemicals, such as phytosterols, policosanols, carotenoids and phenolic compounds, including flavonoids, tannins and anthocyanins *(1–4)*. It is an important cereal consumed as a staple food by people in semi-arid zones of Africa, South America and Asia *(5)*. Sorghum is also used as animal feed in developed countries and is emerging as a feedstock for biofuel production.

Although sorghum is widely cultivated in Africa, its utilisation in the brewing industry is limited. This is due to a myriad of factors including the high gelatinisation temperature of sorghum starch, high tannin content, low level of amylolytic enzymes in malted sorghum and limited technology for processing the grain *(6–8)*. Sorghum is however widely used in the production of traditional fermented opaque beverages such as *pito* and infant foods in West Africa. The grain is mainly used in the preparation of a stiff porridge (*tuo zafi),* a staple food of the inhabitants of the northern regions of Ghana and Nigeria.

Lager style beers are clear European beers brewed from barley malt. In brewing lager beers from sorghum malt, the decantation mashing process is applied whereby the sorghum mash is allowed to sediment and the supernatant is decanted and kept aside to be recombined with the thick mash after cooking to gelatinise the starch *(9–12)*. This process is used to retain enzyme activity and avoid denaturation at the high temperature used for gelatinisation of sorghum starch. Several studies have been conducted on identifying sorghum varieties that are suitable for malting and brewing of lager type beers *(8, 13–18)*. Although some progress has been made in Ghana regarding the development of standard process for malting sorghum for industrial production of traditional sorghum beer or *pito (19)*, the same cannot be said about using malted sorghum for lager production in breweries where unmalted sorghum is used in limited quantities as adjunct. In some cases, the breweries resort to mashing unmalted sorghum with a cocktail of commercial enzymes, a situation which has resulted in lack of development of malthouses, poor return for the sorghum value chain and non-optimal use of the grain in West Africa.

To promote the use of sorghum malt in the brewing industry, the government of Ghana is collaborating with other West African countries and development partners such as Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), International Fund for Agricultural Development (IFAD)/International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), United Nations Industrial Development Organization (UNIDO) and Common Fund for Commodities. Several interventions are in place to research sorghum breeding, establish laboratories, a pilot malting and brewing plant to perform trials on brewing with sorghum *(18)*. As a result, several improved varieties of sorghum which are comparable to Nigerian cultivars SK5912, KSV8 and ICSV 400, that are known to have good malting and brewing potential *(8)*, have been developed by Savanna Agricultural Research Institute (SARI) of the Council for Scientific and Industrial Research (CSIR) in Ghana, to meet the needs of the local brewing industry. This study, conducted at the CSIR-Food Research Institute, evaluated the varieties

* Correspondence to: Gregory Komlaga, Food Technology Research Division, Council for Scientific and Industrial Research-Food Research Institute (CSIR-FRI), Box M20, Accra, Ghana. Email: gkomlaga@yahoo.com

[1] Food Technology Research Division, Council for Scientific and Industrial Research-Food Research Institute (CSIR-FRI), Box M20, Accra, Ghana

[2] Department of Biochemistry, School of Biological Sciences, University Posts, University of Cape Coast, Cape Coast, Ghana

cultivated by CSIR-SARI, to identify those that could be used for lager beer brewing without the need for supplementary enzymes.

The critical quality parameters for the malting and brewing potential of sorghum are germinative energy, diastatic power, extract yield (as hot water extract), and free amino nitrogen (FAN). Germinative energy determines the viability of the grain and is a measure of the percentage that will germinate to produce malt. Diastatic Power is the combined activity of beta and alpha amylases for converting gelatinised starch into sugars for fermentation. Extract yield is the measure of the soluble materials that have been formed from the sorghum endosperm into the mash and FAN measures the level of the nitrogen compounds that are a nutrient for yeast during fermentation. Attenuation Limit is a measure of the quantity of fermentable sugars that have been extracted from the malt into the mash. Extract yield and Attenuation Limit are both dependent on the Diastatic Power of the malt. Diastatic Power is therefore the most critical quality parameter for the suitability of sorghum malt for use in brewing lager type beers. Sorghum varieties that produce malts with inadequate diastatic power are not suitable for the production of Lager style beers which typically have an alcohol content of 5% ABV.

