



Sustainable Production of African Traditional Beers With Focus on *Dolo*, a West African Sorghum-Based Alcoholic Beverage

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Spontaneously fermented sorghum beers remain by far the most popular traditional cereal-based alcoholic beverages in Africa. Known under various common names (traditional beers, sorghum beers, opaque, native or indigenous beers) they are also recognized under various local names depending on the region or ethnic group. *Dolo* and *pito* are two similar traditional beers popular in West African countries including Burkina Faso, Mali, Ghana, Benin, Togo, Nigeria and Ivory Coast. These low-alcoholic beers are nutritious and contribute to the nutritional balance of local populations, as well as to their socio-cultural and economic well-being. The production of African traditional beers remains one of the major economic activities, creating employment and generating substantial income that contributes to livelihoods as well as the countries' economic systems. Their processing (malting and brewing) is still artisanal, based on traditional family know-how. The brewing process involves either an acidification and an alcoholic fermentation phases, or a mixed fermentation combining LAB and yeasts. *Saccharomyces cerevisiae* has been identified as the dominant yeast species involved in the alcoholic fermentation, with a biodiversity at strain level. LAB involved in the processing belong to the genera of *Limosilactobacillus*, *Lactobacillus*, *Pediococcus*, *Leuconostoc*, *Lactococcus*, *Streptococcus*, and *Enterococcus*. Molds (*Aspergillus*, *Penicillium*, *Rhizopus*, *Geotrichum*), and acetic bacteria are often associated with the malting and brewing processes. Challenges for sustainable production of African sorghum beer include inconsistent supply of raw materials, variability in product quality and safety, high energy consumption and its impact on the environment, poor packaging and short shelf-life. For sustainable and environmentally-friendly production of African sorghum beers, there is the need to assess the processing methods and address sustainability challenges. Strategies should promote wider distribution and adoption of improved sorghum varieties among farmers, prevent losses through the adoption of good storage practices of raw material, promote the adoption of improved cook stoves by the brewers, develop and adopt starter cultures for controlled fermentation,

regulate the production through the establishment of quality standards and better valorize by-products and wastes to increase the competitiveness of the value chain. Appropriate packaging and stabilization processes should be developed to extend the shelf-life and diversify the channels for sustainable distribution of African cereal-based alcoholic beverages.

Keywords: ethnic alcoholic beverages, African traditional sorghum beers, fermentation, sustainable production, *pito*, *Saccharomyces cerevisiae*

INTRODUCTION

Fermentation is one of the oldest methods used by man to process and preserve agricultural products. In addition to prolonging shelf-life, fermentation confers many beneficial effects such as probiotic attributes, enrichment of essential nutrients, improvement in safety, organoleptic characteristics, digestibility and edibility, and reduction of volume and cooking time of fermented products (Taur et al., 1984; Uzogara et al., 1990; Steinkraus, 1995; Holzapfel, 1997; Simango, 1997; Oluwafemi, 2020). Depending on geographical area, the dietary habits and cultural practices of the populations, various fermented products are produced from raw agricultural materials (Campbell-Platt, 1987; Steinkraus, 1996). In Africa, there is a diversity of traditional fermented beverages produced from starchy or sweet raw materials including cereals, tubers, fruits, palm sap, cane sugar, honey etc.). However, traditional beer remain by far the most commonly produced fermented beverage that stands out among the cultural food heritage of African societies. Commonly called sorghum or millet beers, opaque beers, autochthonous or indigenous beers, these drinks are known under various local names depending on the region of production or ethnic groups (Kayodé et al., 2007; Sawadogo-Lingani et al., 2007; Aka et al., 2008; Osseyi et al., 2011; Lyumugabe et al., 2012; Bayoï and Djoulde, 2017; Touwang et al., 2018). West African sorghum beers such as *dolo* and *pito* produced in Burkina-Faso and Ghana respectively are continuously fermenting unfiltered drinks containing insoluble substances and yeasts, mildly alcoholic and acidic with a characteristic taste, aroma and flavor appreciated by the consuming populations (Odunfa, 1985; Sefa-Dedeh and Asante, 1988; Yao et al., 1995; Sawadogo-Lingani et al., 2007; Djè et al., 2008; Sawadogo-Lingani, 2010; Kouame et al., 2015). Consumers also attribute therapeutic properties (laxative, anti-malarial and anti-hemorrhoidal) to African opaque beer (Enou, 1997; Amané et al., 2005; Aka et al., 2010). Although these therapeutic properties are mostly not scientifically proven, it has been extensively reported that sorghum grains and its subsequent food products including sorghum beers are excellent sources of nutrients (sugars, proteins, amino acids, vitamins, organic acids, minerals), contain health promoting constituents (polyphenols, bioactive lipids, policosanols, phytosterols, dietary fiber) and contribute to the well-being of local populations (Chevassus-Agnes et al., 1979; Nout, 1987; Leguizamón et al., 2009; Maoura and Pourquie, 2009; Abdoul-latif et al., 2012, 2013; Lee et al., 2014; Pontieri and Del Giudice, 2016; Oluwafemi, 2020). Additionally, these beverages play important socio-cultural and economic roles in the African society. The production and sale

of traditional beers remain a significant sources of income-generating activity in the agricultural value chain, contributing to the economic systems in Africa (Odunfa, 1985; Sefa-Dedeh and Asante, 1988; Maoura et al., 2006; Pale et al., 2011; Aka et al., 2017).

The production of *dolo* and *pito*, as well as other traditional sorghum beers is generally artisanal and a traditional family skill passed down from one generation to another. In general, the production of African sorghum beer consists of malting sorghum grains and brewing of the beer. A spontaneous uncontrolled lactic fermentation has been reported to occur during the soaking of sorghum grains in the malting process. The dominant LAB species involved in the acidification phase of *dolo* production have been identified as *Limosilactobacillus fermentum* (Basonym: *Lactobacillus fermentum*), *Pediococcus acidilactici*, *Weissella confusa*, *Enterococcus faecium*, *Pediococcus pentosaceus* and *Lactococcus lactis* ssp. *lactis* (Sawadogo-Lingani et al., 2010; Zheng et al., 2020). Similarly, the lactic acid bacteria generally involved in the brewing of traditional African beers include the genera *Limosilactobacillus*, *Lactobacillus*, *Pediococcus*, *Leuconostoc*, *Lactococcus*, *Streptococcus* and *Enterococcus* (Sawadogo-Lingani et al., 2007; N'Guessan et al., 2011; Lyumugabe et al., 2012; Adimpong et al., 2013; Greppi et al., 2013; Coulibaly et al., 2014; Oriola et al., 2017; Zheng et al., 2020). Molds of the genera *Aspergillus*, *Penicillium*, *Rhizopus* and *Geotrichum* as well as acetic acid bacteria are often associated with malting and brewing of African sorghum beers (Ilori et al., 1991; Ogundiwin et al., 1991; Lyumugabe et al., 2012; Zaukuu et al., 2016; Touwang et al., 2018). Alcoholic fermentation of *dolo* and *pito* in Burkina-faso and Ghana respectively are dominated by the species *Saccharomyces cerevisiae* (45–99%) with a biodiversity of strains of other species such as *Torulaspora delbrueckii*, *Geotrichum candidum*, *Kloeckera apiculata*, *Candida tropicalis*, *C. krusei*, *C. albicans*, *C. glabrata*, *C. utilis*, *Pichia* spp., *Kluyveromyces* spp. (Demuyakor and Ohta, 1991; Sanni and Lonner, 1993; Konlani et al., 1996; Sefa-Dedeh et al., 1999; van der Aa Kühle et al., 2001; Jespersen, 2003; Glover et al., 2005; Kolawole et al., 2007; Kayodé et al., 2011; Dossou et al., 2014; Zaukuu et al., 2016). Previous attempts have been made to develop starter cultures to control and optimize the lactic fermentation of sorghum wort as well as the alcoholic fermentation of African sorghum beer (Sefa-Dedeh et al., 1999; Orji et al., 2003; Sawadogo-Lingani et al., 2008a,b; Glover et al., 2009; Yao et al., 2009; N'Guessan et al., 2010, 2011, 2016; Adewara and Ogunbanwo, 2013; Coulibaly et al., 2014), but these have not been successful at an industrial scale and still remain at the laboratory or pilot production stage.

Development of the beer manufacturing sector in Africa is constrained by a number of factors such as the artisanal nature of the process, low output of production, variability in quality from one production batch to another and short shelf life. In order to overcome these constraints, it is necessary to analyze the available data and knowledge, assess the level of resolution of these constraints for sustainable production and to make appropriate recommendations for further developments. It is within this framework that the present review was undertaken to present an inventory of the available scientific data and information on the physico-chemical, nutritional and organoleptic characteristics, fermentation practices, microbiological characteristics and valorization of by-products. Furthermore, constraints and strategies for sustainable production of African traditional beers have been presented with focus on *dolo* production in West Africa.

OVERVIEW OF AFRICAN TRADITIONAL SORGHUM BEERS

Typology of African Traditional Beers

African traditional sorghum beers vary slightly in manufacturing processes and product characteristics according to the geographical location of production. Common sorghum-based traditional beers produced in different African countries with variations in alcohol contents are shown in **Figure 1**. Throughout Africa, sorghum beers with similar or slight variations in process and product characteristics may be known by different names according to the region of production or ethnic origin of the beer. For example, sorghum beer is known as *kefir*, *bantu* or *utshwala* in South Africa (Schwartz, 1956; Novellie, 1968; Novellie and De Schaepdrijver, 1986), *pito* or *burukutu* in Ghana, Togo and Nigeria (Ekundayo, 1969; Demuyakor and Ohta, 1991; Sanni, 1993; Sefa-Dedeh et al., 1999), *dolo*, *doro* or *tchapalo* in Burkina Faso, Mali, Senegal and Côte d'Ivoire (Yao et al., 1995; Konlani et al., 1996; Bougouma, 2002), *tchoukoutou* or *chakpalo* in Benin, Togo, and northern Nigeria (Hounhouigan, 2003), *otika* in Nigeria and Ghana (Faparusi et al., 1973; Sefa-Dedeh and Asante, 1988; Chinyere and Onyekwere, 1996), *bili-bili*, *ambga*, *red kapsiki*, or *dora-bonga* in Chad, Cameroon and Central Africa (Nanadoum, 2001; Nso et al., 2003; Maoura et al., 2005), *omalovu*, *tombo*, or *epwaka* in Namibia, *ikigage* or *awarwa* in Rwanda (Lyumugabe et al., 2010), *merissa* in Sudan (Dirar, 1978), *talla* in Ethiopia (Steinkraus, 2002; Blandino et al., 2003), *mtama* in Tanzania (Tisekwa, 1989), *munkoyo* in Congo and Zambia (Herbert, 2003), *doro*, *chibuku*, *uthwala* or *chikokivana* in Zimbabwe (Chamunorwa et al., 2002; Togo et al., 2002), *busaa* in Kenya (Nout, 1980). In Burkina Faso, *dolo* is produced throughout the country with slight differences in process or product characteristics depending on the producing ethnic groups. Thus, in Burkina Faso, varieties of *dolo* such as *dolo mossi*, *dagara*, *lobi*, *samo*, *bissa*, *bobo*, *turqua* are produced by different ethnic groups (Bougouma, 2002; Sawadogo-Lingani, 2010). Similarly, in Ghana, the production of *pito* which originates from the northern parts of the country is now widely produced throughout the country. There are different variants

of *pito* depending on the method of wort extraction and the fermentation technique practiced by the different ethnic groups in northern Ghana, leading to varieties such as *Nandom pito*, *Kokomba pito* and *Dagarti pito* (Sefa-Dedeh, 1991; Sefa-Dedeh et al., 1999).

Socio-Cultural and Economic Importance of Traditional Sorghum Beer

Traditional sorghum beers play important socio-cultural and economic roles in Africa. Once prepared in family settings and used in ritual ceremonies in honor of ancestors and spirits to establish communication between the visible and invisible world, traditional sorghum beers have now become a common drink among the general population. *Dolo* and *pito* are undoubtedly the most popular ancestral alcoholic drink in West Africa and are widely produced and consumed in both rural and urban communities. In Burkina Faso, about 75% of the sorghum produced is used for the production of *dolo* which is consumed by nearly 60% of the population (Sawadogo-Lingani et al., 2007). Traditional sorghum beer is almost always used for traditional ceremonies and socio-cultural events such as weddings, baptisms, funerals, enthronements, initiations and festivals (Sanni and Lonner, 1993; Sawadogo-Lingani et al., 2007; Aka et al., 2010; Oyewole and Isah, 2012; Coulibaly et al., 2014).

