INDONESIAN JOURNAL OF LIFE SCIENCES

Volume 6, No. 1, March 2024

REVIEW ARTICLE

Comprehensive Utilization of Sorghum (*Sorghum bicolor*) in the Food Industry and Its Nutritional Properties: A Review

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A B S T R A C T

Sorghum is one of the potential local carbohydrate sources in Indonesia. It is rich in nutrients. However, the utilization of sorghum as a staple food in Indonesia is lacking due to limited information on the cultivation, processing, and nutritional properties of sorghum. Hence, it is crucial to encourage the consumption and utilization of sorghum to promote food diversification and sustainability. Sorghum has a distinct classification depending on its variety, and each component has its own discrete functionality, with red sorghum being the most utilized variety in Indonesia. Sorghum is high in fiber and protein (6.7 g/100 g and 10.6 g/100 g, respectively), therefore contributing to the low glycemic index of sorghum. Several health benefits are possessed by sorghum, including anti-diabetic and antihypertensive properties. Moreover, the gluten-free nature of sorghum makes it suitable for people suffering from celiac disease. The utilization of sorghum and its processing were also discussed comprehensively in this review, including the utilization of sorghum as a rice substitute, gluten-free flour, syrup, sweet soy sauce, and plant-based milk. As such, the implementation of sorghum in Indonesia should be further optimized and promoted due to its beneficial properties as well as diverse utilization.

K E Y W O R D S

Food diversification, Food processing, Nutritional properties, Sorghum bicolor, Utilization

H I G H L I G H T S

- Sorghum as a potential local carbohydrate source is able to promote food diversification and sustainability.
- The utilization of discrete functionality possessed by sorghum has allowed several varieties of food products to be developed, including syrup, sorghum flour baked goods, milk, and popcorn.
- The consumption and implementation of sorghum are highly encouraged due to its gluten-free nature and health benefits consisting of high protein, and fiber content, as well as bioactive compounds.

INTRODUCTION

The staple food in Indonesia largely relies on one commodity, namely rice. The production of rice itself solely depends on the availability of rice fields, which continually declines as many of these lands are now utilized for non-agricultural purposes, such as housing or industries, whilst Indonesia's population ceaselessly increases (Septiadi & Joka, 2019). Indonesians have a high dependency on rice which increases its demand, while the amount of domestic rice production fluctuates and tends to dwindle down. The need for rice as a staple reaches up to 0.2 million tonnes/year for 229 million people, denoting around 132 kg/capita/year (Amarilis et al., 2019). Meanwhile, the constant decrease in rice production in Indonesia since 2017 and a nonoptimal distribution line have resulted in the reliance on imports in order to have a net surplus of rice availability in the country (Ruvananda & Taufiq, 2022). Unfortunately, the development, cultivation, and processing of non-rice staple food are still lacking in Indonesia. In reality, local carbohydrate food sources other than rice are still uncommon, despite their diversity, including sorghum (Widowati, 2016). This is also in accordance with a study done by Rozi et al. (2023), who stated that rice is still the dominant staple food in the country, while sorghum is not listed as part of the major staple food, regardless of socioeconomic status.

In the year 2020, The Ministry of Agriculture launched *Program Bantuan Benih Pangan* (seed relief grant program) to increase food diversification and sustainability, including sorghum as one of the main alternatives (Ruslan, 2021). Postharvest processing of sorghum needs to be encouraged to increase the physical, nutritional, and sensory properties of sorghum. Currently, sorghum utilization and processing in Indonesia are still limited, with Nusa Tenggara Timur having the most producers and consumers of sorghum in Indonesia (Lestari et al., 2019). For the most part, it has only been used as livestock feed in Indonesia due to its low costs, adaptive qualities, and better nutritional properties, such as its high protein, high fiber, high energy, low fat, and amino acid composition (Hidayat, 2021). Sorghum has not been optimally functionalized as its trade value has not reached the potential of other cereals such as rice, corn, cassava, wheat, or beans (Suarni & Subagio, 2013). Therefore, this review will cover the overview of sorghum, its beneficial properties, and nutritional value, as well as the current utilization of sorghum in the world that could be implemented in Indonesia in order to increase the local productivity and consumption of sorghum, hence contributing to Indonesia's food safety.

MATERIAL AND METHODS

In order to find relevant information for this review, a thorough literature search was done to find primary research based on the literature found on the Google Scholar database and discovering the topic related to sorghum applications, nutritional information, and health impacts, with the format being [(("Sorghum" OR "Sorghum bicolor") AND ("Nutritional properties" OR "Nutrition" OR "Function") AND ("Food" AND ("Industry" OR "Health")) AND ("Properties" AND ("Physicochemical" OR "Nutritional")) AND ("food" AND ("application" OR "Substitution")) AND ("food" AND ("application" OR "Substitution")) AND ("Food" AND ("Sustainability" OR "Diversity")) AND ("Properties" AND ("Organoleptic" OR "Sensory) - review)]. Determination of eligibility regarding inclusion for the identified papers was done by filtering at minimum four impartial reviewers looking at the titles and abstracts for each of the publications found. Other criteria used for inclusion were nutritional relevance, food industry application feasibility, and sustainability. After the purveyance of the chosen articles, the final inclusion was examined based on the established inclusion criteria. A total of 20 articles were selected from the inclusion of 229 articles, which did not fulfill the criteria of being irrelevant, only peripherally mentioned sorghum, or did not properly elaborate on the sought-after information. There may be literature conducted in languages other than English and Indonesian that are excluded to avoid the possible introduction of publication bias.