Materials and methods

Twenty-six sorghum varieties cultivated at the SARI of the Council for Scientific and Industrial Research (CSIR), Ghana were used for the study.

Germinative energy

The germinative energy of the sorghum varieties was determined according to the method of the European Brewery Convention *(20)* with slight modifications. Three batches of 100 randomly selected grains of each variety were placed in a 9 cm diameter petri dish lined with two pieces of Whatman No. 1 filter paper, moistened with 4 mL of distilled water. This was incubated at 29°C and the number of chitted grains counted at 24 hour intervals over a period of 72 hours.

Malting

Each sorghum variety (2 kg) was weighed and washed four times in 6L of potable water. Immature and floating grains were recovered and discarded. The grains were sanitised *(21)* by soaking in 0.5% (w/v) NaOH solution for three hours. The sanitized grains were washed three times with 10L of potable water and steeped at 29°C in 5L potable water for twelve hours. The steep liquor was drained off and the grains washed once with 6L of fresh potable water. The grains were steeped again in 6L of tap water for four hours after which the grains were removed from the water and air-rested for two hours. The steeping of the grains continued (in 6L of water) for another two hours after which the grains were transferred to malting trays (24cm x 48cm x 6cm) for germination at 29°C in a dark room for five days. The germinating grains were sprayed with 100 mL of potable water twice daily (8am and 4pm) using spray bottle. Malting was halted after the fifth day and the green malt was dryed at 50°C in a forced air oven for 16 hours. The grains were de-rooted manually after drying (by rubbing the warm germinated grains on a wire mesh) and then milled with a Buhler Miag disc mill (Buhler Universal, DLFU, Buhler GmbH, Braunsschweig).

Moisture of green malt

The moisture content of the green malt of the sorghum varieties was determined using Air Oven Method *(22)*.

Gelatinisation temperature

The pasting characteristics of the malt samples were determined using Visco-Amylograph (Viscograph-E, Brabender GmbH & Co, KG, Illinois, USA). The moisture content of the milled malt flour was determined using Sartorius MA 45 (Sartorius AG, Goettingen, Germany) moisture analyser. Viscograph-E software determined the quantities of flour and distilled water which were mixed to form a consistent slurry with no lumps.

Hot water extract

The hot water extract of malt was prepared using standard mashing procedures *(23)*. Milled malt (50g) was added to 200 mL of distilled water in a beaker at 45°C and held for 30 min in a mashing bath (Bender and Horbein, Model MA3E) with continuous stirring before raising the temperature to 62°C (1°C/min) and holding it for 15 min. The mash was then removed and left at room temperature for 60 min to sediment. An aliquot (60 mL) of the supernatant (enzyme rich extract) was decanted. The remaining thick mash was boiled for 10 min under continuous stirring and then cooled to 62°C. The supernatant was added to the cooked sediment, mixed, heated to 62°C and held for 15 min, before raising the temperature to 72°C at 1°C/min. Saccharification was checked every 10 min for 60 min using the iodine starch test. At the end of 60 min, the mash was cooled to room temperature and made up to 250 g with distilled water. The resulting wort was filtered through a fluted Whatman no. 3 filter paper and used for the measurement of extract, amino nitrogen, limit attenuation and diastatic power.

Extract in °Plato (g/100 g), was measured using an Anton Paar density meter, model 35 N (Anton Paar GmbH, Graz, Austria).

Extract yield was calculated using the relationship:

$$\text{Extract yield } (\%);\ \text{as} - \text{is};\ Y_1 = E\,(H + 500)/(100\text{–}E)$$

$$\textit{Extract yield } (\%) \textit{ on dry matter } (dm),\ Y_2 = Y_1 \times 100/(100\text{–}H)$$

where Y_1 is the extract content of sample, as-is (%), Y_2 is the extract content in dry matter (%), E is the extract content of wort in gram/100 g and H is the moisture content of malt (%).