The production of *dolo* in Burkina Faso and similar alcoholic beverages in other West African countries is a female dominated activity that generates substantial income and contributes to the socio-economic development of local populations (Kayode et al., 2005; Maoura et al., 2006; Sawadogo-Lingani, 2010; Pale et al., 2011). West African women have a long and well-documented tradition of entrepreneurial skills (Mandel, 2004), particularly in the food processing microenterprises. In Burkina Faso, women who are engaged in the production and sale of *dolo*, called *dolotières*, represent about 15% of the women population (Herbert, 2003). These women are often organized into associations or cooperatives and licensed to manufacture *dolo* and run a *cabaret* or *dolodrome* (sale joint for *dolo*). Depending on production capacity, a single sorghum malt production unit in Ouagadougou, the city of Burkina Faso, or other lager cities such as Tamale in Ghana employs about 4–6 people, including at least two men for the execution of specific tasks, with employees receiving monthly salaries (Sawadogo-Lingani, 2010). In Ouagadougou, it is estimated that 600 *dolotières* produce 36 million liters of *dolo* per year, which translates to about 9,000 tons of sorghum malt per year. According to Broutin et al. (2003), the production yield is about 4 liters of *dolo* per kilogram of sorghum malt in Burkina Faso, 2 liters of *tchoukoutou* per kilogram of sorghum malt in Benin and 4 liters of *chakpalo* per kilogram of maize malt in Benin. A survey in 2007, showed that the profits from *tchoukoutou* production in Benin, range from 2,365 to 17,212 fcfa per month (1 euro = 656 fcfa) depending on beer yield and quantity of raw grains transformed. The income generated from the production and sale of sorghum beers is often used to support household activities or invested in children's education (Kayodé et al., 2007). In Abidjan (Côte d'Ivoire), there are more than a hundred

tchapalodrômes (places of production and marketing of *tchapalo*) (Yao et al., 1995; Enou, 1997; Aka et al., 2008; Fokou et al., 2016). Thus, a real traditional sorghum beer industry has developed in West Africa, providing livelihoods for several families (Kayode et al., 2005; N'Guessan, 2009; Pale et al., 2011). The African Sorghum beer industry brings together different actors in the value chain including cereal farmers producing, transporters, distributors and traders, producers and traders of sorghum malts and traditional beers, and consumers.

Physico-Chemical, Nutritional, and Organoleptic Characteristics

Physico-chemical and nutritional characteristics of African traditional beers are sparsely reported in literature. The physico-chemical and nutritional parameters usually reported in literature include pH, alcohol content, dry matter, total sugars, proteins, phenolic compounds and antioxidants (Table 1). Generally, pH varies from 3.2 to 3.6 for *dolo* and 3.2 to 5.0 for *pito*. These pH values reported for *dolo* and *pito* are similar to the pH of other African traditional beers such as *tchapalo* from Ivory Coast (pH 3.3–3.6), *tchoukoutou* from Benin (pH 3.0–3.8), *bili-bili* from Cameroon and Central Africa Republic (pH 3.5–4.4), *red kapsiki* from Cameroon (pH 2.4–3.3), *ikigage* from Rwanda (pH 3.9) and *merissa* from Sudan (pH 4.0). Alcohol contents also vary from 1.4 to 3.5% (v/v) for *dolo* and from 1.94 to 4.0% (v/v) for *pito* whereas dry matter contents range from 3.8 to 8.2% for *dolo* and from 5 to 7% for *pito*. It thus appears that African opaque beers are acidic alcoholic beverages, and this high acidity is important for the microbiological safety of these drinks. The pH depends

on the method of extraction of sorghum malt wort, particularly, conditions such as duration, temperature during the acidification phase, which is carried out by spontaneous uncontrolled lactic acid fermentation. The dry matter contents of *dolo* (3.8–8.2%) and *pito* (5.0–7.0%) are highly variable and lower than that of *tchapalo* (8.4–8.5%), *red kapsiki* (7.0–7.5%) and *tchoukoutou* (15.4–20.2%). Generally, dry matter content of sorghum beers depends on sorghum grain characteristics, malting efficiency and decantation/filtration operation conditions. Traditional sorghum beers contain insoluble substances and yeasts (Rooney and Serna-Saldivar, 1991; Kouame et al., 2015). These insoluble substances are mainly starch fragments and dextrans that have not been degraded during mashing and fermentation (Glennie and Wight, 1986). Similar to dry matter content, the alcohol contents of *dolo* (1.4–3.5%) and *pito* (2.0–5.0%) are very variable but remains within the normal range of alcohol contents of other African traditional sorghum beers which generally vary from 2.0 to 5.2% (v/v) as shown in Table 1. The alcohol content of traditional African sorghum beers depends on the duration of the alcoholic fermentation, the concentration of fermentable sugars in the wort and thus on the quality of malt and efficiency of the brewing process. *Dolo* contains phenolic compounds at higher levels than western beer and white wine (Abdoul-latif et al., 2012). In general, traditional sorghum beers contain starch, sugars, proteins, fats, vitamins and minerals (Chitsika and Mudimbu, 1992). They are rich in calories, B-group vitamins (thiamine, folic acid, riboflavin, nicotinic acid) and essential amino acids such as lysine (Chevassus-Agnes et al., 1979; Lyumugabe et al., 2012). According to Holzappel (2002),

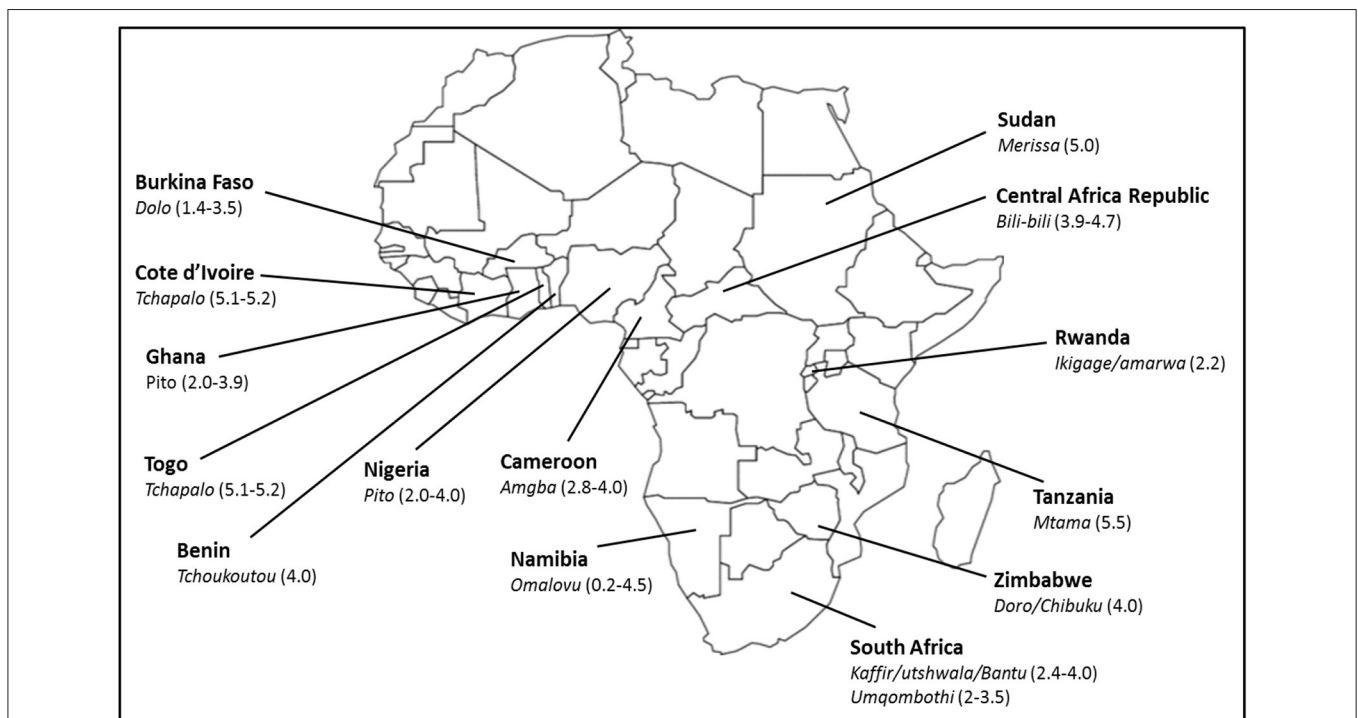


FIGURE 1 | Common traditional sorghum beers (% alcohol [v/v]) produced in Africa.

TABLE 1 | Physico-chemical characteristics and proximate composition of African traditional sorghum beers.

| Name | Country | pH | Titratable acidity (%lactic acid) | Dry matter (g/100 ML or %) | Alcohol (% v/v) | Total sugars (g/100 mL) | Proteins (g/100 mL) | Other | References |
|----------------------------------|--------------------------|-----------|-----------------------------------|----------------------------|-----------------|-----------------------------|---|---|--|
| <i>Dolo</i> | Burkina Faso | 3.2–3.6 | nr | nr | nr | nr | nr | nr | Sawadogo-Lingani et al., 2007; Glover et al., 2009 |
| | | 3.40–3.60 | nr | 3.77–8.16 | 1.40–3.50 | 1.1–8.4 mg/100 ml | 1.1–6.5 mg/100 ml | Total phenol: 437–578 μ g GAE/ml Proanthocyanidins: 38 and 55 μ g APE/ml TEAC: 57 and 349 μ mol/L | Abdoul-latif et al., 2012, 2013 |
| <i>Pito</i> | Ghana, Nigeria | 3.4 | nr | nr | nr | nr | nr | nr | Sawadogo-Lingani et al., 2007 |
| | | 3.4–3.6 | 0.72–0.96 | 2.92–4.68 | 1.40–3.68 | 0.86–2.35 | 0.14–0.39 | nr | Sefa-Dedeh, 1991 |
| | | 3.5–5 | nr | nr | 2–4 | nr | nr | nr | Zaukuu et al., 2016 |
| | | 3.2–3.6 | nr | 5.0–7.0% (soluble extract) | 1.96–3.93 | nr | nr | nr | Ayirezang et al., 2016 |
| <i>Tchapalo</i> | Côte d'ivoire | 3.33–3.63 | 0.9–0.99 | 8.4–8.5 (soluble solids) | 5.08–5.22 | 8.84 | nr | nr | Aka et al., 2008 |
| <i>Tchoukoutou/chakpalo</i> | Benin, Togo | 3.0–3.8 | 0.5–0.8 | 15.4–20.2 | 4.0 | nr | 3.7–7.9%dm | nr | Kayodé et al., 2007, 2011; Osseyi et al., 2011 |
| <i>Amgba/bili bili</i> | Cameroon | 3.5–4.4 | nr | nr | 2.75–4.0 | 0.13–0.66 (reducing sugars) | 0.47–0.85 (soluble proteins) Free amino nitrogen (FAN): 8.69–52.14 mg/L | 484.8–540.9 | Touwang et al., 2018 |
| <i>Red kapsiki beer</i> | Cameroon | 2.40–3.26 | 0.67–0.81 | 7.0–7.46% (Soluble matter) | 3.85–4.28 | 41.8–72.9 g/L | nr | 843–1150 mg/L total phenol 750–1,300 mg/L Flavanols | Bayoï and Djoulde, 2017 |
| <i>Bili-bili/Dora-bonga</i> | Central African Republic | 3.44–3.60 | nr | nr | 3.94–4.66 | 0.65–0.67% | 2.79–2.90% 3.80–3.82% | nr | Lango-Yaya et al., 2020 |
| <i>Ikigage/amarwa</i> | Rwanda | 3.9 | nr | nr | 2.2 | nr | 0.92 | nr | Lyumugabe et al., 2010 |
| <i>Merissa</i> | Sudan | 4.0 | nr | nr | 5.0 | nr | nr | nr | Lyumugabe et al., 2012 |
| <i>Doro or chibuku</i> | Zimbabwe | nr | nr | nr | 4.0 | nr | nr | nr | Lyumugabe et al., 2012 |
| African traditional sorghum beer | No specific country | 3.3–4 | 0.26 | 5–13 | 2–4.5 | nr | nr | nr | Lyumugabe et al., 2012 |

nr, not reported.

pito contains essential minerals such as zinc (Zn), calcium (Ca), magnesium (Mg) and iron (Fe), which are important micronutrients. Due to its nutritional characteristics, FAO (1995) describes African opaque beer as more of food than a drink. Consumers attribute some therapeutic virtues (laxative, analgesic, anti-malarial, anti-hemorrhoidal, energetic, dietary properties) to their consumption, even though such claims are not scientifically proven (Enou, 1997; Amané et al., 2005; Kayodé et al., 2007; Aka et al., 2010). According to Zaukuu et al. (2016), *pito* is widely consumed as a ceremonial drink in Ghana for its refreshing taste and nutritional characteristics as it provides consumers with a wide range of important polyphenols, micro- and macronutrients that play important roles in the prevention of diseases related to metabolic imbalances such as gastrointestinal disorders, inflammation, obesity and hypertension. In general, however, detailed information on the nutritional and health benefits of West African traditional sorghum beers are scarce and scanty. For a better valorization of these ethnic drinks, it is necessary to undertake research works to highlight their nutritional values and make these data available and accessible in order to be able to evaluate their real contribution to the nutrient intake and well-being of consumers.