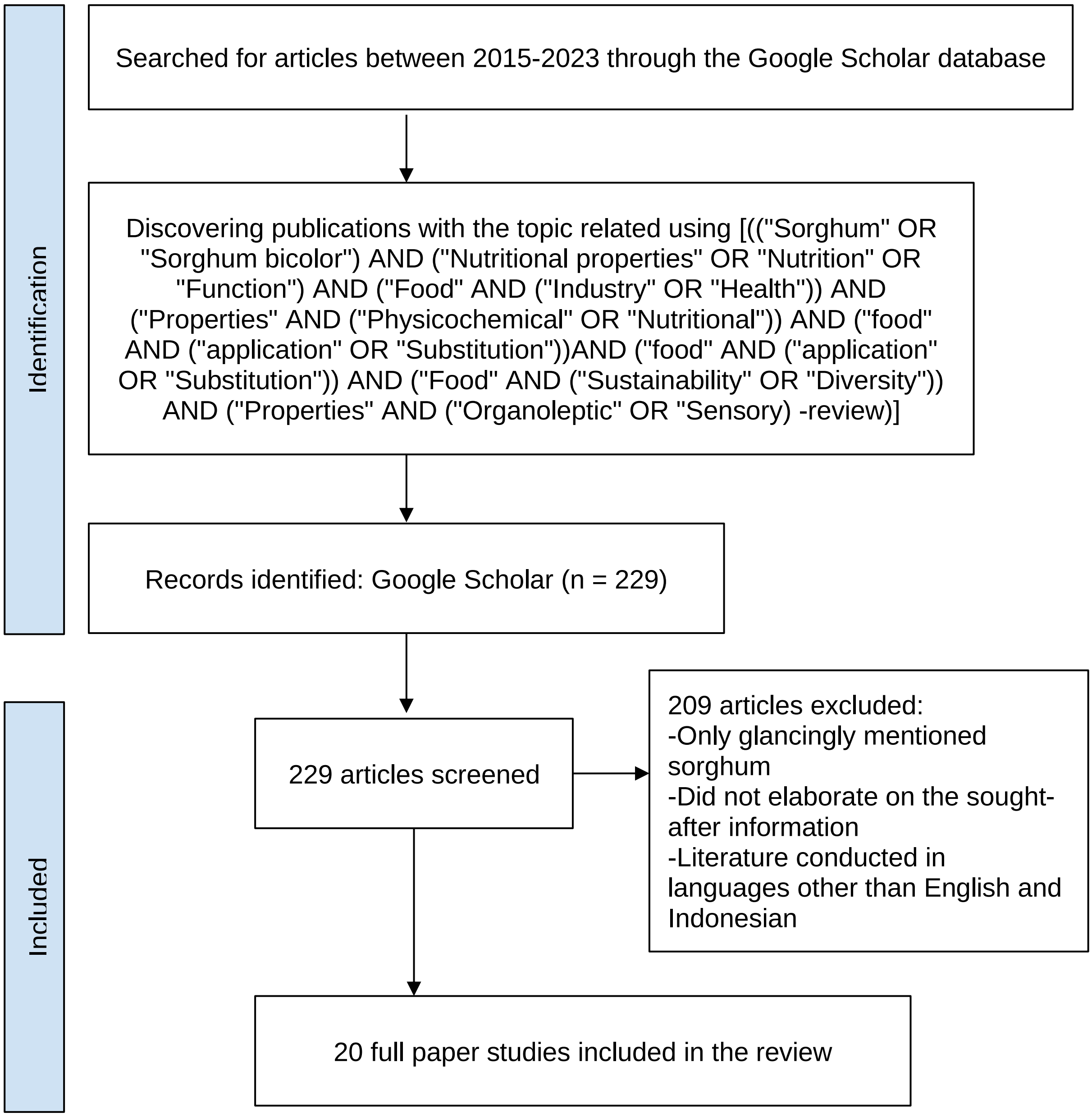

Figure 1. Study workflow

RESULTS

Table 1. Result summary of highlighted papers

Reference	Focus of Paper	Description of Paper
Mugalavai et al., 2020	Nutritional properties of sorghum composite flours	Mentioned variants of composite flours as a food fortification method. The composite flours were made of sorghum, maize, grain amaranth, baobab, and butternut, all at different variants. It was found that with the sorghum at a higher proportion, it would lead to a better potential to improve the nutritional status of consumers, especially their first and fourth formulations, which have 8.1% and 8.6% protein contents, respectively. The formulations were encouraged for children between the ages of 6 to 59 months.

Reference	**Focus of Paper**	**Description of Paper**
Ashraf et al., 2022	Composition and antioxidant quantification in multigrain food	The paper focused on an array of grains and quantified their composition regarding the composite flour made from chickpea, masoor, sorghum, legumes, and maize along with whole wheat. Total flavonoids and phenolic contents were also measured, with antioxidant activity checked using a DPPH assay. This research found that sorghum has the highest fat content among all samples (9.40 ± 0.30%). No antioxidant activity assessment was done on individual grains. However, utilizing a composite flour blend of grains and legumes produced high-potential antioxidant capabilities.
Haliza & Widowati, 2020	Sorghum application in food industry	This research highlighted one of the uses for sorghum in the food industry through instant porridge, while emphasizing the necessity of selecting a low tannin sorghum due to the bitter taste related to higher tannin content. With multiple ratios of sorghum flour to tapioca to the ratio of water, the optimum ratio of 80:20 sorghum:tapioca flour, with a 1:11 water ratio; the values of 4.93% water content, 5.92% fat, 0.49% ash, 8.37% protein, and 85.2% carbohydrate; an average of acceptability at 4 from a scale of 1 to 5, with 1 being extreme dislike, and 5 being extreme like.
Tadesse et al., 2019	Sorghum application in food industry	Conducted application of sorghum into the food industry through an extrusion process with different parameters, which are defatted soy meal flour concentration supplementation, barrel temperature, and feed moisture. It was found that barrel temperature had a significant impact on the reduction of tannin and phytic acid content. The addition of defatted soy resulted in a significant increase in crude protein, fat, moisture, ash, fiber, Ca, and Fe content. However, carbohydrate content was reduced. The likability and acceptability were based on a 7-point hedonic scale and resulted in the highest of 5.76 average for color, flavor, and overall acceptability from all formulations.
Banwo et al., 2021	Antioxidant capacity of sorghum	Utilized lactic acid bacteria in the fermentation of millets and sorghum to increase the nutritional properties, which increased the total phenolic and flavonoid content where the antioxidant capability from DPPH assay was found to be 60.3%.
Prabhakar & More, 2017	Physicochemical and sensorial properties of sorghum	This research evaluated the effect of adding different proportions of finger millet on the chemical, sensory, and microbial properties of sorghum papad. It was discovered that sorghum-finger millet papad formulated with 40% finger millet flour had shown good acceptability with changes in the sensory and microbial properties.
Shalaby et al., 2018	Sorghum as complementary food	Development of cereal and legumes-based supplementary food for young children and estimation of chemical composition, physical properties, and sensory assessment of complementary foods made from five distinct formulas were done in this research. It was discovered that formula with 20g of wheat flour, 20g of rice powder, 40g of defatted soybean flour, 10g of carrot powder, and 10g of skim milk powder was recommended due to their higher protein and micronutrient contents than the remaining formula.
Yi et al., 2022	Industry application and physicochemical	This paper focused on the composition of whole grains and described how the process of extrusion can affect their