Free amino nitrogen

Free amino nitrogen (FAN) was determined using the international ninhydrin colorimetric method *(24)*.

Limit attenuation

Limit attenuation was determined in triplicate using 20 mL of wort *(25)*.

Diastatic power

Diastatic power was determined using the peptone extraction method *(26)*.

Results and discussion

Germinative energy, hydration of green malt and gelatinisation temperature.

The characteristic of sorghum grain of paramount importance to the maltster is germinative energy (GE) which is an indication of the potential of the grains to germinate. The GE of malting grains should not be lower than 96% *(19)* and is crucial in the selection of grains for malting as it is indicative of seed viability, maturity, physical and microbiological integrity. Table 1 shows that nine out of the 26 sorghum varieties had a germinative energy outside the acceptable limits (< 96%) and therefore were not a good malt for brewing. The moisture content of the green sorghum malts (Table 1) ranges from 36.1 to 46.7% with nine of the varieties recording moisture content below 40%. Quality parameters such as diastatic power, extract yield, extent of cell wall modification and malting loss are highly correlated to out-of-steep moisture content of Sorghum malt *(6, 27)*. Most of the sorghum varieties had out-of-steep moisture contents above 40% in agreement with the literature *(28)*.

The gelatinisation temperatures of the sorghum varieties screened range from 73.1 to 80.6°C (Table 1). During the mashing process barley malt starch gelatinises between 59 and 63°C, a temperature at which the starch conversion enzymes are active *(28)*. The relatively high starch gelatinisation temperatures of sorghum varieties would not support starch hydrolysis by the amylases as the enzymes would be destroyed in the mash. For this reason, mashing with 100% sorghum needs to be performed using a double mashing (decantation) method as reported in earlier studies *(9–12)*.

Table 1. Germination energy, green malt hydration and gelatinisation temperature of the sorghum varieties

Sorghum variety	GE (%)*	Moisture of green malt (%)*	Gelatinisation temperature (°C)*
Kadaga	97 ± 1.0	41.9 ± 0.3	78.8 ± 0.2
Mankaraga	96 ± 0.0	44.0 ± 0.1	76.4 ± 0.5
Belko	96 ± 0.0	36.8 ± 0.5	76.3 ± 0.3
Kapeli	90 ± 0.0	46.3 ± 0.2	78.5 ± 0.4
Nakpaji	98 ± 0.0	39.5 ± 0.1	76.0 ± 0.1
Zelle	95 ± 1.0	37.5 ± 0.0	77.4 ± 0.2
Keriga	96 ± 0.0	40.9 ± 0.0	77.7 ± 0.0
Kazea Nanga	100 ± 0.0	44.3 ± 0.1	79.3 ± 0.1
Yakpaji	98 ± 0.0	39.4 ± 0.6	77.5 ± 0.2
Global 2000	97 ± 0.0	44.1 ± 0.3	78.8 ± 0.3
Bunbago	98 ± 0.0	41.6 ± 0.4	77.9 ± 0.4
Kazea	99 ± 0.0	42.9 ± 0.0	76.1 ± 0.1
Naga	93 ± 1.0	40.1 ± 0.2	73.1 ± 0.1
Kapaala	90 ± 0.0	38.5 ± 0.1	78.3 ± 0.1
Kazea Gare	96 ± 0.0	41.6 ± 0.0	75.9 ± 0.3
Berko	98 ± 0.0	41.8 ± 0.2	76.7 ± 0.3
Dwaagy	97 ± 0.0	43.3 ± 0.2	73.7 ± 0.3
Belko Pielik 2	99 ± 1.0	36.1 ± 0.4	80.6 ± 0.4
Belko Pielik 1	96 ± 0.0	36.6 ± 0.1	78.9 ± 0.2
Nyonso	93 ± 0.0	39.9 ± 0.3	79.4 ± 0.2
Kazea Gyeri	96 ± 0.0	43.8 ± 0.2	76.9 ± 0.0
Kazea Peela	93 ± 0.0	46.7 ± 0.2	76.1 ± 0.2
Chari Bile	85 ± 1.0	42.6 ± 0.4	77.0 ± 0.3
Kyere	97 ± 1.0	40.9 ± 0.1	75.3 ± 0.2
Ayufuful	89 ± 2.0	37.8 ± 0.2	75.6 ± 0.1
Kapeli Tam	84 ± 0.0	43.9 ± 0.2	77.2 ± 0.3