African opaque beers are characterized by the variation in their organoleptic characteristics from one production batch to another (Lyumugabe et al., 2012), due to the artisanal nature of the manufacturing process. As far as organoleptic characteristics are concerned, there is no specific description for *dolo* and *pito*. These two drinks, like other African traditional sorghum beers are generally opaque, cloudy, low in alcohol, unfiltered and unstable, and contain insoluble substances and yeasts (Rooney and Serna-Saldivar, 1991; Kouame et al., 2015). African sorghum beers have an acidic or sour taste, which corroborates with their low pH values, have a touch of fruitiness and a characteristic color varying from pale buff to pinkish brown depending on the variety of raw cereal grains used for their production.

PROCESSING OF AFRICAN TRADITIONAL SORGHUM BEER

The traditional processing of African sorghum beers consists of two main phases: malting of sorghum grains and brewing of traditional beer from sorghum malt. The main brewing operations comprises the extraction of wort which includes crushing of sorghum malt, mashing, acidification/saccharification, cooking and cooling. Wort extraction is followed by alcoholic fermentation of the wort using indigenous yeasts. Depending on the ethnic group or local region of production, the brewing process involves either a separate acidification step and an alcoholic fermentation step, or a mixed fermentation combining lactic acid bacteria and yeasts.

Raw Materials

The main raw material for the production of African traditional beer is sorghum grains. Common species of sorghum such as *Sorghum bicolor*, *Sorghum vulgare* and *Sorghum guineense* are generally used alone or in combination with other cereal grains

such as maize or millet. However, in a few instances, maize or millet alone is used for the production of African traditional beer (Table 2).

Sorghum grains intended for the production of *dolo* and other similar African beers must have high starch and amylose contents and a high to medium diastatic power after malting (Dicko et al., 2006; Tchienbou, 2006). Pigmented sorghum varieties (red or brown) are the most commonly used. White varieties of sorghum are usually not used alone for the production of African beers but often used in combination with red or brown sorghum varieties because consumers prefer colored beers which they also perceive to be healthier (Kayode et al., 2005; Sawadogo-Lingani et al., 2010). In an attempt to select appropriate sorghum varieties for the production of *dolo* and *tchoukoutou* in Burkina Faso and Benin, malting properties and brewing characteristics of nineteen varieties of sorghum was assessed (Tchienbou, 2006). The assessment led to the nineteen varieties belonging to one of three major groups. The first group comprising seven varieties of sorghum (*Sotakaman*, *Zomoaha 2*, *Natisoya 1*, *Kioédéré*, *Mewin*, *Chassisoya*, *Chabicoman PR*) had high diastatic power and high β -amylase activity and were rated excellent for the production of *dolo* and *tchoukoutou*. The second group made up of eleven varieties (*Agbanni*, *Natisoya 2*, *Chabicoman PN*, *Soniya*, *Fissouka*, *Zoueloure*, *Banninga*, *Pisnou*, *Kapelga*, *Vrac Cotonou*, *Gnossiconi*) with medium amylase activity may also be suitable for sorghum beer, while the last group of one variety (*Zomoaha 1*) had very low amylase activity and its use as a brewing malt is of little interest among traditional beer brewers (Tchienbou, 2006). The advantage of all these sorghum varieties is their relatively high availability, presumably due to some favorable agronomic properties and the ability to germinate even after months of storage. In a survey to identify the types and characteristics of sorghum grains preferred for malting and brewing of *dolo* in Burkina Faso, it was shown that red sorghum is the most preferred grain type because of its consistent ability to sprout well during the malting process (Songre-Ouattara et al., 2016). It is obvious that perception criteria and preferences of the actors (*malteuses* and brewers) are diverse. It will thus be appropriate to scientifically develop a better systematic and qualitative approach to characterizing sorghum quality attributes for African beer production.

Generally, processors use wort properties such as sweetness as an indicator of the quality of the beer. The sweeter the wort, the better or stronger the beer will become due to available fermentable carbohydrates in the wort.

Traditional Malting of Sorghum Grain

Different traditional sorghum malting processes in Africa have been reported in literature (Table 2). The main operations that are common to traditional malting of sorghum grains for beer production include steeping of sorghum grains, sprouting and sun drying of sprouted grains. The total duration of the entire traditional malting process varies between 7 and 12 days. Soaking time vary from 5 to 48 h for sorghum malt for *dolo* production, and from 14 to 48 h for malt for *pito* production. These steeping times are comparable to those indicated for

TABLE 2 | Main steps of traditional malting processes of sorghum for the production of African traditional sorghum beers.

| Name of final product | Raw material | Steps of the processing | Microorganisms involved | References |
|-------------------------------|---|---|--|--|
| <i>Dolo</i> | <ul style="list-style-type: none"> • Red sorghum • White sorghum | <ul style="list-style-type: none"> • Cleaning • Steeping (14–24 h) • Draining • Germination (3–4 days) • Sun drying (2–3 days) | <i>Limosilactobacillus</i> spp. <i>(Lactobacillus spp.)</i> <i>Pediococcus</i> spp. <i>Weissella</i> spp. <i>Enterococcus</i> spp. <i>Lactococcus</i> spp. | Sawadogo-Lingani, 2010 |
| | Red sorghum | <ul style="list-style-type: none"> • Cleaning • Steeping (24–48 h) • Draining • Germination (2–4 days) • Sun drying (2–4 days) | nr | Broutin et al., 2003 |
| | <ul style="list-style-type: none"> • Red sorghum • White sorghum • Millet | <ul style="list-style-type: none"> • Cleaning • Steeping (5–25 h) • Draining • Germination (57–96 h) • Short sun drying (30 min) • Maturation in heap (24–96h) • Sun drying (32–82h) | nr | Traoré et al., 2004 |
| | <ul style="list-style-type: none"> • Red sorghum • White sorghum | <ul style="list-style-type: none"> • Cleaning • Steeping (12–48 h) • Draining • Germination (2–5 days) • Sun drying (2–3days) | nr | Bougouma et al., 2008 |
| <i>Pito</i> | Red sorghum, white sorghum, maize | <ul style="list-style-type: none"> • Cleaning • Steeping (14–24 h) • Draining • Germination (3–4 days) • Sun drying (2–3 days) | <i>Limosilactobacillus fermentum</i> <i>Ped. acidilactici</i> <i>Ped. pentosaceus</i> <i>Weissella confusa</i> <i>Enterococcus faecium</i> <i>Lactococcus lactis</i> ssp. <i>lactis</i> | Sawadogo-Lingani et al., 2010 |
| | <ul style="list-style-type: none"> • Red and white sorghum • Maize | <ul style="list-style-type: none"> • Cleaning • Steeping (24–48 h) • Draining • Germination (4–5 days) • Sun drying | nr | Lyumugabe et al., 2012 |
| <i>Tchapalo</i> | Red sorghum | <ul style="list-style-type: none"> • Cleaning • Steeping (7–12 h) • Germination (3 days) • Sun drying (1–2 days) | nr | Yao et al., 1995; Aka et al., 2008; Coulibaly et al., 2014 |
| <i>Tchoukoutou chakpalo</i> | <ul style="list-style-type: none"> • Red sorghum • Brown sorghum • Millet • Maize | <ul style="list-style-type: none"> • Cleaning • Steeping (9–12 h; 12–24 h) • Draining • Germination (3–4 days) • Sun drying (1–2 day) | nr | Lyumugabe et al., 2012; Dossou et al., 2014 |
| <i>Bili bili or Amgba</i> | <ul style="list-style-type: none"> • Sorghum • Millet | <ul style="list-style-type: none"> • Steeping (12–72 h) • Washing & Draining (12 h) • Germination (2–4 days) • Maturation in sacks (24–72 h) • Sun drying (1–2 day) | nr | Chevassus-Agnes et al., 1979; Lyumugabe et al., 2012; Touwang et al., 2018 |
| <i>Red kapsiki beer or Te</i> | Sorghum, Maize | <ul style="list-style-type: none"> • Washing • Steeping • Draining • Germination (2–3 days) • Sun drying (6–10h) | nr | Bayoï and Djoulde, 2017 |
| <i>Bili-Bili</i> | Sorghum | <ul style="list-style-type: none"> • Washing • Steeping (24–72 h) • Germination in heap (24–36 h) • Germination in thin layers (4 days) • Sun drying | nr | Lango-Yaya et al., 2020 |

(Continued)

TABLE 2 | Continued

| Name of final product | Raw material | Steps of the processing | Microorganisms involved | References |
|---------------------------------|--------------|---|-------------------------|------------------------|
| <i>Ikigage</i> or <i>amarwa</i> | Red sorghum | <ul style="list-style-type: none"> • Washing • Steeping (24 h) • Draining • Germination (24 h) • Sun drying (2–3 days) | nr | Lyumugabe et al., 2012 |
| <i>Doro</i> | Red sorghum | <ul style="list-style-type: none"> • Cleaning • Steeping (24 h) • Germination (sacks, 2–3 days) • Sun drying (3 days) | nr | Lyumugabe et al., 2012 |

nr, not reported.

the malting of sorghum for the production of *tchoukoutou* (9–24 h), *tchapalo* (7–12 h), *bili-bili* (24–72 h), *ikigage* (24 h) and *doro* (24 h) (Table 2). Thus, the shortest steeping times are 5–7 h and the longest steeping times are 24–72 h. Soaking of grains during traditional malting process is generally done at room temperature in cans and jars half buried in the ground for better thermal insulation. Steeping brings the moisture content of the grain to levels that are favorable for respiration and metabolic activities and for the mobilization of primary and secondary metabolites, making germination possible. Steeping has an influence on the quality of malt as it contributes to the elimination of flatulence factors (stachyose, raffinose) and the reduction of phytate content through leaching. The quality of sorghum malt (diastatic power, free amino acids and soluble extract) is also positively correlated with the moisture content of the grain at the end of steeping (Dewar et al., 1997). According to the European Brewery Convention (EBC), a well-soaked barley grain should have a final moisture content of about 43–45 and 33–45% for millet and sorghum grains (Aisien and Ghosh, 1978; Malleshi and Desikachar, 1986; Agu and Palmer, 1998; Ogbonna et al., 2004). In addition, water absorption depends on several factors such as the composition of the steeping water, grain variety, grain storage conditions, soaking time and temperature. Soaking conditions for millet and sorghum generally reported in the literature range from 8 to 51 h at temperatures between 25 and 35°C, with most being between 16 and 24 h at a temperature of 30°C. The overall quality of malt increases with the steeping time. The diastatic power of sorghum malt increases with the steeping temperature with an optimum at 30°C while the malt extract and free amino acids are higher with steeping temperature of 25°C (Dewar et al., 1997; Tchienbou, 2006). Prolonged soaking period can lead to rapid germination, high losses of nutrients (Pathirana et al., 1983; Bhise et al., 1988), or putrefaction of the grains rather than germination (Shambe et al., 1989). For effect of the composition of water, the steeping of the sorghum grain in alkaline water [0.1% of Ca(OH)₂, KOH or NaOH] has been shown to significantly enhance the diastatic power of sorghum malt and β -amylase activity (Okungbowa et al., 2002). Furthermore, aeration of sorghum grains during steeping has a positive impact on malt quality as it leads to an increase in the percentage of sprouted grains, soluble dry matter of the malt,

total nitrogen and free amino acids contents (Dewar et al., 1997). Beta et al. (1995) found that malts from sorghum grains soaked in jars with poor aeration had lower diastase, α and β -amylase activity and protein content compared to malts obtained from sorghum grains soaked in an aerated container.

The duration of sprouting varies from 2 to 5 days for sorghum malt used for the production of *doro* and from 3 to 5 days for malt used for *pito* production (Table 2). These durations are comparable to the germination times reported for the malting of sorghum grains for the production of *tchapalo* (3 days), *tchoukoutou* (3–4 days), *bili-bili* (2–4 days) and *red kapsiki* (2–3 days). Germination of grains in traditional malting takes place at room temperature and away from direct sunlight in cans, baskets, on cemented floors, on tarpaulins or plastic sheets, with watering at variable time intervals to maintain humidity (Flidied et al., 1996; Bougouma et al., 2008). In air germination, the thickness of the layer can reach 30–50 cm thick. In Burkina Faso, this step may be followed by a maturation phase known as “high germination” where the grains are placed in piles on the floor or in a basket covered with burlap, mats or plastic sheets, with temperatures reaching 60°C at the core of the grain piles (Bougouma et al., 2008). Temperature, germination time and relative air humidity are reported to have significant influence on malt quality. Optimal germination temperatures for sorghum and millet are reported to be between 25 and 30°C. Germination of at 20°C reduces malting losses due to high root growth whereas germination at 30°C causes high losses but increases amylase activity (Agu and Palmer, 1997b). Sorghum malts germinated at 25°C give a better wort quality when compared to sorghum malts germinated at 20°C. Sorghum germination at 30°C for more than 4 days results in a decrease in peptides in the wort (Agu and Palmer, 1999). The α -amylase activity is optimal on the third day of germination and is higher in white sorghum malts than in red sorghum malts, whereas the β -amylase activity is optimal on the third and fourth days of germination (at 30°C) for red and white sorghum respectively (Uvere et al., 2000). The grains are generally germinated at humidities between 85 and 100%. Under uncontrolled moisture conditions such as germination in traditional malting, the grains are reportedly watered at various time intervals i.e., every 8 h (Taylor, 1983), every 6 h (Taylor et al., 1994) or 2–3 times a day

based on visual observation of grain dryness (Pelembé et al., 2004).