Reference	Focus of Paper	Description of Paper
	properties of sorghum	physicochemical properties. In this paper, it was discovered that extrusion can effectively improve the functional properties of whole grains, and consuming extruded whole grains can decrease the risk of chronic disease.
Patekar et al., 2017	Physicochemical and mineral content of sorghum	The research focused on the various kinds of sorghum genotypes and how the mineral contents along with the physicochemical properties might be different among them. It was discovered that micronutrients such as magnesium, iron, and proteins vary in the different sorghum genotypes.
Alavi et al., 2019	Sorghum application	This paper focused on two applications of sorghum in extruded foods and describes the pilot-scale twin screw extrusion study on the evaluation and processing of sorghum-based pre-cooked pasta in the fusion of rice. In addition, sorghum-rice pasta showed a better cooking quality than its semolina counterpart with lower cooking loss (3.2-4.0%) and higher water uptake (115.4%).
Sharma et al., 2016	Sorghum growing and post-harvest treatment	Recent trends in the field of post-harvest management of agricultural commodities, specifically perishables, were discussed in this paper. Different sections including post-harvest losses, physiology, handling, as well as packaging, processing, and quality addition were presented.
Mohammed et al., 2016	Sorghum application	The paper focused on using sorghum flour and its derivatives (such as those combined with sorghum barley) as a way to produce weaning food. From the research, the product shows potential to be developed for weaning food, as it exhibited low final viscosity along with other characteristics such as low pasting temperature.
Neto et al., 2017	Sorghum growth properties	The focus was on the difference in sorghum cultivars with different purposes' impact on the nutritional properties of the plant. Based on this, it was discovered which strains had the preferred and better nutritional composition.
Kim et al., 2018	Sorghum physicochemical properties	Based on the different types of sorghum the study utilized, significant amounts of flavonoid and polyphenol content were different along with their antioxidant capacity due to differences in harvesting time.
Kiprotich et al., 2015	Sorghum growing and nutritional properties	In this research, it was discovered that sorghum varieties are capable of being used in different industries and can be a good alternative to other varieties. Moreover, a significant correlation between yielding ability and plant height was found with hybrids, which tend to give lower amounts of tannins, thereby affecting the starch amount and decreasing the suitability of sorghum for industrial and domestic use in the long term.

DISCUSSIONS

Varieties of sorghum

Sorghum is an annual grass with strong aerial roots passing through the soil and has a hard, smooth stem along with parallel venation leaves that are both often covered with a wax layer (Kumar, 2016). Sorghum's varieties itself can be classified into 5 basic races: *bicolor* (B), *guinea* (G), *caudatum* (C), *kafir* (K), and *durra* (D). The basic races can then be cross-bred, producing intermediate races. Furthermore, through genotyping of the plant, many specific variants have been discovered present within the basic races and their cross-breed results (Ruperao et al., 2023). Even so, these different races are pragmatically classified based on the morphological features of the panicle and grain. For instance, bicolor has persistent spikelets and grain elongation, while kafir has roughly symmetrical grain, as seen in Fig 2.

Currently, twenty-two sorghum genus have been cultivated, with *Sorghum bicolor L. Moench* contributing the most to the extensive diversity of the cultivated varieties due to the wide range of ecological habitats, soils, vegetation, farming systems, and socioeconomic conditions in the regions where this particular species is cultivated, specifically in the northeast quadrant of Africa, while the other species or subspecies are generally wild or weedy (Ndlovu et al., 2021; Venkateswaran et al., 2019). It is a vital crop species around the world, as it is able to be grown in semi-arid, subtropical, and tropical regions due to its heat and drought tolerance. Sorghum is very responsive towards favorable conditions in terms of productivity (Rooney, 2016). *Sorghum bicolor*'s variation comprises a mixture of types, ranging from those with low sugar stalk (grain types) to high sugar stalk, which comprises 10-25% sugar in their stalk juice, both at the grain's maturity stage (Regassa & Wortmann, 2014).

Sorghum plantation and consumption worldwide

Sorghum is a staple food crop consumed mostly in African, American, and Asian subcontinents, having high yield potential compared to other crops like rice, wheat, and maize (Ratnavathi & Pathil, 2014). Sorghum has an average worldwide production of 59.46 million metric tons from 2016 to 2020, with an increasing trend each year (FAOSTAT, 2022). Furthermore, as Indonesia plans to expand its cultivation, the production is estimated to keep increasing (Syuryawati et al., 2021). The assessment conducted by Khalifa & Eltahir (2023) shows that the sustainability of sorghum cultivation experienced a decrease in trend from 1961-2020 in two major sorghum-producing countries: Sudan and India (FAO, 2022). Moreover, in comparison to other crops, sorghum has a lower global average yield in terms of tonnes per area in hectare and also is slower with respect to its genetic yield grain (Pfeiffer et al., 2019).

Among the regions that employ sorghum plantation, Africa has the highest production rate, with 143.87 million metric tons produced from this region, encompassing 48.4% of the world’s sorghum production. Nigeria is the main sorghum producer in Africa, followed by Ethiopia, Sudan, and Niger; producing 34.32, 25.27, 22.31, and 9.88 millions metric tons within the range of five years, respectively (2016-2020). During the same period of time, 40.43 million metric tons of sorghum were produced in Asia. However, about 36% (14.48 million metric tons) of it was produced solely in China. Meanwhile, the production of sorghum in Indonesia was about 20,000-30,000 metric tons, despite the plantation being done in various regions, such as Java, South and Southeast Sulawesi, along with East and West Nusa Tenggara (Wiloso et al., 2020). Therefore, as a way to increase the production of sorghum in Indonesia, the government urges to expand the plantation area as well as promote sorghum to gain the general population’s interest. The results of this endeavor could be seen through the production of sorghum having reached around 15 thousand tons that was harvested from four thousand hectares of six different provinces as of June 2022 (Pujiharti et al., 2022).

The production of sorghum globally has not reached the yield potential, which shows that sorghum is not well-developed, although some regions have started cultivating sorghum (Central Bureau of Statistics, 2022; Mundia et al., 2019). This is due to the traditional reputation of coarse grain being primarily used as animal feed and labeled as ‘the poor man’s food’ for the people of lower than middle class status (Rao et al., 2017). In Indonesia, sorghum has been introduced and known for a long time. However, the development is not as advanced as wheat and corn due to the limitation that only several small regions utilize sorghum as a crop (Syafruddin et al., 2017). This plant has quite a huge potential to be developed; but in reality, it has not been optimum enough and generally not as famous as other crops amongst the public because of the peeling process that is still difficult to be done (Yusriani et al., 2024).

The statistical results are affected because of the challenges in sorghum development, and one of the factors is due to the seedlings aspect. Seed quality is the main requirement needed to increase the productivity of sorghum development, where according to Subagio & Suryawati (2013), the availability of sorghum seed in terms of quantity and quality for farm level has not been fulfilled yet. Three main aspects that need to be considered for the quality of seeds are the seed production techniques, techniques to maintain the quality of the distributed seeds, and the seed quality detection technique. Therefore, the usage of superior-quality seed varieties contributes significantly to the phenotypic appearance and the yield components of the plants (Pabendon, 2018). Research conducted by Mukkun et al. (2018) reports that farmers in East Nusa Tenggara area have not been able to produce superior varieties of seeds. This is due to the unavailable storage facilities, which reduces the selling price for farmers as they would be selling uncertain seeds that would affect the success of sorghum seed provision.