* Each value represents the mean of triplicate determinations.

Diastatic power

Diastatic power is the combined activity of beta and alpha amylases which are responsible for converting gelatinised starch into sugars for fermentation. Diastatic power is the critical quality parameter for the suitability of sorghum malt for use in brewing lager type beers. The DP of the malted sorghum varieties are reported in Table 2 which range from 55 to 75.3 WK units. Agbale et al. *(29)* reported an average DP of 83.86 WK units for sorghum malt compared to an average of 340 WK units for barley malts *(29)*. Reported values for industrial sorghum malt used for brewing opaque sorghum beers in South Africa range from 37 to 86 WK units *(30)*. Attempts to use 100% sorghum malts in lager beer production have encountered several problems including low diastatic activity due to the low levels of β-amylase activity *(15)* and limited endosperm cell wall modification *(31)*. The combined effect of these limitations results in the slow and incomplete starch hydrolysis during mashing with accompanying long saccharification times, low extract yield, slow wort and beer filtration. Sorghum brews tend to be turbid and have short shelf-life due to high residual starch content *(32)*. Accordingly, much emphasis is focused on malting conditions such as steeping and germination to improve the diastatic activity *(19, 33–35)* in sorghum malts to improve the extract yield and reduce saccharification time. Of the sorghum varieties in this study, most had a DP below the values previously reported *(19)*. Sorghum malts with DP <70 WK units were not considered in this work as these malts did not produce the desirable levels of fermentable extracts after saccharification. Five of the 26 sorghum varieties - *Kadaga, Nakpaji, Kazea Nanga, Global 2000 and Kyere* - screened (Table 2) were selected as having desirable diastatic power for lager type beer brewing based on this consideration.

Limit Attenuation

The limit attenuation of the sorghum varieties (Table 2) ranged from 64.9 to 81.8%, most of which fall below the recommended figure of 80% *(28)*. The results compare with other work *(8, 15, 17–19)* but are higher in five varieties in this study. Degree of fermentation is an important indicator of brewery production and profitability, since it determines the yield of alcohol in the brewing process as well as the efficiency of fermentation. The greater the attenuation, the more sugar that has been converted into alcohol *(36)*. Beers brewed from sorghum malt are low in alcohol because of the low level of β-amylase activity *(15)*. Table 2 indicate that five varieties - *Kadaga, Nakpaji, Kazea Nanga, Global 2000* and *Kyere* - had limit attenuation of > 80% and were selected as having potential for malt production and lager type brewing.

Extract yield

Extract yield is the amount of soluble material obtained by the aqueous extraction of malt. Malt with extract yield <75.0% dry matter is not economical for use in brewing as much of the carbohydrate and protein will remain insoluble and be lost in the spent grain. Sorghum malt with a minimum diastatic power of