Germination or sprouting enriches cereal malts with hydrolytic enzymes, sugars, free amino acids, vitamins and improves technological and nutritional quality (Chavan et al., 1981; Malleshi et al., 1989; Taylor and Robbins, 1993; Taylor and Dewar, 1994; Sripriya et al., 1997; Elmaki et al., 1999; Mbofung and Fombang, 2003; Traoré et al., 2004). According to Wang and Fields (1978), germination increases the lysine, tryptophan and methionine contents with an increase in relative nutrient value from - 55.5 to 66.8% (ungerminated kernels) to 78.3–99.5 (sprouted kernels) for maize and sorghum. Demuyakor and Ohta (1992) reported that maltose, glucose and dextrans are the major sugars produced by starch hydrolysis during germination of sorghum varieties in Ghana, while triose, raffinose and xylose appear in small amounts. Traoré et al. (2004) also found significant levels of fructose, glucose and sucrose in sorghum malt from Burkina Faso. On the other hand, germination promotes the release of cyanide due to high concentrations in young shoots and rootlets of germinated sorghum (Panasiuk and Bills, 1984; Aniche, 1990; Ahmed et al., 1996; Uvere et al., 2000; Traoré et al., 2004). However, the removal of rootlets and further processing are reported to reduce the hydrocyanic acid content of malted grains by over 90% (Dada and Dendy, 1988). During traditional sorghum malting, partial polishing of the dried malt by removing part of the roots and stalks is carried out. Similarly, during the brewing of *dolo*, roots and stalks are also partially removed during the mashing process. According to *dolo* brewers, this is done to reduce bitterness and astringency in *dolo*. In Burkina Faso, Traoré et al. (2004) showed that the degermination of sorghum malt promotes a reduction in cyanide content by about 72% and 74% in millet and sorghum malts, respectively, although the process leads to a decrease in amylase and protein contents.

Following sprouting, the germinated grains are sun dried for periods varying from 2 to 4 days for malt intended for the production of traditional African beers (Table 2). However, shorter drying times (6–24 h) are reported for malt intended for the production of *tchapalo*, *bili-bili* and *red kapsiki*. Drying time in traditional malting processes depends on climatic conditions and layer thickness. The green malt is generally spread on the ground, on cemented areas, on mats or plastic sheets, inside concessions, along tared streets, or on the roofs of houses (Bougouma et al., 2008; Aka et al., 2017). Drying times are generally dependent on the intensity of available sunshine and wind speed. During sun-drying, malt is also exposed to bad weather and contaminations from humans, pets, wild birds, city pollution, dust and other impurities carried by the wind.

Drying lowers the water activity of malt thereby favoring the blocking of enzymatic activity, stabilizing and enhancing preservation of the malt (Galzy and Moulin, 1991). The cyanide content of germinated grains decreases during drying (Aniche, 1990; Traoré et al., 2004). The temperature and drying time as well as the relative humidity of the air have an influence on the quality of the malt. Drying temperatures for sorghum and millet malts range from 30 to 65°C with different scales (Aisien, 1982; Lasekan, 1991; Demuyakor and Ohta, 1992). The scale generally

chosen is drying at 50°C for 24 h (Beta et al., 1995; Subramanian et al., 1995; Igyor et al., 2001). Amylase activity decreases as the drying temperature increases. Thus, for example, drying sorghum malt at 35, 40, and 45°C reduces its diastatic activity by 7.7, 8.7, and 12.4% respectively (Agu and Palmer, 1996). According to Traoré et al. (2004), sun drying during traditional malting reduces α -amylase activity in millet and sorghum by 16%. Owuama and Ashemo (1994) found low protein and sugar content and thus enzyme inactivation in sorghum malts dried at 65°C compared to those dried at 55°C or at 55°C for 6 h and then 65°C. According to Uvere et al. (2000), drying at 50°C decreases amylase activity and alcohol yield in *burukutu*. For some authors, the best drying conditions are a temperature of 50 to 55°C, a drying time of 24 h and protection against contamination (Morrall et al., 1986; Owuama and Ashemo, 1994; Uriyo and Eigel, 1999; Uvere et al., 2000; Okungbowa et al., 2002). The evaluation of three stabilization modes (freezing at -18°C, freeze-drying, drying at 45°C) on the amylase activity of sorghum malts showed that all these modes lead to a loss of amylase activity, and drying has a greater negative effect than the other two (Tchuenbou, 2006).

Several studies have shown that optimum malting conditions are different for different millet and sorghum varieties, as varieties react differently to extrinsic factors as temperature and aeration that can influence malting and malt quality (Demuyakor and Ohta, 1992; Subramanian et al., 1995). The rate of water absorption and the saturation water content during steeping depend on the varieties. According to Agu and Palmer (1997a), colored sorghum varieties have a higher α and β -amylase activity than white varieties but gives more losses during malting. Similarly, Eneje et al. (2004) concluded that yellow maize has higher enzyme activity and extract yield than white maize. On the other hand, some studies have reached opposite results, which would reflect the impossibility of absolute grading of kernels with respect to their germination ability according to their color. In addition, high-protein grains yield high-protein malts and extracts (Odibo et al., 2002). Under the same malting conditions, some varieties have their β and α -amylase activity optimal after 3 and 4 days of germination, while for others these activities continue to increase with germination time (Agu and Palmer, 1997b). There are varieties that produce more α -amylase and/or β -amylases (Dufour et al., 1992; Subramanian et al., 1995) or varieties that are more sensitive to anoxic conditions than others (Beta et al., 1995). Malt quality is defined by its intended use. Thus, for brewing malts, quality is determined by the diastatic power (activity of hydrolysis of starch into fermentable sugars through the activity of α and β -amylase, α -glucosidase and limit dextrinase) and the water-soluble extract. The production of hydrolytic enzymes in malted grains is a complex phenomenon, influenced by extrinsic (environmental and agro-climatic conditions) and intrinsic factors (genetics, grain composition, albumen structure and texture, etc) and malting conditions. The water-soluble malt extract (soluble dry matter) is decisive for having a wort containing fermentable sugars (maltose, glucose) and amino acids needed as a source of carbon and nitrogen for beer yeasts. The conditions of sorghum malting and the factors that can influence the quality of the

malt are generally related to an optimum diastatic power, the achievement of a high content of malt extract and free amino acids, and a minimum loss of material during malting. The optimal conditions for the traditional malting of sorghum to obtain a quality malt are soaking to a maximum hydration of 33–36%, germination at 25–30°C for 3–5 days and a drying temperature of the green malt below 65°C (Demuyakor and Ohta, 1992; Agu and Palmer, 1998).

The enzymes generated during malting are essential for brewing operations to obtain a wort rich in soluble matter including fermentable sugars, amino acids and peptides that are also essential for the growth and development of lactic acid bacteria and yeasts. The development of toxinogenic molds and undesirable bacteria in grains during germination can have harmful effects on the quality of malt and finished products, and present health risks for the consumer (Flannigan et al., 1982; Galzy and Moulin, 1991). Malting has a major impact on the composition of sorghum grain, reducing the concentration of anti-nutrients in sprouted grain and improving the bioavailability of certain minerals and overall nutritional quality (Svanberg and Sandberg, 1989; Morero et al., 1991; Mbofung and Fombang, 2003). A reduction in phytates and tannins is generally observed during the malting of sorghum grains and the rate of reduction is a function of soaking and germination times and temperatures (Svanberg and Sandberg, 1989; Mahgoub and Elhag, 1998; Mbofung and Fombang, 2003; Traoré et al., 2004).

Brewing of African Traditional Sorghum Beer

The process of brewing traditional African sorghum beer is artisanal in nature and the equipment used are mainly composed of basic materials such as gourds, jars and canaries made of baked clay, cast iron pots, aluminum, iron or plastic recovery barrels, and woven straw baskets. The main source of energy for the brewing of sorghum beer in Africa is firewood with the use of traditional tripod-stone fireplaces, improved fireplaces built in *banco* and equipped with chimneys (Pale et al., 2010; Sawadogo-Lingani, 2010).

Brewing is the step that produces the fermentable wort for alcoholic fermentation to yield the traditional beer. It is the stage in which starch and proteins are hydrolyzed into fermentable sugars and nitrogen compounds by the enzymes synthesized during malting. Few studies have been carried out on the technological and biochemical aspects related to the traditional brewing of *dolo* and *pito* as well as other similar traditional beers. Majority of existing works on African sorghum beers are limited to a description of the traditional processes from various traditional production units as well as the identification of the microorganisms involved in the process (Table 3). Traditional brewing of *dolo* or *pito* is a long and complex process lasting for about 48 h (Sawadogo-Lingani et al., 2007; Sawadogo-Lingani, 2010). Figure 2 shows the general flow diagram for the brewing of *dolo* in Burkina Faso and *Dagarti pito* in Tamale (Northern Ghana). Red sorghum malt is used exclusively for the brewing of *dolo* in Burkina Faso by of the Mossi women and other ethnic groups where sorghum malt is

generally purchased from malt manufacturing hubs (*Malteuses*). In South-Western Burkina Faso (Gaoua) and North Ghana (Tamale), *dolo* or *dagarti pito* is produced by women of the Dagara and Dagarti ethnic groups from a mixture (50:50) of red and white sorghum malt or with white sorghum malt alone, where the beer brewers produce the sorghum malt by themselves (Sawadogo-Lingani, 2010). The brewing operations for *dolo* and *pito* are also similar and generally comprise milling of sorghum malt, mashing, acidification/saccharification, cooking and concentration, cooling, decanting and alcoholic fermentation of the wort by indigenous yeasts (Table 3). Mashing as a sub-operation include diluting the malt flour in water, settling and collecting the supernatant, boiling the pellet, mixing the cooked pellet and the supernatant. The duration of the operations and sub-operations vary among different traditional production units. In the traditional brewing of *dolo* and *pito*, the settling time of the aqueous malt flour suspension, which is highly variable (20 min to 12 h), is comparable to the settling times in the brewing processes of Benin's *tchoukoutou* (1 to 2 h), Côte d'Ivoire's *tchapalo* (20 to 30 min), Cameroon's *bili-bili* and *red kapsiki* (1 to 2 h) and Rwanda's *ikigage* (3 h) (Table 3).

During the mashing, technological adjuvants are widely used. These adjuvants are extracts of local mucilaginous plants used as flocculating agents to promote settling and clarification of the wort. The plants generally used are yolga (*Grewia bicolor* Juss), okra [*Abelmoschus esculentus* (L) Moench], baobab leaves (*Adansonia digitata*), kapok (*Bombax costatum*), taasalogo (*Bridelia micrantha*), boundou (*Ceratothera cesamoides*) or bouldvanka (*Chirococcus esculentus*) (Sefa-Dedeh, 1991; Nanadoum, 2001; Bougouma, 2002; Bougouma et al., 2008; Pale et al., 2010). The aqueous extract of these plants (leaves, bark or fruits) has a sticky appearance and is rich in mucilaginous substances. After settling, the supernatant is decanted into a jar and then the remaining pellet (sediment) is heated to boiling point to gelatinize the residual starch and then mixed with the supernatant. For *dolo* and *pito*, the residual starch is heated to a temperature of about 59–68°C. Similar temperatures (65–70°C) have been reported for *tchoukoutou*, *ambga* and *bili-bili* (Lyumugabe et al., 2012; Lango-Yaya et al., 2020). Sorghum starch gelatinization temperatures range between 67 and 81°C (Akingbala et al., 1982). The hydrolytic enzymes in the sorghum malt extract (supernatant) hydrolyze the gelatinized starch and the concentration of fermentable sugars in the must increases. Analogous with modern beer brewing, the principle of mashing is based on infusion and/or decoction to extract fermentable wort by the solubilization of soluble substances in water and the enzymatic hydrolysis of starch and other macromolecules. While barley wort is reported to contain more maltose than glucose (Dufour et al., 1992) sorghum malt worts is reported to contain similar levels of glucose and maltose (Taylor, 1992; Byrne et al., 1993), and the difference has been attributed to the low levels of β -amylase in sorghum malt (Palmer, 1989).