Based on a report by Mashao and Prinsloo (n.d.), there are several requirements for the cultivation of sorghum in order to achieve its maximum yield, one of which is well-drained soil. This is due to sorghum growing optimally in the soil at a pH of between 5.5 to 8.5 and a clay percentage of between 10 to 30%. However, with regards to the climatic requirements, it is divided into three categories: Temperature, number of days, and the amount of water needed. Considering the fact that sorghum is a warm-weather crop, it requires high temperatures to boost its germination and growth. The germination would require a minimum temperature of between 7 to 10°C, while it would increase up to 15°C after the seed has germinated for about 80% within 10 to 12 days. The growth and development after the germination process has an optimal temperature of 27 to 30°C with a fairly stable rainfall pattern. Furthermore, sorghum is a short-day plant, which has a longer night period with the optimum photoperiod between 10-11 hours, and an estimated frost-free period of 120-140 days. Lastly, with regards to water requirements, sorghum has a relatively high tolerance to drought in comparison to other grain crops due to its branched root system and small leaf area. Thus, the production potential of sorghum does depend on many factors, which are the factors that have been previously mentioned and also include external factors such as planting density, fertilization process, cultivar or species choice, and even weed and pest control considerations. Hence, the other reason for the drawback of sorghum development is due to the pre and post-harvest treatment, where the problems faced are the land management, post-harvesting handling, as well as processing. For example, in East Nusa Tenggara, it is difficult to plant sorghum there due to the rocky and uneven land to prepare for cultivation (Winarti et al., 2020). Whereas the postharvest handling is correlated to the structure of the sorghum seed that has a hard shell, needing special treatment to process so that it could become rice sorghum to accelerate the process, it is done by using an agriculture device, especially a thresher and a moxerizer (an agricultural device that accelerates the process of special treatment to convert sorghum into rice sorghum). Furthermore, sorghum seeds have short shelf-lives due to their susceptibility to flea attacks. In accordance with Gourgouta et al. (2021), *Sitophilus spp.* is the flea that experiences the most rapid growth on the sorghum seed during storage, which is followed by *Tribolium castaneum* as the secondary pest.

In the field, farmers still need more assistance and information for the cultivation of sorghum techniques, such as irrigation systems, the addition of fertilizer, along with pest and disease control, making the sorghum management a challenge as well. Hence, the collaboration must be conducted by stakeholders with different sectors such as agriculture, husbandry, industry, and electricity or energy institutions (Lestari et al., 2019). The preferable traits of sorghum varieties would be good taste, high yield, resistance to bird damage, insect pests and diseases, early maturity, as well as drought tolerance to increase production and reduce losses during pre- and post-harvest (Mofokeng et al., 2016). In addition to that, other barriers to the cultivation of sorghum in Indonesia after the management are the processing machinery, the technical guidance on how to incorporate sorghum into a variety of products, and the marketing strategy itself. These obstacles mentioned should be overcome with the help and collaboration between researchers, local governments, private sectors, and regulation of sorghum development that aims to achieve national food security and public health (Widowati & Luna, 2022).

Physicochemical and nutritional properties of sorghum

Sorghum is rich in nutrients and contains a variety of both macro and micronutrients that carry benefits for our body. Sorghum especially highlights its protein and fiber content. However, it has a diverse nutritional content. **Table 2** below presents the complete nutritional content of sorghum.

Table 2. Nutrients found in 100 grams of Sorghum, Retrieved from FoodData Central (2019).

Name	Amount	Unit
Energy	329	kcal
Protein	10.6	g
Total Lipid (fat)	3.46	g
Carbohydrate, by difference	72.1	g
Fiber, total dietary	6.7	g
Sugars, total including NutritionLabeling and Education Act of 1990	2.53	g
Calcium, Ca	13	mg
Iron, Fe	4.5	mg
Magnesium, Mg	165	mg
Phosphorus, P	289	mg
Potassium, K	363	mg
Sodium, Na	2	mg
Zinc, Zn	1.67	mg
Manganese, Mn	1.6	mg
Selenium, Se	12.2	µg
Thiamin	0.332	mg
Niacin	3.69	mg
Pantothenic acid	0.367	mg

Aside from the nutritional value, sorghum also has low glycemic index (GI) and is gluten-free, which is beneficial for those with dietary limitations (Pontieri et al., 2013; Prasad et al., 2014). Glycemic index of sorghum was reported as low (<55). The low GI properties of sorghum allows the slow increment of blood glucose following its consumption, hence maintaining the blood glucose better compared to high GI foods, such as white rice (Lal et al., 2021; Prasad et al., 2014). The Indonesian government has also shown their interest in promoting sorghum as a staple food in the diets of the wider population (Indonesian Agency for

Agricultural Research and Development, 2022). The article supports this decision with different claims regarding the nutritional value of sorghum, such as its protein content and micronutrient content.

Sorghum generally contains high amounts of protein in comparison to other grains such as rice, which has been a staple food in much of the Indonesian population (Bantacut, 2014). Different studies have shown a wide range of protein content when it comes to rice, some having shown values as low as about 6.7% while others having noted higher amounts of up to 16% (Hoogenkamp et al., 2017; Mota et al., 2016). However, it must be noted that much of the protein content of rice is found in the bran, which is often removed in order to obtain white rice grains. Similarly, the protein content of sorghum can also range widely depending on the type, variety, presence of water stress, and other factors during its growth and development (Queiroz et al., 2015). The protein content of different sorghum genotype varieties can range from between 7.8% to 19%, with a mean of 13.4% for the Durra variety, which has the highest protein content (Queiroz et al., 2015; Rhodes et al., 2017).

Calculations on the digestible indispensable amino acid score (DIAAS) of sorghum has also been done by de Vries - Ten Have et al. (2020), and results show that the largest DIAAS scores were found in the aromatic amino acids and leucine where it is, on average, larger than 1. The large DIAAS score indicates that the requirements of both aromatic amino acids and leucine per day will be met if sorghum is consumed (Bailey & Stein, 2019). Even so, the digestibility of lysine and sulfur amino acids are the lowest among the other amino acids found, such as histidine, leucine, valine, and aromatic amino acids. To compensate for this, sorghum can be cooked with 2-mercaptoethanol (ME) or reducing agents, including sodium metabisulphite and glutathione, as they can prevent the formation of protein polymers, hence improving the protein digestibility (Zarei et al., 2022). As for home cooking applications, soaking, boiling, or fermenting sorghum could be done to increase its protein digestibility. Soaking could be done overnight or until 20 hours. For boiling, it is recommended to have a water-to-sorghum ratio of 3:1, and let it simmer for approximately half an hour. Meanwhile, the fermentation of sorghum could be done with the inoculation of lactic acid bacteria (Bora et al., 2019; Puntigam et al., 2021). These processes remove the antinutritional factors present in the grain and promote protein denaturation to be more accessible to the body (Gunawan et al., 2022).