Table 2. Malt and wort parameters of the sorghum varieties

Sorghum variety	Diastatic power (WK units)*	Extract yield (dm basis) (%)*	Limit attenuation (%)*	Free amino nitrogen (mg/L)*
*Kadaga***	74.3 ± 0.4	84.3 ± 0.4	80.2 ± 0.1	263.4 ± 0.1
Mankaraga	63.4 ± 0.3	68.8 ± 0.5	71.8 ± 0.3	296.0 ± 0.5
Belko	62.2 ± 0.2	69.4 ± 0.6	70.4 ± 0.2	187.1 ± 0.4
Kapeli	61.3 ± 0.1	66.8 ± 0.5	69.5 ± 0.1	219.7 ± 0.2
*Nakpaji***	71.2 ± 0.3	80.5 ± 0.5	80.0 ± 0.4	206.7 ± 0.4
Zelle	57.0 ± 0.0	65.5 ± 0.9	68.3 ± 0.0	254.5 ± 0.3
Keriga	56.7 ± 0.1	66.1 ± 0.6	67.8 ± 0.1	308.4 ± 0.1
*Kazea Nanga***	72.5 ± 0.2	80.1 ± 0.6	80.4 ± 0.2	155.3 ± 0.2
Yakpaji	65.3 ± 0.4	74.2 ± 0.4	76.9 ± 0.2	148.2 ± 0.0
*Global 2000***	71.8 ± 0.5	80.7 ± 0.4	80.1 ± 0.1	219.8 ± 0.0
Bunbago	63.3 ± 0.3	67.1 ± 0.5	70.2 ± 0.3	226.3 ± 0.3
Kazea	65.5 ± 0.2	73.3 ± 0.4	76.9 ± 0.1	236.7 ± 0.6
Naga	67.7 ± 0.3	72.1 ± 0.3	74.3 ± 0.3	172.2 ± 0.4
Kapaala	62.0 ± 0.3	71.0 ± 0.5	73.9 ± 0.1	139.4 ± 0.3
Kazea Gare	56.6 ± 0.2	65.0 ± 0.6	67.2 ± 0.2	162.6 ± 0.1
Berko	60.0 ± 0.1	67.5 ± 0.6	70.2 ± 0.2	223.2 ± 0.0
Dwaagy	63.3 ± 0.1	71.5 ± 0.5	73.1 ± 0.0	202.0 ± 0.1
Belko Pielik 2	60.7 ± 0.0	65.7 ± 0.3	69.6 ± 0.2	162.1 ± 0.2
Belko Pielik 1	59.2 ± 0.1	64.5 ± 0.4	70.0 ± 0.1	168.0 ± 0.4
Nyonso	55.0 ± 0.3	65.0 ± 0.9	66.0 ± 0.3	146.4 ± 0.2
Kazea Gyeri	61.0 ± 0.4	69.1 ± 0.5	70.1 ± 0.2	232.9 ± 0.3
Kazea Peela	59.5 ± 0.3	66.9 ± 0.5	68.8 ± 0.2	198.3 ± 0.5
Chari Bile	58.3 ± 0.2	65.6 ± 0.7	74.2 ± 0.1	244.6 ± 0.2
*Kyere***	75.3 ± 0.1	86.6 ± 0.6	81.8 ± 0.0	254.0 ± 0.3
Ayufuful	60.7 ± 0.0	69.7 ± 1.0	70.4 ± 0.0	215.0 ± 0.4
Kapeli Tam	55.2 ± 0.1	66.4 ± 0.5	64.9 ± 0.3	155.1 ± 0.1

* Each value represents the mean of triplicate determinations.
** Varieties with desirable malt and wort characteristics.

50 WK units has sufficient enzyme activity to produce a wort with fermentability above 75% *(18)*. The extract yield on a dry matter basis in this study (Table 2) ranged from 64.5 to 86.6% with most of the varieties below the recommended value of 77-83% dm *(37)*.

One critical condition when considering extract yield is that the mash must completely saccharify within reasonable time. Of the 26 varieties screened, five had extract yields greater than 77% with average complete saccharification time of one hour. Most of the varieties that had the extract yield below 77% took many hours to completely saccharify. This reflects the relatively low diastatic power of those varieties. Accordingly, five (*Kadaga, Nakpaji, Kazea Nanga, Global 2000, and Kyere*) varieties were selected as having potential for commercial lager beer brewing.