During African sorghum beer brewing, another important process following starch gelatinization and hydrolysis is acidification/saccharification. The mixture of the gelatinized residual starch and the malt wort supernatant is acidified by spontaneous lactic fermentation at ambient temperature for

TABLE 3 | Mains steps of brewing processes of African traditional beers and microorganisms involved.

| Name of product | Country | Raw material | Steps of the processing | Microorganisms involved | References |
|-------------------------------------|---------------------|--|--|---|---|
| <i>Dolo</i> and <i>Dagarti pito</i> | Burkina Faso, Ghana | Malted sorghum, malted millet or maize | <ul style="list-style-type: none"> • Grinding • Mixing malted flour with water (1 vol flour for 5–10 vol water) • Decantation (20 min–12 h) • Heating the sediment until boiling (97–98°C) • Mixing with the supernatant (59–68°C) • Acidification (12–16 h) • Boiling (3–5 h) • Cooling and decantation (4–5 h) • Alcoholic fermentation (9–14 h) with traditional starter yeast | <ul style="list-style-type: none"> • <i>Limosilactobacillus fermentum</i> (<i>lactobacillus fermentum</i>) • <i>Lactobacillus delbrueckii</i> subsp <i>jakobsenii</i> (<i>Lactobacillus delbrueckii</i> subsp <i>delbrueckii</i>) • <i>Lactobacillus delbrueckii</i> subsp. <i>bulgaricus</i> • <i>Pediococcus acidilactici</i> • <i>Lactobacillus lactis</i> • <i>Lactococcus lactis</i> • <i>Saccharomyces cerevisiae</i> (dominant at 45–90%) | Konlani et al., 1996; van der Aa Kühle et al., 2001; Broutin et al., 2003; Sawadogo-Lingani et al., 2007; Glover et al., 2009; Lyumugabe et al., 2012 |
| <i>Pito</i> | Ghana, Nigeria | Malted sorghum, millet or maize | <ul style="list-style-type: none"> • Grinding • Mixing with water • Boiling (3–4 h) • Acidification (12 h) • Dilution • Cooking (3 h) • Cooling • Alcoholic fermentation (12–24 h) with local starter yeast | <ul style="list-style-type: none"> • <i>Limosilactobacillus fermentum</i> (<i>lactobacillus fermentum</i>) • <i>Lactobacillus delbrueckii</i>, • <i>Lactobacillus</i> spp. • <i>Leuconostoc</i> spp. • <i>Saccharomyces cerevisiae</i> dominant at 45% • <i>Candida tropicalis</i> • <i>Kloeckera apiculata</i> • <i>Hansenula anomala</i> • <i>Torulaspora delbrueckii</i> • <i>Schizosaccharomyces pombe</i> • <i>Kluyveromyces africanus</i> • <i>Saccharomyces cerevisiae</i>, • <i>Debaryomyces hansenii</i> • <i>Pichia anomala</i> • <i>Aspergillus clavatus</i>, • <i>Mucor hiemalis</i>, • <i>Cladosporium sphaerospermum</i>, • <i>Cladosporium herbarum</i> • <i>Bacillus subtilis</i>, • <i>Candida</i> spp., • <i>Geotrichum candidum</i> | Sefa-Dedeh et al., 1999; van der Aa Kühle et al., 2001; Kolawole et al., 2007; Lyumugabe et al., 2012; Zaukuu et al., 2016 |
| <i>Tchoukoutou/chakpalo</i> | Benin | Malted sorghum, millet or maize | <ul style="list-style-type: none"> • Grinding (fine flour) • Mixing with water • Decantation (1–2 h) • Boiling of the sediment (2h) • Mixing with the supernatant (65–70°C) • Acidification (13–14 h) • Filtration • Boiling (6–9 h) • Cooling • Alcoholic fermentation (13–14 h) with traditional leaven | <ul style="list-style-type: none"> • <i>Limosilactobacillus fermentum</i> (<i>lactobacillus fermentum</i>) • <i>Lactobacillus divergens</i> • <i>Lactobacillus fructivorans</i> • <i>Lactobacillus</i> sp. • <i>Saccharomyces cerevisiae</i> (dominant 68%) • <i>Candida albicans</i> (11%) • <i>Torulaspora delbrueckii</i> • <i>Saccharomyces pastorianus</i> • <i>Candida kunwiensis</i> • <i>Dekkera anomala</i> • <i>Candida etchellsii</i> • <i>Clavispora lusitaniae</i> • <i>Candida krusei</i> | Kayode et al., 2005; Kayodé et al., 2007, 2011; Lyumugabe et al., 2012; Greppi et al., 2013; Dossou et al., 2014 |

(Continued)

TABLE 3 | Continued

| Name of product | Country | Raw material | Steps of the processing | Microorganisms involved | References |
|-------------------------|---------------|---------------------------------|--|---|--|
| <i>Tchapalo</i> | Côte d'Ivoire | Malted sorghum, millet or maize | <ul style="list-style-type: none"> • Grinding • Mixing with water • Decantation (20–30 min) • Boiling of the sediment (100°C, 2–2 h 30) • Mixing with the supernatant • Acidification (9–12 h) • Filtration • Cooking (100°C, 4–5 h) • Cooling (5–6 h) • Alcoholic fermentation with traditional levean (9–12 h) | <ul style="list-style-type: none"> • <i>Hanseniaspora guillemontii</i> • <i>Debaryomyces nepalensis</i> • <i>Candida glabrata</i> • <i>Kluyveromyces marxianus</i> • <i>Hanseniaspora uvaru</i> • <i>Limosilactobacillus fermentum</i> (<i>Lactobacillus fermentum</i>) • <i>Lactobacillus cellobiosus</i> • <i>Lactobacillus brevis</i> • <i>Lactobacillus coprophilus</i> • <i>Lactobacillus plantarum</i> • <i>Lactobacillus hilgardii</i> • <i>Enterococcus</i> sp., • <i>Pediococcus</i> sp. • <i>Leuconostoc</i> sp. • <i>Saccharomyces cerevisiae</i> • <i>Candida tropicalis</i> • <i>Pichia kudriavzevii</i> • <i>Pichia kluyveri</i> • <i>Kodamaea ohmeri</i> • <i>Meyerozyma caribbica</i> | Aka et al., 2008, 2017; Djè et al., 2009; N'Guessan et al., 2011; Coulibaly et al., 2014 |
| <i>Burkutu/Burukutu</i> | Nigeria | Malted sorghum, millet or maize | nr | <ul style="list-style-type: none"> • <i>Lactobacillus plantarum</i> • <i>Lactobacillus brevis</i> • <i>Limosilactobacillus fermentum</i> (<i>Lactobacillus fermentum</i>) • <i>Lactobacillus pentosus</i> • <i>Lactococcus lactis</i> • <i>Leuconostoc mesenteroides</i> • <i>Pediococcus damnosus</i> • <i>Pediococcus pentosaceus</i> • <i>Streptococcus thermophilus</i> • <i>Saccharomyces cerevisiae</i> • <i>Saccharomyces chavelieri</i> • <i>Saccharomyces</i> sp. • <i>Candida acetobacter</i> • <i>Candida utilis</i> • <i>Candida spherica</i> • <i>Candida pelliculosa</i> • <i>Rhodotorula glutinis</i> • <i>Rhodotorula mucilaginoso</i> • <i>Cryptococcus albidu</i> | van der Aa Kühle et al., 2001; Blandino et al., 2003; Jimoh et al., 2012; Lyumugabe et al., 2012; Adewara and Ogunbanwo, 2013) |
| <i>Otika alcoholic</i> | Nigeria | Malted sorghum | nr | <ul style="list-style-type: none"> • <i>Lactobacillus brevis</i>, • <i>Limosilactobacillus fermentum</i> (<i>Lactobacillus fermentum</i>) • <i>Lactobacillus plantarum</i>, • <i>Leuconostoc mesenteroides</i>, • <i>Enterobacter clocae</i>, • <i>Saccharomyces cerevisiae</i> • <i>Candida krusei</i>, | Oriola et al., 2017; Oluwafemi, 2020 |

(Continued)

TABLE 3 | Continued

| Name of product | Country | Raw material | Steps of the processing | Microorganisms involved | References |
|--|--------------------------|--------------------------|--|--|---|
| <i>Doro</i> or <i>Chibuku</i> | Zimbabwe | Malted red sorghum | <ul style="list-style-type: none"> • Milling • Mixing with water (7 kg/24 l) • Boiling (3–5 h) • Cooling • Lactic fermentation (48 h) • Alcoholic fermentation (5–7 days) | <ul style="list-style-type: none"> • <i>Candida tropicalis</i> • <i>Bacillus cereus</i> • <i>Bacillus subtilis</i> • <i>Lactobacillus plantarum</i> • <i>Lactobacillus delbrueckii</i> • <i>Lactobacillus</i> sp • <i>Lactococcus lactis</i> • <i>Lactococcus raffinolactis</i> • <i>Lactococcus lactis</i> subsp. <i>lactis</i> • <i>Leuconostoc mesenteroides</i> subsp. <i>mesenteroides</i> • <i>Streptococcus</i> sp. • <i>Enterococcus</i> sp • <i>Saccharomyces cerevisiae</i> | Chamunorwa et al., 2002; Togo et al., 2002; Jespersen, 2003; Lyumugabe et al., 2012 |
| <i>Bili bili</i> or <i>Amgba</i> <i>Bili bili (Tchad)</i> | Cameroon Tchad | Malted sorghum or millet | <ul style="list-style-type: none"> • Grinding (fine flour) • Mixing with water • Decantation (1–3 h) • Cooking of the sediment • Mixing with the supernatant (65–70°C) • Acidification (9–18 h) • Cooking (100°C) • Cooling (30°C) • Alcoholic fermentation (12–24 h) with traditional leaven | <ul style="list-style-type: none"> • Lactic acid bacteria • <i>Saccharomyces cerevisiae</i> • <i>Kluyveromyces marxianus</i> • <i>Cryptococcus albidus</i> • <i>Debaryomyces hansenii</i> • <i>Candida melibiosica</i> • <i>Dekkera bruxellensis</i> • <i>Rhodotorula mucilaginosa</i> • <i>Torulaspora delbrueckii</i> | Maoura et al., 2005; Lyumugabe et al., 2012; Touwang et al., 2018 |
| <i>Red kapsiki beer</i> or <i>Te</i> | Cameroon | Malted Sorghum or maize | <ul style="list-style-type: none"> • Grinding • Mixing with water (1:9, w/v) • Decantation (1–3 h) • Cooking of the sediment (3–5 h) • Cooling • Mixing with the supernatant • Decantation & Acidification (overnight) • Cooking of the sour wort (5–10 h) • Cooling • Alcoholic fermentation (12 h at least) with artisanal starter | <ul style="list-style-type: none"> • Spore forming bacteria • Coliforms • Streptococcus • <i>Salmonella</i> • <i>Shigella</i> • Sulfite-reducing clostridia | Bayoi and Djoulde, 2017 |
| <i>Bili-bili</i> | Central African Republic | Malted sorghum | <ul style="list-style-type: none"> • Grinding (crude) • Mixing with water • Decantation (1–2 h) • Heating the sediment until boiling • Mixing with the supernatant (65–70°C) • Cooking • Decantation & cooling • Alcoholic fermentation (10 h) with traditional leaven | <ul style="list-style-type: none"> • <i>Lactobacillus</i> • Lactic acid bacteria • Enterococci • Streptococci • Coliforms • Yeasts | Lango-Yaya et al., 2020 |
| <i>Ikigage</i> or <i>amarwa</i> | Rwanda | Malted red sorghum | <ul style="list-style-type: none"> • Grinding • Mixing with water (infusion, 63–71°C) • Cooling • Decantation (3 h) • Fermentation with addition of leaven (30°C, 12–24 h) | <ul style="list-style-type: none"> • <i>Limosilactobacillus fermentum</i> (<i>lactobacillus fermentum</i>) • <i>Lactobacillus buchneri</i> • <i>Lactobacillus</i> sp • <i>Saccharomyces cerevisiae</i> • <i>Candida inconspicua</i> | Lyumugabe et al., 2010, 2012 |

(Continued)