Another one of the biggest selling points in its nutritional value is its high fiber content. Sources have stated that sorghum typically contains around 6.7% and can range between 6% and up to 8% dietary fiber content (USDA, 2019; Widowati & Luna, 2022). In comparison, milled rice typically has a fiber content of around 0.2-0.5% (Liu et al., 2022). This fiber content contributes to the low GI of sorghum (Afandi et al., 2021). This is very important when it is compared to other major carbohydrate sources such as rice, as the difference between the two is quite significant. When compared directly, data from the Glycemic Index database of the University of Sydney shows that the glycemic index of cooked white rice can range from 70 to 80, classifying it as a high GI food while cooked sorghum grains have a glycemic index that ranges between 62-64, which classifies it as a medium GI food (Prasad et al., 2014; The University of Sydney, n.d.). Other sources have also found that the glycemic index of sorghum can go as low as 32, and the result depends on the sorghum variety, processing methods, as well as differences in other nutritional contents that may affect glucose absorption, such as fat (Kim et al., 2019). The lower GI content allows sorghum to be more suitable for diabetics who have impaired glucose tolerance (Zafar et al., 2019). This low score can be attributed to a variety of factors, including the higher amylopectin content compared to amylose and the presence of fat as well as fiber (Giuntini et al., 2022).

On top of the beneficial macromolecules, sorghum also contains a wide variety of micronutrients such as phosphorus (289 mg/100 g), zinc (1.67 mg/100 g), calcium (13 mg/100 g), magnesium (165 mg/100 g), potassium (363 mg/100 g), vitamin B-6 (0.443 mg/100 g), vitamin E (0.5 mg/100 g), and especially iron (4.5 mg/100 g) (Akin et al., 2022; Serna-Saldivar & Espinosa-Ramirez, 2019; USDA, 2019). The Indonesian

Agricultural Research and Development Agency has stated that one of their main nutritional reasons for pushing sorghum over other grains is for its high iron content of 3-4.5 mg/100 g (Gaddameedi et al., 2022; Indonesian Agency for Agricultural Research and Development, 2022). When compared to rice, which only has 0.2 mg/100 g, the amount of iron in sorghum is a big leap in a to combat the prevalent issue of iron deficiency and stunting (Boonyaves et al., 2017; Laksono et al., 2022; Manikam, 2021; Sari et al., 2019). Biofortification is also possible in sorghum, and research by Gaddameedi et al. (2022) and Debelo et al. (2020) have shown that the iron content of sorghum can be increased up to 6 mg/100g.

Certain bioactive compounds are also present within sorghum, several of which are beneficial to the human body. Polyphenolic compounds and policosanols in sorghum have been found to benefit the gut microbiota as well as several parameters that were associated with obesity, inflammation, diabetes, and hypertension (de Morais Cardoso et al., 2015; Espitia-Hernández et al., 2017). The polyphenolic compounds of note are primarily phenolic acids and 3-deoxyanthocyanins, which have shown desirable effects against the previously mentioned diseases in *in vitro* studies. The study has shown that the phenolic compounds in particular have shown antidiabetic effects when fed to diabetic rats (Ofosu et al., 2020). However, one of the phenolic compounds, tannins, has both a positive and negative effect on the body when consumed. Tannins have been shown to reduce body weight in animals, and researchers suggest that this reduction in body weight can happen in humans where it would be beneficial to those with obesity (Manzoor et al., 2021). The same compound has also been shown to increase the growth of healthy gut bacteria and inhibit the growth of pathogenic bacteria (Ritchie et al., 2015). The downside to tannins is that they reduce the bioavailability of non-heme iron through the chelation of the iron-forming complexes (Delimont et al., 2017; Kapil, 2017).

Other antinutrients present in sorghum include phytic acid, cyanogenic glucosides, trypsin inhibitors oxalates, etc. (Gunawan et al., 2022). Cyanogenic glucosides mainly function as a defense towards herbivores, as they are the bioactive substances that can release harmful hydrogen cyanide (Rosati et al., 2019). While phytic acid is primarily made of phytin and functions to decrease mineral availability or absorption by binding to calcium, magnesium, and iron due to their strong affinities with the minerals (Astley & Finglas, 2016). Similar to phytic acid, oxalates can prevent the absorption of calcium by forming calcium oxalate crystals when bound to the dietary calcium (Serna-Saldivar & Espinosa-Ramírez, 2019).

Different studies have looked into the different treatments and processing methods and the effect they have on the antinutritional factors. Ayuba et al. (2020) conducted a study that looked at the effect of soaking and dehulling, from which the results were a significant reduction in tannin and phytates. Premilling, which includes washing, soaking, and malting, has also been shown to reduce the amount of tannin, phytate, and oxalate (Keyata et al., 2021). Mohapatra et al. (2019) have also shown that cooking, fermentation, steaming, and flaking can decrease the tannin content significantly by 17%, 30%, 35% and 39%, respectively. Other than the mentioned methods, there are also several other traditional processing procedures, including grinding, roasting, and germination, used to lower the amount of antinutrients contained in sorghum. In addition, combining a variety of processes such as submersion in NaOH solution followed by fermentation have been proven to reduce the antinutrients content in sorghum (Gunawan et al., 2022)

Utilization of sorghum in food product

Sorghum plants can be used in various ways, with grain used for human sustenance, including rice, bread, porridge, cakes, and noodles. At the same time, the stem of sorghum is used in monosodium glutamate (MSG) and sugar production as a sugarcane substitute. Moreover, the stem and foliage of sorghum can also be used to produce bioenergy and biomaterials, such as particle board and brooms, as well as animal feed and pasture (Lestari et al., 2019; Prasad & Mishra, 2023). Due to its multidisciplinary applications, the value of sorghum for commercial purposes, such as food product formulations, is currently at its highest point

(Duff et al., 2019). The importance of sorghum as a commercial crop in recent years has allowed the development of several value-added sorghum-based food products. For example, sorghum-based popcorn is now sold as a snack in parts of India and Africa (Yenagi et al., 2004). In addition to popcorn, several other sorghum-based food products are gaining popularity, such as rice substitutes, gluten-free flour, syrup, sweet soy sauce, and milk (McGinnis & Painter, 2020; Noerhartati et al., 2020; Thilakarathna et al., 2022; Yuwono et al., 2020).