Free amino nitrogen

Free amino nitrogen (FAN) in the wort is essential for the growth and metabolism of yeast during alcoholic fermentation. The recommended minimum FAN concentration for fermentation is reported to be 150 mg/L *(38, 39)*. Apart from three sorghum varieties - *Kapaala*, *Yakpaji* and *Nyonso* - all the other varieties in this study satisfy the FAN condition for selection for malt production and brewing (Table 2). The FAN values obtained in this study compare with other reports *(8, 17–19)*. Common FAN values for sweet worts range from 140 to 260 mg/L *(40)*. The FAN values obtained in this study indicate only *Kapaala* is outside of this range. This implies that the worts produced by the sorghum varieties reported here had adequate amounts of amino nitrogen for lager style brewing in agreement with Taylor & Boyd *(41)*.

Conclusions

Most of the sorghum varieties had germinative energy above 96% and ex-steep moisture contents above 40% which are both ideal for producing good malt for lager brewing. The gelatinisation temperatures of the starch in the grains were relatively high (between 73.1 and 80.6°C). Mashing with 100% sorghum needs to be performed using the double mashing (decantation) method to avoid denaturing the amylases during mashing. The FAN values obtained from the study indicate that the worts from the majority of the sorghum varieties had adequate amounts of nitrogen to support yeast growth during fermentation. Five of the 26 sorghum varieties screened had desirable diastatic power resulting in good extract yield and high attenuation of the wort. Five sorghum varieties met all the recommended malt and wort characteristics (germinative energy, diastatic power, extract yield, limit attenuation, free amino nitrogen) for lager style brewing. This suggests that five varieties of sorghum - *Kadaga, Nakpaji, Kazea Nanga, Global 2000, Kyere* - could be used as raw material (100%) for lager beer production without the need for exogenous enzymes. There is the need however to conduct pilot scale malting and brewing trials to validate these findings. Once this is achieved, there would be economic benefit for stakeholders in the sorghum value chain and savings on the reduced importation of brewing materials.

Author contributions

Gregory Komlaga - conceptualisation, methodology, software, validation, investigation, data curation, writing/editing, visualisation, supervision, project administration, funding acquisition.
Caleb Agbale - software, formal analysis, writing/editing, investigation, data curation.
Thomas Najah - investigation, formal analysis, project administration.
Solomon Dowuona - investigation, formal analysis, project administration.

Acknowledgements

This publication is an output of CFC/UNIDO/Government of Ghana/CSIR-Food research Institute Sorghum Malt Project funded by Common Fund for Commodities (CFC) and UNIDO for the benefit of developing countries. The views expressed are not necessarily those of CFC and UNIDO.