TABLE 3 | Continued

| Name of product | Country | Raw material | Steps of the processing | Microorganisms involved | References |
|---------------------------------|--------------|--|--|--|--|
| Merissa | Sudan | Malted red sorghum or millet, Sorghum grains | <ul style="list-style-type: none"> • Grinding • Mixing with water • Lactic fermentation (36 h) • Alcoholic fermentation (8–10 h) | <ul style="list-style-type: none"> • <i>Issatchenkia orientalis</i> • <i>Candida magnolia</i> • <i>Candida humilis</i> • Lactic acid bacteria • Acetic acid bacteria • <i>Saccharomyces</i> spp. | Dirar, 1994 |
| Kaffir beer/bantu beer/utshwala | South Africa | Sorghum | nr | <ul style="list-style-type: none"> • <i>Limosilactobacillus fermentum</i> (<i>lactobacillus fermentum</i>) • <i>Lactobacillus plantarum</i> • <i>Lactobacillus brevis</i> • <i>Lactococcus dextranicum</i> • <i>Saccharomyces cerevisiae</i> • <i>Candida krusei</i> • <i>Kloeckera apiculata</i> | van der Walt, 1956; Lyumugabe et al., 2012 |

nr, not reported.

between 12 and 16 h (Sawadogo-Lingani et al., 2007). This duration is similar to those of the acidification of *tchoukoutou* wort (13–14 h), *tchapalo* (9–12 h) and *bili-bili* (9–18 h), but shorter than the acidification times of *chibuku* (48 h) and *merissa* (36 h). This acidification/saccharification is a spontaneous lactic fermentation characterized by a drop in pH and growth of lactic acid bacterial counts reaching 8.8–9.9 log cfu/ml at the end of acidification (Sawadogo-Lingani et al., 2007). The predominance of lactic acid bacteria as the original flora in raw sorghum grains and their proliferation during steeping perhaps give LAB a competitive advantage in the brewing of *dolo* or *pito*, leading to their dominance in acidification of sorghum wort (Sawadogo-Lingani et al., 2007, 2010; Sawadogo-Lingani, 2010). The common LAB species involved in the acidification of *dolo* wort include *Limosilactobacillus fermentum* (Basonym: *Lactobacillus fermentum*), *Lactobacillus delbrueckii* subsp. *jakobsenii* (Basonym: *Lactobacillus delbrueckii* subsp. *delbrueckii*), *Pediococcus acidilactici*, *Lactobacillus lactis* and *Leuconostoc* spp., with a predominance of *Limosilactobacillus fermentum* (Sawadogo-Lingani et al., 2007; Adimpong et al., 2013; Zheng et al., 2020). Various other species of *Lactobacillus*, *Pediococcus*, *Lactococcus*, *Leuconostoc*, *Enterococcus* and *Streptococcus* genera have also reportedly been associated to the spontaneous fermentation of *dolo* and *pito* wort and others similar traditional beers such as *Tchoukoutou*, *Tchapalo*, *Burkutu*, *Bili-bili*, *Chibuku*, *Otika*, *Red kapsiki*, and *Ikigage* (Table 3). The spontaneous and uncontrolled lactic acid fermentation found during the steeping of sorghum grains for malting has also been dominated by lactic acid bacteria with *Limosilactobacillus fermentum* as the dominant species (Sawadogo-Lingani et al., 2010), perhaps giving a competitive advantage to this species during acidification of *dolo* and *pito* wort in the brewing phase. Following acidification, the sour supernatant/wort is collected and undergoes boiled for long hours during which water is lost through evaporation and concentrates the wort. In the

production of *dolo* and *pito*, this boiling can take between 3 and 5 h. This duration of wort boiling is similar to those reported for other African traditional sorghum beers such as *tchapalo* wort (4–5 h) and *chibuku* wort (3–5 h), but shorter than the boiling times of the *tchoukoutou* (6–9 h) and *red kapsiki* (5–10 h). The boiled concentrated wort is then cooled to room temperature and undergoes alcoholic fermentation.

Alcoholic fermentation of sorghum wort for the production of African traditional beers is generally achieved by the back-slopping technique where part of a previous fermented beer (usually collected from the bottom sediments of previous production) or indigenous dried yeast leaven obtained from previous production is used to inoculate the new batch. The yeast biomass from the previous production is collected, sun-dried and then stored to be used as a local starter culture for subsequent productions. In certain localities, the fresh yeasts are fixed on wooden or fiber supports, or woven belt and these supports are introduced into the canaries containing the wort for fermentation (Sefa-Dedeh, 1991). In most case of African traditional sorghum beers, sorghum wort is inoculated with traditional yeasts and fermentation duration varies between 8 and 24 h at ambient temperature. The duration of fermentation varies from 9 to 14 h for *dolo* and *pito*, similar to that of *tchapalo* (9–12 h) and *merissa* (8–10 h), but shorter than the fermentation times for *tchoukoutou* (12–24 h) and *bili-bili* (12–24 h) while *chibuku* has the longest fermentation time of about 5–7 days. In Western breweries, the fermentation is ensured by selected yeast strains (*S. cerevisiae* or *S. carlsbergensis*) and the fermentation time ranges between 8 and 15 days at 10–16°C (Waites et al., 2001). Fermentation is the important step by which yeast converts the sugars of the wort into ethyl alcohol. Interest in the characterization and identification of the yeasts responsible for the alcoholic fermentation of African traditional beers including *dolo* and *pito* has been demonstrated in several studies (Table 3). It is found that *Saccharomyces cerevisiae* is the dominant species responsible for the alcoholic

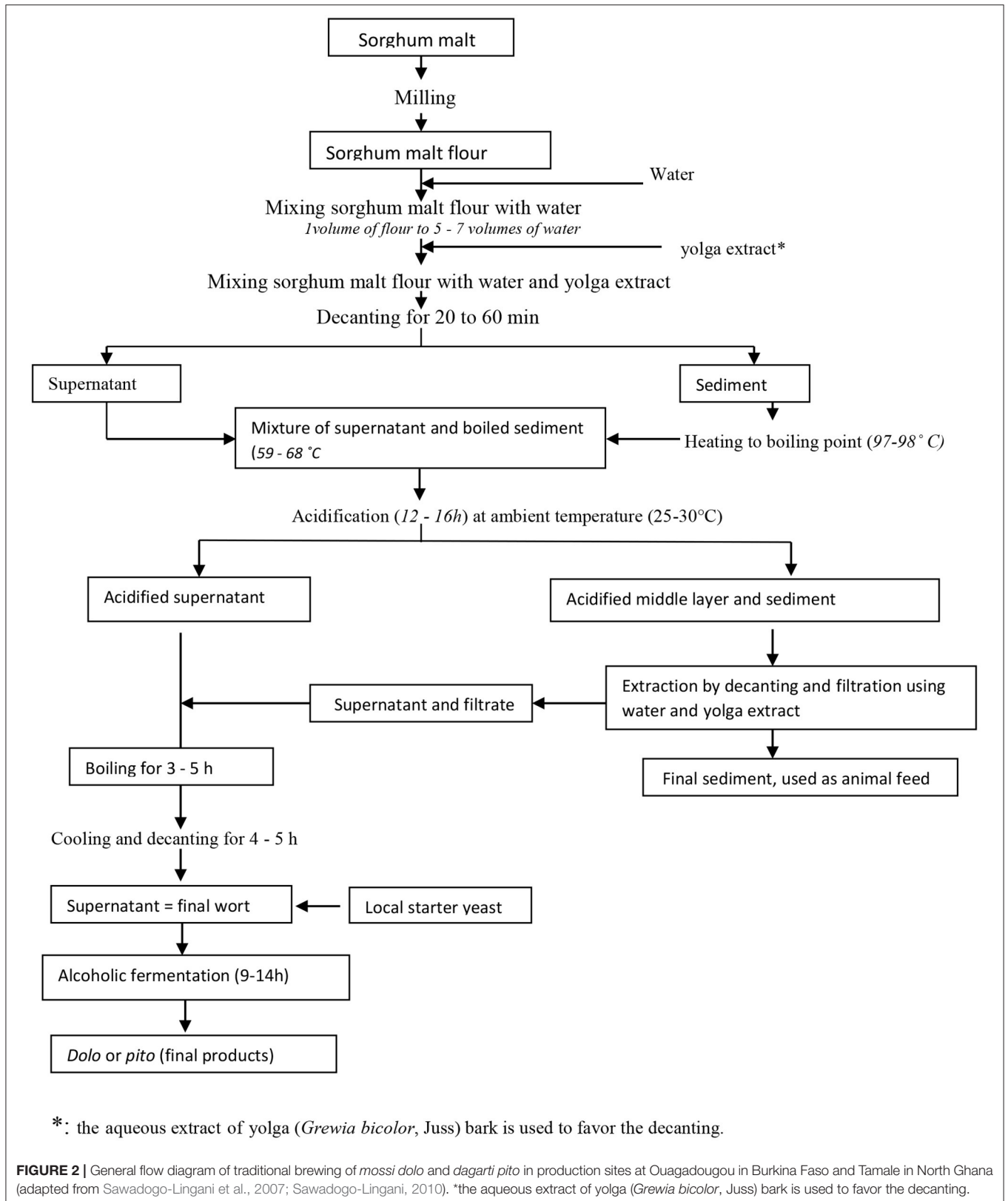


FIGURE 2 | General flow diagram of traditional brewing of *mossi dolo* and *dagarti pito* in production sites at Ouagadougou in Burkina Faso and Tamale in North Ghana (adapted from Sawadogo-Lingani et al., 2007; Sawadogo-Lingani, 2010). *the aqueous extract of yolga (*Grewia bicolor*, Juss) bark is used to favor the decanting.

fermentation of *dolo* and *pito* as well as other African traditional beers. Other yeast species identified during the fermentation of African sorghum beers include *S. pastorianu*, *S. chavelier*, *Candida* spp., *Kloeckera* spp., *Hansenula* spp., *Torulaspora* spp., *Schizosaccharomyces* spp., *Kluyveromyces* spp., *Debaryomyces* spp., *Pichia* spp., *Dekkera* spp., *Clavispora* spp., *Hanseniaspora* spp., *Rhodotorula* spp., *Cryptococcus* spp. (Table 3). However, most of these yeasts are considered contaminants not taken part in the fermentation; some may even be pathogenic and affect the safety of the traditional sorghum beer.

Packaging, Storage, and Shelf Life

At the end of alcoholic fermentation, *dolo* or *pito* is well frothy and sparkling, and ready for consumption. Traditional sorghum beers such as *dolo* and *pito* do not undergo filtration or stabilization and are consumed in the active fermentation state. The *dolo* or *pito* is packaged in canaries, jars, plastic buckets or barrels of 20 or 5 L cans for sale to consumers in cabarets or to *dolo* retailers. At the cabarets, *dolo* is served and drunk in gourds. African traditional sorghum beers have a poor keeping quality with a shelf-life of about 24–72 h at ambient temperature (Novellie and De Schaepprijver, 1986; Tisekwa, 1989; Broutin et al., 2003; Maoura and Pourquie, 2009; Lyumugabe et al., 2010; Aka et al., 2017). A few investigations (Osseyi et al., 2011; Dahouenon-Ahoussi et al., 2012; Ayirezang et al., 2016) have been conducted in an attempt to improve the shelf-life of *dolo* and *pito* or similar beers. Recent investigations show that the shelf-life of *pito* can be extended through pasteurization and/or the addition of *Moringa oleifera* leaf extract for up to 28 days. However, *pito* samples that contained the *moringa* extract were less favored by consumers (Ayirezang et al., 2016). According to Dahouenon-Ahoussi et al. (2012), the use of essential oil of Citronella (*Cymbopogon citratus*) at 1 ml/L was effective in stabilizing African sorghum beer against the spoilage effects of continued fermentation. Rodrigue Christian et al. (2014) also evaluated the influence of *Hemizygia bracteosa* (Benth) leaf powder on the quality of *chakpalo* produced in Benin and reported that the use of the powdered leaves during mashing had an effect on the physico-chemical parameters, providing a slightly sweet drink, less acidic, with low alcohol content.

SAFETY OF AFRICAN SORGHUM BEERS

The microbiological and sanitary quality of sorghum malt, as well as the resulting risks, are highly dependent on the malting conditions. The conditions necessary for soaking and germination (temperature of 30°C, humidity above 85%) are also ideal for the proliferation of the inherent microflora of the raw cereal grains, generally consisting of yeasts, molds, enterobacteria, lactic acid bacteria and spore-forming aerobic bacteria. Although lactic acid bacteria have dominated in the spontaneous fermentation during sorghum grain steeping for malt production, the frequent association of other undesirable microorganisms compromises the quality and safety of sorghum malts. In general, bacterial species of safety concern such as *Escherichia coli*, *Enterobacter cloacae*, *Enterobacter aerogenes*, *Pseudomonas aeruginosa*, *Bacillus cereus*,

Stapylococcus aureus, *Klesiella aerogenes*, *Sarcina* spp., and molds such as *Botryodiplodia theobromae*, *Aspergillus flavus*, *Aspergillus niger*, *Rhizopus stolonifer*, *Penicillium* spp., *Fusarium* spp., have been identified in sorghum grains and malts (Ilori et al., 1991; Ogundiwin et al., 1991). However, like many other traditional African fermented foods and beverages, sorghum beers are generally considered to be microbiologically safe due to the antimicrobial effects exerted during lactic acid fermentation, the alcohol content as well as the long cooking hours of sorghum malt wort prior to alcoholic fermentation which potentially eliminates pathogenic microorganisms. This notwithstanding, the spontaneous nature of the fermentation processes (without properly defined starter cultures), poor control measures (including time-temperature) during fermentation and poor post-processing handling including packaging predisposes these products to contamination by pathogenic microorganisms.