Rice and grain substitute

Sorghum has been consumed in various forms around the world, e.g. baked bread, porridge, tortillas, couscous, gruel, steam-cooked products, alcoholic and non-alcoholic beverages, and specifically to those who are wheat intolerant (Batey, 2017; Fitrahtunnisa et al., 2020). Other than to replace rice, sorghum could also be utilized as a substitute for whole grain breakfasts such as cereals in several other countries. The expanded extruded products such as snacks and breakfast cereals are very popular due to their crispness, ease of use, and consumption. In several developing countries such as the United States and Brazil, these are made with corn, rice, or wheat as their raw material.

Sorghum has a lower cost and is easier to use than maize. However, the utilization for this purpose has not been done until recently (Queiroz et al., 2014). A study conducted by Anunciação et al. (2017) evaluated the comparison of sorghum and wheat whole grain breakfasts to observe the sensorial acceptance as well as its bioactive component. The sorghum grains (genotype SC319) were first grown and then harvested before being milled into flour using a disc mill. While milling, the flour mixture was added with 10% sucrose, fine granulated sugar, and 0.5% of iodized salt (NaCl), and subsequently processed in a co-rotating intermeshing twin-screw extruder. The machinery was set at a constant screw speed and temperature profile ranging from 30-140°C from feeding to the outlet (Vargas-Solórzano et al., 2014). Afterwards, the formulation was placed in the feeding zone by a twin-screw, loss-in-weight gravimetric feeder, and monitored by the Schenck Process EasyServe software. Distilled water was inserted through a port measuring 5.25 mm in internal diameter between the first and second feeding zones from the start of the barrel using a plunger metering pump, to compensate for the moisture difference in samples and provide the final moisture content of 12%. The samples were obtained over 15-20 mins and grounded into particles 212 µm small. The whole-grain wheat breakfast was done with a similar procedure to the sorghum one. The whole-grain sorghum and whole-grain wheat breakfast cereals were stored in polyethylene bags at 10 ± 2°C until the day of the analysis. The result shows that the sensorial acceptance of whole-grain sorghum breakfast cereal was higher than the whole-grain wheat cereal at $p < 0.05$, where only the sorghum breakfast cereal was considered acceptable due to the presenting index of acceptance being greater than 70% (Anunciação et al., 2017). Hence, sorghum has the sensory potential to replace traditional cereals and is an excellent option for the food industry (Pujiharti et al., 2022). Sorghums are classified according to their usage, which in this case, the grain sorghums of the *Caffrotum* group were cultivated mainly for their grains. It is similarly done to the cultivation of corn or maize, which are used to make human food and beverages as well as animal feeding (Zarei et al., 2022). The main carbohydrate of sorghum is starch, which could be found as granules in the endosperm (Khalid et al., 2022).

A study conducted by Faturochman et al. (2022) displays the methods of producing instant analog rice using a combination of sorghum flour and moringa flour modified from the step conducted by Kurniasari et al. (2020). Firstly, the mixed flour of pregelatinized sorghum flour and moringa leaf flour is gradually added with water until approximately 100-150% of the total mixture. Then, it is kneaded until the dough is smooth and ready to be shaped. The shaping process helps with the cylindrical pasta-shaped mold, where the dough of size ± 5 mm was shaped similarly to the rice. The drying process involves the usage of a food dehydrator at a temperature of 60°C for 2.5 hours. The dried results are left to cool to room temperature, upon which the instant analog rice produced could be packed.

Another study conducted by Widowati & Luna (2022) introduces the innovative product of sorghum rice to address rural communities in dry climate areas having to make sorghum in the steamed form, which is processed traditionally before consumption (Widowati, 2016). Sorghum grains have a harder texture than rice, corn, and wheat: Thus, the cooking process takes longer time, with sources suggesting up to 60 minutes of cooking time compared to rice, which usually only takes 15-20 minutes (Paoletti et al., 2022). However, society today prefers a more practical lifestyle. Hence, an instantly cooked sorghum is proposed, as it could be cooked and served in a short amount of time, where the preparation for this goes through several stages, namely cooking, freezing, and drying (Akhila et al., 2017). This instant product is very practical and does not require much time after going through both physical and chemical treatments, which improves the hydration of the product (Luna et al., 2015; Sasmitaloka et al., 2019). The process was firstly done by polishing the sorghum grains 95-100%, which was then soaked in the salt solution for 2 hours. The soaked sorghum was washed afterwards to remove the remaining salt and drained to be cooked using an electric cooker with a ratio of 1:3 with water. Instantly cooked sorghum is ready to be consumed after being rehydrated with hot water for 5 minutes.

The same author also proposed another product, which is sorghum fermented products such as sorghum *tape*. The product was initially made from glutinous rice, but instead replaced with glutinous sorghum that has been polished 95-100% and soaked overnight. Then, it is drained and steamed until fully cooked, before being thawed until it is cold enough. It was then inoculated with 0.3% yeast and allowed to ferment for 2-3 days before being ready for consumption. Fermentation itself leads to the modification of sorghum substrate and the production of metabolites that will further affect the taste, appearance, texture, color, shelf-life, and nutritional properties of the derived product (Adebo, 2020).

Gluten-free flour

Another derivative product of sorghum is sorghum flour, which has a high marketability due to its nature of being a gluten-free grain (Dube et al., 2020). In particular, the rising demand comes from people who opt for a gluten-free diet, especially those who suffer from celiac disease, or also known as gluten intolerance (Adebowale et al., 2020; Atteno et al., 2014). Thus, sorghum has been an appealing alternative for wheat in food production (Gerken et al., 2023).

Generally, sorghum undergoes milling to obtain sorghum flour. Recent development utilizes small roller mills in sorghum flour production due to its efficiency and high yield as compared to the traditional milling technique (Dahir et al., 2015). Flour itself is a versatile ingredient that has been used to make various products. Specifically for sorghum flour, its applications in food products include breads, cakes, and pasta (Adiamo et al., 2017). However, it was found that in such products, the absence of gluten leads to undesired properties in the end product, specifically in their texture, crumbliness, and taste. This is due to gluten being the main factor of the visco-elastic properties of the product (Padalino et al., 2016). Moreover, many aspects play a role in the end product, such as the processing type for sorghum flour production, as well as the addition or substitution of ingredients in the manufacturing process of a product.

In regards to gluten-free bread making, the processing type of the sorghum grain to produce the flour is crucial for the end-product's properties. Trappey et al. (2014) carried out research to observe the effect of different sorghum flour extrusion rates and particle sizes on the quality of gluten-free sorghum bread. Results showed that sorghum bread with lower extraction rate—having lower fiber and higher starch content—as well as smaller particle size resulted in products with preferable characteristics, including higher loaf volume, softer bread crumbs, as well as improved texture and appearance.