References

1. Cardoso LM, Montini TA, Pinheiro SS, Pinheiro-Sant'Ana HM, Martino HSD, Moreira AVB. 2014. Effects of processing with dry heat and wet heat on the antioxidant profile of sorghum. *Food Chem.* 152:210-217. https://10.1016/j.foodchem.2013.11.106.
2. Chávez DWH, Ascheri JLR, Carvalho CWP, Godoy RLD, Pacheco S. 2017. Sorghum and roasted coffee blends as a novel extruded product: Bioactive compounds and antioxidant capacity. *J Funct Foods* 29:93-103. https://doi.org/10.1016/j.jff.2016.12.012
3. Llopart EE, Drago SR. 2016. Physicochemical properties of sorghum and technological aptitude for popping nutritional changes after popping. *Lebensmittel-Wissenschaft + Technologie* 71:316-322. https://doi.org/10.1016/j.lwt.2016.04.006
4. Stefoska-Needham A, Beck EJ, Johnson SK, Tapsell LC. 2015. Sorghum: an underutilized cereal whole grain with the potential to assist in the prevention of chronic disease. *Food Rev Int* 31:401-437. https://doi.org/10.1080/87559129.2015.1022832
5. Proietti I, Frazzoli C, Mantovani A. 2015. Exploiting nutritional value of staple foods in the world's semi-arid areas: risks, benefits, challenges and opportunities of sorghum. *Healthcare* 3:172-193. https://doi.org/10.3390/healthcare3020172
6. Ezeogu LI, Okolo BN. 1994. Effect of final warm water steep and air rest cycles on malt properties of three improved Nigerian sorghum cultivars. *J Inst Brew* 100:335–338. https://doi.org/10.1002/j.2050-0416.1994.tb00832.x
7. Ogbonna AC. 2011. Current developments in malting and brewing trials with sorghum in Nigeria: A review. *J Inst Brew* 117:394–400. https://doi.org/10.1002/j.2050-0416.2011.tb00485.x
8. Ogu EO, Odibo FJC, Agu RC, Palmer GH. 2006. Quality assessment of different sorghum varieties for their brewing potential. *J Inst Brew* 112:117–121. https://doi.org/10.1002/j.2050-0416.2006.tb00241.x
9. Espinosa-Ramírez J, Pérez-Carrillo E, Serna-Saldívar SO. 2013. Production of brewing worts from different types of sorghum malts and adjuncts supplemented with β-Amylase or amyloglucosidase. *J Am Soc Brew Chem* 71:49-56. https://doi.org/10.1094/ASBCJ-2013-0125-01
10. Osorio-Morales S, Serna-Saldívar S, Chavez J. 2000. Production of brewing adjuncts and sweet worts from different types of sorghum. *J Am Soc Brew Chem* 58:21-25. https://doi.org/10.1094/ASBCJ-58-0021
11. Taylor JRN. 2003. Overview: importance of sorghum in Africa, P21. Department of Food Science, University of Pretoria, Pretoria 0002, South Africa.
12. Palmer GH. 1989. Cereals in Malting and Brewing, 61-242. In: G. H. Palmer (ed), *Cereal Science and Technology*. Aberdeen University Press: Aberdeen, Scotland.
13. Okungbowa J, Obeta JAN, Ezeogu LI. 2002. Sorghum β-amylase production: Relationship with grain cultivar, steep regime, steep liquor composition and kilning temperature. *J Inst Brew* 108:362-370. https://doi.org/10.1002/j.2050-0416.2002.tb00562.x
14. Iwuoha CI, Aina JO. 1997. Effects of steeping condition and germination time on the alpha-amylase activity, phenolics content and malting loss of Nigerian local red and hybrid Short Kaura sorghum malts. *Food Chem* 58: 289-295. https://doi.org/10.1016/0308-8146(95)00215-4
15. Duffour JP, Melotte L, Srebrnik S. 1992. Sorghum malts for the production of a lager beer. *J Am Soc Brew Chem* 50:110-119. https://doi.org/10.1094/ASBCJ-50-0110
16. Aniche GN, Palmer GH. 1990. Development of amylolytic activity in sorghum and barley malt. *J Inst Brew* 96: 377-379. https://doi.org/10.1002/j.2050-0416.1990.tb01043.x
17. Agu, RC, Palmer GH. 1998. A reassessment of sorghum for lager-beer brewing. *Bioresour Technol Rep* 66:253-261. https://doi.org/10.1016/S0960-8524(98)00047-9
18. UNIDO (2007). Technical report on the industrial development of sorghum malt for the brewing industry, UNIDO/CFC Sorghum Malt Project, Accra, Ghana.
19. Djameh C, Saalia FK, Sinayobye E, Budu A, Essilfie G, Mensah-Brown H, Sefa-Dedeh S. 2015. Optimization of the sorghum malting process for pito production in Ghana. *J Inst Brew* 121:106–112. https://doi.org/10.1002/jib.191
20. European Brewing Convention 1987. *Analytica – EBC*, 4th ed., Analytica EBC, Fachverlag Hans Carl, Nürnberg.
21. Lefyedi ML, Taylor JRN. 2006. Effect of dilute alkaline steeping on the microbial contamination, toxicity and diastatic power of sorghum malt. *J Inst Brew* 112:108–116. https://doi.org/10.1002/j.2050-0416.2006.tb00240.x
22. Helrich K. 1990. AOAC: Official methods of analysis (Volume 1), 15th edition, AOAC 925.10.
23. Duffour JP 1994. Standard methods for sorghum malt analysis – hot water extract, p. 27. *Sorghum Analytical Handbook*, CDI file no. GHA.3004.FB.03, University of Otago, Dunedin.
24. European Brewing Convention 1998. The EBC ninhydrin method 4.10.
25. European Brewing Convention 2006. Analytica - EBC Method 4.11.1.
26. South African Bureau of Standards 1970. SABS Method 235. Standard test method for the determination of the diastatic power of malts prepared from sorghum including bird-proof varieties, and from millet, South African Bureau of Standards, Pretoria.
27. Badau MH, Nkama I, Jideani IA. 2006. Steep-out moisture, malting loss, and diastatic power of pearl millet and sorghum as affected by germination time and cultivar. *Int J Food Prop* 9:261-272. https://doi.org/10.1080/10942910600596233
28. Kunze W. 2004. *Technology Brewing and Malting*, 3rd International edition, VLB Berlin, Berlin, Germany.
29. Agbale MC, Adamafio NA, Agyemang KOG, Sackey ST. 2007. Malting and brewing properties of selected cereals cultivated in Ghana. *Journal of Ghana Science Association* 9:146-154.
30. Diaber KH, Taylor RNJ. 1995. Opaque Beers, p 229-319. In: Dendy DAV (ed), *Sorghum and Millets – Chemistry and Technology*. American Association of Cereal Chemists, Inc, St. Paul, Minnesota, USA.
31. Illori MO, Ogundiwin JO, Adewusi SRA. 1991. Sorghum malt brewing with sorghum/maize adjuncts. *Brew Distil Int* 21:10-13.
32. Glennie CW. 1988. Starch hydrolysis during sorghum beer brewing. *Starch* 40:259-261. https://doi.org/10.1002/star.19880400706
33. Awoyinka OA, Adebawo OO. 2008. Influence of malting time on α and β amylase secretion in Nigerian amylolytic maize cultivars. *Afr J Agric Res* 3:7-12.
34. Dziedzoave NT, Grafham AJ, Westby A, Komlaga G. 2010. Comparative assessment of amylolytic and cellulolytic enzyme activity of malts prepared from tropical cereals. *Food Control* 21:1349-1353. https://doi.org/10.1016/j.foodcont.2010.04.008