Another safety concern for African sorghum beers is related to handling and storage conditions of the raw materials (cereal grains) which predispose them to mycotoxin contamination due to growth of toxigenic molds. Mycotoxins isolated from sorghum and millet grains include *patulin*, *trichothecene*, *zearalenone* and *aflatoxins* (McFarlane et al., 1995). In addition, Dufour et al. (1992) in a survey showed that about 80% of sorghum varieties from Taiwan and Africa (South Africa, Cameroon, Burundi, Ghana, Kenya, Nigeria, Rwanda, and Sudan) were contaminated with aflatoxins; 19% of which were contaminated before malting, and 52% after malting. Moreover, Matumba et al. (2011) indicated the presence of aflatoxins at levels of 6.6 to 54.6 µg/kg in a sorghum malt from Malawi. However, red varieties of sorghum which are commonly used to produce African sorghum beer are less susceptible to the development of aflatoxins than white varieties (Ratnavathi and Sashidhar, 2000), because of their richness in tannins that provide a protective role against grain mold. Additionally, the production process of African sorghum beer has been shown to decrease mycotoxin levels although the process does not completely eliminate these toxins (Trinder, 1988; Dufour et al., 1992). There is therefore the need to incorporate safety standards throughout the production process of African sorghum beers, beginning with supply of quality raw materials through fermentation to post-processing handling, packaging and distribution.

USE AND VALORIZATION OF BY-PRODUCTS FROM DOLO PRODUCTION

The valorization of by-products contributes to improving the competitiveness and sustainability of the African sorghum beer sector. Currently, valorization undertaken by actors are related to yeast biomass and *dolo* dreche. In *dolo* production units, the yeast biomass settling at the bottom of packaging containers such as canaries, jars, buckets, barrels, cans and gourds is collected, washed with water and then sun dried. The dried yeast called *rabilé* (Burkina Faso) or *dambeli* (Northern Ghana) is packaged in plastic bags and marketed as food yeast. In

addition to its use as a local fermenter or starter for the alcoholic fermentation of sorghum malt wort, dried yeast is used as a food condiment in the preparation of sauces, dishes and grilled chickens by local population and in some restaurants. An important source of protein, amino acids and B-group vitamins, dry yeast gives flavor to dishes and improves their nutritional value, contributing to the improvement of the diet of consuming populations. Yeast biomass is well-known for its richness in proteins, essential amino acids, fatty acids and B-group vitamins. A good valorization strategy could allow to better valorize this by-product of traditional breweries for its use as a food additive in human and animal food, as unicellular proteins and a source of vitamins.

Dolo dreche or spent grain, the solid residue obtained after rinsing and filtering the mash after acidification by spontaneous lactic fermentation, is recovered for animal feed. It is marketed to pig farmers. Indeed, in Burkina Faso, pig production, mainly managed by women who own 60% of the country's farms, is one of the fastest growing livestock sectors. It is gaining importance in societies where there is a shift from ruminant to monogastric livestock production, with higher rates of return and advantageous feed efficiency. The majority of farmers use locally abundant raw materials such as artisanal sorghum (*dolo*) brewers' spent grains. For the supply of *dolo dreche*, breeders establish a tacit contract of supply with the *dolotières* for an exclusivity on all its production or then for a given quantity of baskets of *dolo dreche* which are sold between 200 and 500 FCFA per basket of ~10 liters (FAO, 2012). This residue, used as animal feed, still contains nutrients in quantity and quality such as sugars, dietary fiber, proteins, fats, minerals, vitamins etc. Even though research and innovation are still missing in an African context, it is obvious that it can be better valorized and used in human food and thus contribute to the achievement of food and nutritional security of local populations. Collected under appropriate conditions followed by adequate pre-treatment (drying, grinding, sieving, etc.), it can be used in human food. The residues from sieving could still be used as animal feed.

As traditional breweries in Africa are heavy consumers of firewood, and they generate large quantities of incandescent embers, some of which are often extinguished to provide charcoal. This charcoal is sold to households and contributes to increasing the income of traditional brewers. Similarly, large quantities of wood ash are also generated, which are sold to traditional potash manufacturer. The potash is sold and used as ingredient for local soap preparation, as food ingredient to neutralize acidity, make alkaline or softener in the preparation of dishes, and in the processing of fermented seeds (*maari*, *mandchoua*, *bikalga*, etc) used as food condiments (Thorsen et al., 2015; Kere-Kando et al., 2020).

CONSTRAINTS AND STRATEGIES FOR SUSTAINABLE PRODUCTION OF SORGHUM BEER

The African traditional sorghum beer is an ethnic beverage that is facing constraints for its development and expansion

outside the production regions. Some of these constraints, their implications and prospects for sustainable production are summarized in **Table 4**. Various research works have been undertaken to bring innovations and value-addition to African traditional beer processes. Initial approaches for sustainable production of African sorghum beers were aimed at optimizing and controlling fermentation processes through the development of starter cultures (Sefa-Dedeh et al., 1999; Orji et al., 2003; Glover et al., 2005, 2009; Maoura et al., 2005; Sawadogo-Lingani et al., 2008a,b; Yao et al., 2009; N'Guessan et al., 2010, 2011, 2016; Adewara and Ogunbanwo, 2013; Lyumugabe et al., 2014). **Table 5** summarizes the results of works geared toward developing starter cultures for controlled fermentation of African sorghum beers. These studies have shown, for the most part, that the selected starters lead to a reduction in fermentation time and an improvement in the beer production process. Moreover, these selected starters lead to sorghum beers with physico-chemical and sensory characteristics (pH, color, titratable acidity, alcohol content, specific gravity, taste, flavor) comparable to traditionally produced beers (Sefa-Dedeh et al., 1999; Orji et al., 2003; Glover et al., 2005, 2009; Sawadogo-Lingani et al., 2008b). However, these experiments were carried out on laboratory and pilot scales, and the processes have not been scaled-up or replicated in *dolo* and *pito* production units. The production of yeasts starter cultures with optimal technological properties in dried form can be promoted for that purpose. Collaborative projects such as the GreenGrowth project (DFC No 13-04KU) has established culture collections (Biobank) of microorganisms involved in the processes of West African fermented products including traditional sorghum beers, with the aim of promoting sustainable use of beneficial indigenous microorganisms.

Other innovative work aimed at improving the process of African traditional sorghum beer has been carried out. For example, a fractional factorial plan has been developed and applied to optimize the artisanal process of *tchapalo* (Amané et al., 2012), a traditional beer similar to *dolo* and *pito*. The authors, through the screening of factors, highlighted the importance of some of the processing operations (drying, soaking, germination, type of ferment, fermentation, decanting, cooking, pre-cooking) and critical points for improvements. The establishment and resolution of a mathematical model enabled the proposal of optimum conditions for the production of *tchapalo*. The proposed optimized processing conditions including 15 h of soaking, 72 h of germination, 10 h of drying, 30 min of decantation, 1 h of pre-cooking and 2 h of cooking resulted in a time saving of over 3 days and enabled the production of *tchapalo* with consistent quality. These results constitute the basis for the industrialization of *tchapalo* and may be applicable to other African traditional sorghum beers such as *dolo* and *pito*. In an attempt to improve the sensory characteristics of sorghum beers, local bitter plants such as *Vernonia amygdalina* and *Nauclea diderrichii* were used in the brewing of sorghum beer under laboratory-controlled conditions (Desobgo Zangué et al., 2013). The two bitter plants, commonly used for their medicinal properties, could adequately bitterize sorghum beers and therefore, should be explored to enhance the sensory qualities of African sorghum beers as occurs

TABLE 4 | Challenges and perspectives for sustainable production of African traditional sorghum beers.

| Challenge/constraints | Implications | Perspectives for sustainability |
|--|--|--|
| Decrease in productivity and availability of quality raw material (sorghum) due to climate variability and change | Inconsistent supply of no quality and no standardized cereal (sorghum) leads to high cost of production variable product characteristics including physico-chemical, nutritional and organoleptic properties from one production batch to another | Ensuring a supply of adapted and quality raw materials through the dissemination and extension of improved varieties of cereal (sorghum) suitable for traditional sorghum beer production |
| Artisanal nature of the processing | Time consuming and labour-intensive process. Long cooking/concentration time of the wort with a high consumption of firewood used as the main source of energy. Complex and non-standardized process leads to inconsistent quality and variability in products | Optimize and standardize the process Introduce technological innovations in the process Modernize the production process |
| High consumption of firewood used as the main source of energy | Strong contribution to deforestation with a negative impact on the environment | Develop and implement strategies for the dissemination and adoption of improved stoves |
| Spontaneous fermentations or the used of no properly defined starter cultures | These practices coupled with poor time/temperature controls expose fermented products to undesirable and pathogenic microorganisms, compromising the sanitary quality of sorghum beer and thus the safety of the consumers. | Promote the implementation of good hygiene and manufacturing practices in production units to improve the quality of traditional sorghum beer while maintaining the biodiversity of microorganisms with technological potential. |
| Poor hygiene of the production and sales environment | Contamination from the environment with negative impact on the quality and safety of the final products, and on the safety of the consumers | Regulate the production and selling environment Promote the application of good hygiene practice guides to improve the hygiene of the production and sales environment |
| Unpackaged, poor packaging or inappropriate packaging material used, unstabilized drinks store at ambient conditions for selling | Contamination of the product by the environment in addition to the continuation of fermentation which induces a short shelf-life (1–3 days) | Search for an appropriate stabilization and packaging process that preserves the original quality of sorghum beer in order to extend its shelf life for wide distribution and consumption. |
| Lack of control of technological and sanitary parameters sanitary quality of the products (raw materials, intermediates products, finished products) during the processing | Variability of the physico-chemical, nutritional and organoleptic characteristics of the products from one production to another; | Promote the regulation of the products of the traditional sorghum beer value chain Develop, disseminate and promote the adoption of technical specifications and products quality standards |
| Weak technological and scientific knowledge of the processing and on the nutritional and therapeutic properties of the finished products. | Process always artisanal and non-standardized Low value added of traditional sorghum beer Distribution market always internal and local | Conduct research to provide in-depth and detailed scientific results on sorghum beer technology and its nutritional and therapeutic characteristics. |

in the use of *Humulus lupulus* in Western beer production. These plants also proved to be excellent sources of free amino acids, thus improving the characteristics of the must before fermentation.

The production of beers from raw agricultural materials in many regions of Sub-Saharan Africa consumes a significant proportion of total wood-fuel. Thus, the cooking/concentration of sorghum beer wort is a high fuel-intensive operation using firewood as the main source of fuel. Being a high energy consuming process with firewood as the main source of fuel in production, the direct environmental impacts are

deforestation and greenhouse gas emissions, with potential negative consequences for the climate. Yaméogo et al. (2013) reported that the people of Vialogo (a village in Burkina Faso) use 1,422 m³ of wood per year for *dolo* production and their needs per year for timber to build huts, attics and sheds were estimated at 25 m³. Today, around 2.7 billion people in developing countries rely on the traditional use of biomass, mostly firewood or charcoal, for cooking. This contributes to deforestation and severe health problems as the related smoke emissions cause respiratory diseases (World Health Organization, 2009).