Another crucial limitation is the lack of gas-holding ability during the fermentation or proofing process, making the bread dense, with little to no expansion (Elgeti et al., 2014). Therefore, additions of other components are needed to improve the characteristics that lead to the acceptability of the bread. Additives such as hydrocolloids are often used to enhance the visco-elastic properties, similar to gluten (Aleksandrova et al., 2021). Research done by Akin & Miller (2017) observed the interaction between different compositions of hydrocolloids and starch with sorghum flour in the production of gluten-free sorghum bread. It was found that a 90:10 ratio of sorghum flour with rice, tapioca, or potato starch produced satisfactory results. Furthermore, hydrocolloids could also be employed in addition to the previous formulation, with 3% and 4% xanthan gum, along with 3% hydroxypropyl methylcellulose added to the sorghum flour combined with rice starch, potato starch, and tapioca starch. The breadmaking itself involved 70% sorghum flour and 30% unmodified potato starch. Furthermore, modified or gelatinized starches from gluten-free sources such as potato and corn are also utilized to improve the quality; especially the organoleptic properties of the bread (Cheng et al., 2022). Despite that, the ratio of the added ingredients to sorghum flour needs to be determined to produce the most preferred gluten-free bread. According to Adzqia et al. (2023), up to 50% substitution level of sorghum flour with tapioca, corn, potato, or rice starch is possible without affecting the loaf volume. According to Cheng et al. (2022), starch is used in gluten-free bread making, as its gelatinization process mimics the properties of gluten. Despite that, sorghum flour could also be employed to improve wheat-based breads. Dube et al. (2020) found that the substitution of 20-30% wheat flour to sorghum flour increased rheological qualities along with sensorial attributes, including texture, appearance, and taste. Hence, sorghum-wheat bread has a higher acceptability as compared to wheat bread alone.

Another product that greatly utilizes sorghum flour is pasta, in which 5 to 100% of sorghum could be used in the making of it (Palavecino et al., 2020). Pasta in general could be produced with the sheeting method, which compresses the dough between two rollers. However, it is not preferable to be used in the production of gluten-free pasta products due to the lack of elasticity and malleability (Pontieri & Del Giudice, 2016; Tao et al., 2021). Therefore, extrusion— specifically cold extrusion— is commonly used in gluten-free pasta manufacturing, including sorghum pasta (Palavecino et al., 2020). It works by passing the extrudate (dough) through a die with blades attached to it, forming pasta that is shaped according to the blades used (Bordoloi & Ganguly, 2014).

In order to overcome the acceptability problem of gluten-free pasta, during the production process of sorghum pasta, ingredients such as egg albumin, egg powder, xanthan gum, or pregelatinized corn starch could be incorporated (Palavecino et al., 2017). Pregelatinized corn starch functions to mimic the presence of gluten; xanthan gum is utilized to reduce cooking loss and enhance the overall cooking quality of pasta; while egg, or its albumin, could provide both benefits (Marti & Pagani, 2013; Paux & Rosentrater, 2018). However, there were other studies that formulated different compositions of sorghum flour with starches or other gluten-free flours — including maize, amaranth, rice, and/or potato— to achieve a sensorially and characteristically acceptable pasta (Fasuan et al., 2021; Ferreira et al., 2016; Paux & Rosentrater, 2018).

Sorghum pasta, with appropriate formulations, could have comparable or even better characteristics than wheat pasta. In addition to the end product being gluten-free, sorghum flour contributes to the high protein and dietary fiber content. Additionally, the polyphenols content enhances the antioxidant properties of the pasta (Palavecino et al., 2018). Alavi et al. (2019) also reported that sorghum-rice pasta has better cooking qualities than wheat pasta, with less cooking loss, higher water absorption, and firmer texture.

With the aforementioned findings, regardless of the food produced from sorghum flour, it is important to consider the properties of the sorghum grains itself, as well as the processing technique and parameters to produce the sorghum flour. Additionally, determination of additives, gums, starch, or other ingredients should be taken into account in order to obtain products with desired characteristics and high acceptability.

Popcorn

Sorghum *(Sorghum bicolor)* is the fifth most common and vital cereal produced globally. With its abundant nutrients, sorghum is selectively used to make popped sorghum or sorghum-based popcorn and is considered as a nutritious snack. Popcorn is a popular snack food made from whole grains and is enjoyed by many people worldwide (Arendt & Zannini, 2013). Generally, popcorn is made from a special type of corn, known as flinty or vitreous maize, which has a hard endosperm with tightly packed starch granules (Saldivar, 2016). Sorghum, similar to maize, also contains a hard, starchy endosperm, which makes it suitable for producing popcorn (Zheng et al., 2016). However, unlike normal regular popped corn, sorghum can produce a significantly small, spherical puffed kernel with a neutral flavor and minimal hulls (Kent & Rooney, 2021).

Sorghum-based popcorn, or popped sorghum, is made through a process called popping, in which the grains are exposed to high heat for a brief period (HTST). This process involves thoroughly cooking the grains and causing the starchy endosperm to expand in size due to the superheated steam produced inside the grain resulting from instant heating (Anjitha et al., 2021; Sharma et al., 2015). Like regular popcorn, popped sorghum is mainly measured by the expansion ratio (ER) and popping efficiency (PE). Expansion ratio (ER) refers to the comparison of volume between popped products and unpopped grains, while popping efficiency (PE) refers to the proportion of popped kernels after the popping process is complete. Grain size, amylose content, and pericarp thickness can affect the sorghum grain's expansion ratio and popping yield. Smaller grain size, higher amylose content, and medium pericarp thickness generally yield good expansion and popping yield. In addition, the moisture content and pre-treatments (e.g. oil and salt addition) also have a crucial role in the quality of popped grains and their characteristics (Mishra et al., 2015).

Syrup and sugar

Sorghum syrups are generally dark amber colored, sweet sticky syrup with a thick consistency. It can simply be used in a 1:1 ratio in baked goods, as a substitute for table sugars, without an unpleasant aftertaste. Sorghum syrups have been applied for generations to drizzle on biscuits, pancakes, waffles, or even toast. Sorghum syrup crystallizes at lower temperatures like honey and will liquify when gently heated (Ratnavathi & Chavan, 2016). The overall gist of the production is that the sorghum's juice is extracted from its stalk, then reduced to the desired consistency by boiling. Principally, good quality syrup is produced from sorghum genotypes with high reducing sugars percentage and a low sucrose percentage in their juice, whilst the production of sugar crystals requires the opposite composition (Abdalbagi & Mohammed, 2020).

Sweet sorghum is popular for food and fermentation because of the large amounts of sugar in its juice, which accounts for anywhere from 20% to 50% of the plant's total dry weight and ranges between 16 and 23°brix (Marwati et al., 2018). The use of sweet sorghum syrup is advantageous by being a low-cost and renewable biomaterial (Badgujar & Bhanage, 2018).