35. Owusu-Mensah E, Oduro I, Sarfo KJ. 2011. Steeping: a way of improving the malting of rice grain. *J Food Biochem* 35:80–91, https://doi.org/10.1111/j.1745-4514.2010.00367.x
36. Krstanovic V, Mastanjevic K, Nedovic V, Mastanjevic K. 2019. The influence of wheat malt quality on final attenuation limit of wort. *Fermentation* 5:89. https://doi.org/10.3390/fermentation5040089
37. Narziss, L. (1980). Die Eigenschaften des Malzes. p 94. In *Abriss der Bierbrauerei*. Wiley-VCH Verlag GmbH, Germany.
38. Kiss Z, Vecseri-Hegyes B, Kun-Farkas G, Hoschke Á. 2011. Optimization of malting and mashing processes for the production of gluten-free beers. *Acta Alimentaria* 40:67-78. https://doi.org/10.1556/aalim.40.2011.suppl.7
39. Wu X, Jampala B, Robbins A, Hays D, Yan S, Xu F, Rooney W, Peterson G, Shi Y, Wang D. 2010. Ethanol fermentation performance of grain sorghums (*Sorghum bicolor*) with modified endosperm matrices. *J Agric Food Chem* 58:9556-9562. https://doi.org/10.1021/jf101555d
40. Matz S. 1991. Brewing and distilling, p. 621-643. In *The Chemistry and Technology of Cereals as Food and Feed*. Van Nostrand/AVI, McAllen, TX.
41. Taylor JR, Boyd HK. 1986. Free α-amino nitrogen production in sorghum beer mashing. *CABI Agric Biosci* 37:1109-1117. https://doi.org/10.1002/jsfa.2740371109