TABLE 5 | Development of starter cultures for controlled fermentation of different African traditional beers.

| Traditional beer | Types of fermentation | Selected strains & characteristic | Results | References |
|------------------|---|---|---|---|
| <i>Dolo</i> | Lactic fermentation and alcoholic fermentation Mixed or co-fermentation (lactic + alcoholic) | <ul style="list-style-type: none"> • <i>Lactobacillus fermentum</i> • <i>Saccharomyces cerevisiae</i> • <i>Lactobacillus fermentum</i> + <i>Saccharomyces cerevisiae</i> • Used as fresh cells suspension | Four strains of <i>Lb. fermentum</i> and one strain of <i>S. cerevisiae</i> were tested in a series of three trials productions: (i) a production of <i>dolo</i> by double lactic fermentation with <i>Lb fermentum</i> , and alcoholic fermentation with <i>S. cerevisiae</i> ; (ii) a production of <i>dolo</i> by lactic and alcoholic mixed or co-fermentation (<i>Lb. fermentum</i> + <i>S. cerevisiae</i>); (iii) a production of <i>dolo</i> in a real environment by a double lactic and then alcoholic fermentation with the same strains. The results showed that the starter cultures reduced the duration of lactic fermentation (9 h instead of 12-16 h) and of lactic + alcoholic fermentation (12 h instead of 21-48 h) in the case of co-fermentation. Furthermore, sensory analysis revealed that the <i>dolos</i> produced with the selected starters had organoleptic and physico-chemical characteristics comparable to those of the traditional <i>dolo</i> and were considered acceptable by the tasters. | Sawadogo-Lingani et al., 2008b; Glover et al., 2009 |
| <i>Tchapalo</i> | Alcoholic fermentation | <ul style="list-style-type: none"> • <i>Saccharomyces cerevisiae</i> • <i>Candida tropicalis</i> • <i>Saccharomyces cerevisiae</i> + <i>Candida tropicalis</i> • Formulation of freeze-dried cells for alcoholic fermentation | Strains <i>Saccharomyces cerevisiae</i> F12-7 and <i>Candida tropicalis</i> C0-7 isolated from sorghum beer were used in a mixed culture at a ratio of 2:1 (<i>C. tropicalis</i> / <i>S. cerevisiae</i>).and freeze-dried using as protective agents (sucrose, glucose, glycerol) and support materials (millet, maize, sorghum and cassava flours) at 1:1 ratio (v/v). The freeze-dried yeasts viabilities were between 4.0% and 10. 6%. sucrose was found to be the best protectant giving cell viabilities of 8.4–10.6%. Millet flour was the best support material after drying. When the freeze-dried yeast powders were stored at 4°C and room temperature (25–28°C) for up to 3 months, the survival rates were the highest with cassava flour as the support material. | N'Guessan et al., 2010, 2011, 2016 |
| <i>Tchapalo</i> | <ul style="list-style-type: none"> • Lactic fermentation • Alcoholic fermentation by commercial yeast | <ul style="list-style-type: none"> • <i>Lactobacillus fermentum</i>, <i>Pediococcus acidilactici</i>, <i>Pediococcus pentosaceus</i>, <i>Lactobacillus plantarum</i> • Used to evaluate as single starter cultures for controlled lactic fermentations of the wort • Commercial <i>Saccharomyces cerevisiae</i> (used at 1%) for controlled alcoholic fermentation during 12 h | LAB strains used as single starter cultures in the sorghum wort for lactic fermentation, grew increasing organic acids and titratable acid and dropping pH. But <i>L. fermentum</i> (strains S6, S42, S45), <i>P. acidilactici</i> (strains S7, S52), and <i>P. pentosaceus</i> (strain S5) acidified quickly the sorghum wort. The <i>tchapalo</i> from that worts were similar to those of obtained by spontaneous fermentation. These starter cultures will be used for sweet wort and <i>tchapalo</i> commercial production and thereby to improve their safety and consumer acceptability of these products | Aka et al., 2020 |
| <i>Pito</i> | Alcoholic fermentation | <i>Saccharomyces cerevisiae</i> | Reduction of fermentation time Better control of the production process Acceptable organoleptic characteristics. | Sefa-Dedeh et al., 1999; Glover et al., 2005 |

(Continued)

TABLE 5 | Continued

| Traditional beer | Types of fermentation | Selected strains & characteristic | Results | References |
|------------------|---|--|--|-------------------------------------|
| <i>Pito</i> | <ul style="list-style-type: none"> • Lactic acid fermentation and alcoholic fermentation • Mixed or co-fermentation (lactic+ alcoholic) | <ul style="list-style-type: none"> • <i>Lactobacillus plantarum</i> • <i>Saccharomyces cerevisiae</i> • <i>Lactobacillus plantarum</i> + <i>Saccharomyces cerevisiae</i> • <i>Pediococcus halophilus</i> + <i>Candida tropicalis</i> • Used as fresh cells suspension | <ul style="list-style-type: none"> • Reduction of fermentation time • Better control of the production process • Acceptable organoleptic characteristics. | Orji et al., 2003; Yao et al., 2009 |
| <i>Burukutu</i> | <ul style="list-style-type: none"> • Lactic acid fermentation • Alcoholic fermentation • Mixed or co-fermentation (lactic+alcoholic) | <ul style="list-style-type: none"> • <i>Lactobacillus fermentum</i> • <i>Saccharomyces cerevisiae</i> • <i>Lactobacillus fermentum</i> + <i>Saccharomyces cerevisiae</i> | <ul style="list-style-type: none"> • Reduction of fermentation time • Better control of the production process • Acceptable organoleptic characteristics. | Adewara and Ogunbanwo, 2013 |
| <i>Burukutu</i> | Alcoholic fermentation | <i>Saccharomyces cerevisiae</i> | <ul style="list-style-type: none"> • Reduction of fermentation time • Better control of the production process • Acceptable organoleptic characteristics | Maoura et al., 2005 |
| <i>Bili bili</i> | Alcoholic fermentation | <i>Saccharomyces cerevisiae</i> | <ul style="list-style-type: none"> • Reduction of fermentation time • Better control of the production process • Acceptable organoleptic characteristics. | Maoura et al., 2005 |

In order to reduce wood consumption and preserve the environment, improved wood or gas fireplaces have been designed and promoted among a few women *dolo* producers in Ouagadougou, Burkina Faso. Improved cook-stoves potentially help to alleviate the negative implications of wood-fuel usage since they increase the efficiency of the cooking process thereby reducing the wood-fuel consumption. The saving rate of the improved cook-stoves is about 25% as compared to a traditional tripod stone stove. This is remarkable, but still below the potential energy savings of about 40% achieved in controlled cooking tests, showing the need to test the effectiveness of new technologies under real world conditions and based on a sufficiently large and representative usage. A program like FAFASO (Foyer Amélioré au Burkina Faso) has been implemented with the objective to evaluate the productive use and to promote the improved cook-stoves for local beer breweries in Burkina Faso. The improved cook-stoves made for breweries (Roundé stoves) are much larger than the household cook-stoves and are made of clay and bricks rather than metal and saves at least 60 to 70% of the firewood needed with a traditional stove for brewing process (Grimm and Jörg, 2013). However, it seems that the saving rate goes rapidly down if the improved stove is badly maintained. In one field test conducted by Sanogo et al. (2011), a damaged improved cook-stove even needed more firewood per liter of *dolo* than a traditional stove, confirming that a rigorous assessment of the effectiveness of such stoves requires a test under real world conditions which includes the status of the stove and how these stoves are maintained. In 2012, about 50% of all breweries in Ouagadougou and Bobo-Dioulasso city adopted another new technology aimed at reducing firewood consumption during brewing of *dolo*. However, since then, the trend of adoption has declined. The exact reasons for this decline are not known and therefore need to be investigated. The improved fireplace designed for *dolo*, seem to be a fixed fireplace, made of refractory

bricks with an opening for the fuel inlet and one or two chimneys for the smoke outlet. It is a multi-purpose firebox that can be built for 2, 3, or 4 pots made of aluminum or fired clay. The selected fireplaces consume 60 and 90% less wood than traditional *dolo* fireplaces. In addition to significantly reducing greenhouse gas (GHG) emissions, the improved fireplaces offer benefits to its users in the form of money savings, reduced carbon monoxide and fine particle emissions that are harmful to health, protection against heat emanating from the fireplace, faster cooking (thus saving time), better cleanliness and convenience (Grimm and Jörg, 2013). In any case, reflection and research should continue to find other sources of energy as a substitute for firewood in a perspective of climate sustainability.

Regarding availability of the raw material, sorghum is one of the main cereals grown in Burkina Faso, as well as in other West African countries. A varietal diversity of this cereal is managed by farmers and national agricultural research centers for various production objectives. Despite various efforts, yields have remained low and the increase in production is mainly due to the expansion of cultivated areas. This situation is aggravated by climate variability and change. Research programs have therefore focused on maintaining sorghum biodiversity and increasing productivity through the participatory development of improved variety lines adapted to local climatic conditions and farmers' needs and preferences (vom Brocke et al., 2014). The same is true for other cereals such as millet, maize and rice. Thus, in the Regional Catalog of Plant Species and Varieties (ECOWAS-UEMOA-CILSS, 2016) there are 1,496 varieties of 11 priority crops including 413 rice varieties, 279 maize varieties, 96 millet varieties and 171 sorghum varieties, all of which are released at the national level. These cereals used as raw materials in the processing of traditional beers are nowadays experiencing significant drop in productivity due to climate variability and change. Breeders in agricultural research centers have developed

better adapted hybrid varieties. In Burkina Faso for example, improved basic and certified seeds are produced by agricultural research centers. basic seeds are also made available to seeds producers for the production of certified improved seed. Certified seeds are subsidized by the State for farmers' organizations at affordable prices. To ensure sustainable production of traditional sorghum beer, strategies should be developed to promote the adoption of these varieties among farmers for a sustainable supply of raw materials.

In terms of innovation in the processing of sorghum beers, private businesses have set up mini breweries that produce small quantities of stabilized *dolo* and *pito*, packaged in bottles and appropriately labeled. Thus, a mini brewery with modern stainless-steel equipment has been designed since 2003 in Ghana in Kwabenya (northern suburb of Accra). This company produces sorghum beer with a capacity of 200 liters of beer per day, three times a week. The local beer industry provides a living for nearly 6,000 people in the northern parts of Ghana where the sorghum is produced farmers as a major crop (Gamba, 2019). In Benin, a small enterprise has been set up to produce traditional *tchapalo* (corn or sorghum beer) packaged in properly labeled brewery bottles in a factory and are sold at competitive price while maintaining its special traditional taste (CTA, 2002). Between the years 2003 and 2004, Zambian Breweries (ZB) launched a clear beer made from locally grown sorghum and has since then been producing African sorghum beer. The "new Eagle" beer which uses locally produced sorghum as its raw materials has opened opens up new market channel for many smallholder farmers who, for the first time, have a sustainable commercial outlet for their sorghum production (CTA, 2006). In Burkina Faso, Unité de Malterie de Ouiditinga (UMAO) has been producing malt from local cereals under controlled conditions for both modern and traditional beers since 1999, and from 2003 has been producing traditional beer (*dolo* or *ram*) and sweet wort (*ran noodo*) packaged in bottles in modern plants with optimized malting and brewing processes. UMAO also offers *dolo* packaged under pressure for festive ceremonies on order. A manual of Good Hygiene Practices for sorghum malting and *dolo* brewing has been developed (Bougouma et al., 2008) for the benefit of women producing sorghum malt and *dolo* brewers in Ouagadougou. The implementation of this manual would improve the quality of *dolo* through the improvement of some technological practices and hygienic environments during malting, brewing and sale of the *dolo*.

Today, new types of consumers, especially young people and urban dwellers, are entering the traditional beverage value chain. These young people, faced with unemployment, idleness and altered lifestyles, indulge in the consumption of alcoholic beverages, prompting *dolo* producers to adopt various bad practices in order to increase the alcoholic strength of *dolo* by adding adulterated hard liquor to satisfy this category of consumers. For a sustainable production of the natural sorghum beer, it is important to properly characterize and conserve the microflora of technological interest to develop them into starter

cultures for controlled fermentation, to regulate the production through the establishment of quality standards in order to preserve their natural and original characteristics and to better valorize by-products and waste to increase the competitiveness of the value chain. The standardization of the process and regulation could lead to a new trend in the production of a range of fermented beverages with different degrees of alcohol content in order to satisfy different categories of consumers without compromising the originality of the beverage. However, the emphasis should be on low-alcohol beer, because there is currently a strong trend for this type of beer in other parts of the world including Europe. Appropriate packaging and stabilization process should be developed to extend the shelf life and diversify the channels of distribution.

CONCLUSIONS

This review presents currently available information on African traditional sorghum beers. It emerges that despite its popularity and its socio-cultural and economic importance, the manufacturing process of this ancestral drink is still artisanal although some innovations have been introduced in recent years. The traditional sorghum beer sector is a promising sector that brings together a diversity of actors. Yet, African sorghum beer production faces sustainability challenges, particularly related to the development of efficient and environmentally friendly processing technologies, raw material supply, variability in product quality and safety, high energy consumption and its associated impact on the environment, poor packaging, and short shelf-life. The development and emergence of this sector will require the development and implementation of strong strategies and actions at all levels of the value chain by the different actors. Thus, for sustainable production African traditional sorghum beers, strategies must be geared toward addressing sustainability challenges by improving quality and availability of raw material supply, processing technology (starter culture adoption), safety, packaging, recycling and waste treatment, as well as methods of improving energy consumption. Actions must be pursued to better valorize traditional sorghum beer and its by-products, assure a sustainable supply of adapted and quality raw materials, optimize and standardize processing technologies for malting, brewing and packaging of sorghum beer. There is also the need to control fermentation systems while preserving the biodiversity of the fermenting microorganisms associated with African sorghum beers.

AUTHOR CONTRIBUTIONS

HS-L designed the manuscript. All authors contributed to writing the manuscript. JO-K, HS-L, and LJ critically revised the manuscript. HS-L, JO-K, RG, BD, MJ, and LJ read and corrected the manuscript. HS-L, JO-K, LJ, and MJ validated the submitted version of the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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