Prior to cutting, the sorghum leaves are initially removed from the stalk once mature, which has been believed to increase the syrup yield as well as its flavor quality. The canes are then cut at ground level with a machete or a similar tool, and stacked in piles. Its seed heads are then harvested, with the best ripe seeds stored for planting, whilst the others stored as a nutritional animal feed. The canes are allowed to sit for at least four or five days to allow the amylase time to work — sitting for up to two weeks. Much of this process is influenced by the weather. The cane is then fed into a sorghum mill or press, where it is crushed (Rao et al., 2016). The light green colored juice is then collected in buckets. The spent cane (also known as pumee) is fed to livestock. The tray for boiling down the syrup is crude and is intended to be heated over a wood fire, as evidenced by the stone chimney. The tray is first filled with water, which is then brought to a boiling point before the cane juice is poured into it. The tray has little channels and is slightly inclined uphill, and the juice is cooked to make sweet syrup (Khalil, 2018). The syrup is pushed uphill with flat tools, and the water evaporates before the syrup is skimmed. Finally, the sticky syrup is poured or ladled into jars from large containers (Ratnavathi & Chavan, 2016).

Willis et al. (2013) had previously examined the colors as well as the physicochemical properties of sorghum syrups. It was evident that the a* (green–red spectrum) and b* (the blue–yellow spectrum) values approached zero, indicative of the dark brown coloration of the syrup. This may have been due to the Maillard reaction during heating treatment as well as from caramelization (Mao et al., 2015). The density varies between 1.30-1.41 due to the effects of carbohydrate concentration in solution, whereby higher sugars concentrations result in higher density (Andrzejewski et al., 2013). Moreover, the syrups had a viscosity of around 3000-4500cP, as solid contents varied and the juice extracted from the stalks have different qualities. The sorghum syrup produced total solid ranging around 70-76°Brix. This amount is relatively similar compared to regular sugar cane syrup with a total solid of 78.7°Brix (Andrzejewski et al., 2013; Belé et al., 2019).

Sorghum can also be used to produce sorghum sugar. In the production of crystalline sorghum sugar, the sorghum stalk juice containing compounds and impurities must first be eliminated. On average, sweet sorghum consists of 85% sucrose, 9% glucose and 6% fructose—but only sucrose may be readily converted to white sugar (Appiah-Nkansah et al., 2019). The addition of lime milk (liming) is the first stage in juice purification, followed by saturation with carbonation gas (primarily carbon dioxide) to precipitate the lime milk in a clarifier and capture the impurities in the raw juice (Hryhorenko et al., 2021). The clarifier's settled solids (mostly calcium carbonate and non-sugars) are filtered in membrane presses and sent to the spent lime storage area, while the clear portion is saturated again in a second carbonation station. Thin resulting juice is the purified juice obtained after subsequent filtration, which is thickened in a multi-effect evaporator into thick juice (Alves et al., 2014). The energy for evaporation is provided by high-pressure steam produced in the boiler house, and the condensed steam is returned to the boiler house. The thin juice, which has been diluted with water during extraction and purification, enters the evaporating station with an average sugar content of 15%, whereas the thick juice leaving the evaporator has an approximate sugar content of 70% (Muktham et al., 2016).

White sugar in crystalline form is eventually obtained from the thick juice through crystallization in vacuum pans at low temperature and pressure. In centrifuges, the mixture of crystals (only sucrose) and mother liquor (green syrup) is separated, wherein the sugar is washed with hot water (Damasceno et al., 2013). After cooling, the wet sugar is dried in a drum drier, screened, and stored in silos, while the syrup from the centrifuges is passed through an additional boiling stage to extract the majority of the remaining sugar. Molasses is the name given to the leftover syrup (Muktham et al., 2016). Despite the fact that molasses contain approximately 50% sugar, the concentration of non-sugar is extremely high—the sugar yield per tonne of sweet juice processed is 109 kg (Erdurmus et al., 2018).

Both sorghum sugar and sorghum syrup benefit from its high macronutrients content. In a study by Eggleston et al. (2022), the protein content of sweet sorghum syrups ranged from 0.9 to 4.0%, and the mean value (1.80%) was proven to be two-fold higher in comparison to the other syrups of corn, honey, agave, maple, cane, and rice (0.96%). Sorghum syrup was also significantly higher in its mean magnesium content (120 mg) than the other syrups (5 mg), crucial to oppose oxidative stress, reducing inflammation and consequently muscle damage (Eggleston et al., 2022). Potassium contents of sorghum syrups were also found to be higher, up to 1710 mg. Potassium is essential for rehydration and preventing muscle cramps, also having been associated with low blood pressure (Pelofske, 2017). In contrast to other syrups, sorghum syrup has also been proven to be a viable iron source, with a mean of 17 mg, while other syrups contained only negligible amounts (<0.5 mg). The amount of sodium in sorghum syrups were considered negligible, of approximately 1–22 mg in consideration of the recommended daily allowance (RDA) for sodium in a 19–50 year adult, which is 1500 mg (Bossola et al., 2020).

Sweet soy sauce (kecap manis)

Sweet soy sauce, known as *kecap manis* locally, is a condiment originating from Indonesia that has been around for thousands of years (Meutia, 2015). The product is made by fermenting black beans that have been washed and inoculated, then filtering the product before and after adding extra seasonings to obtain the final product. Besides black beans, others have also found ways to make *kecap manis* using alternative ingredients, such as jackfruit seeds and especially sorghum (Farida, 2021; Putri et al., 2019). 72% of the composition of sorghum is carbohydrates, allowing it to be utilized as a raw ingredient in the making of other products that require much sugar, such as in the making of beer, starches, syrup, and also *kecap manis* (Abah et al., 2020; USDA, 2019; Yuwono et al., 2020). According to Farida (2021), who produced sorghum soy sauce with different amounts of yeast concentration and fermentation time, sample with 0.1% yeast and 4 weeks fermentation time received the highest overall liking through the hedonic sensory analysis, with color, taste, and viscosity being highlighted in particular. In regards to the processing method, they are similar to the traditional processing steps, with the biochemical processes undergone during fermentation as the main contributor to the organoleptic properties of the soy sauce.

Plant-Based Milk

Plant-based milks can be made out of a variety of nuts, grains, and legumes such as soy, cashew, almonds, oats, and quinoa (Sethi et al., 2016). A suggestion to improve some of the existing plant-based milk in the market is through the addition of sorghum into the formula, with a ratio of 20% sorghum being preferable, as it provides a strong antioxidant effect along with possibly improving organoleptic properties and increasing the fat and protein contents (Fadly et al., 2021). Furthermore, the addition of sorghum adds phenolic compounds and policosanols, which act as antioxidants in the body (de Morais Cardoso et al., 2015). Studies done have studied the possibility of mixing sorghum in the form of paste in order to achieve the nutritional benefits without affecting much of the sensorial properties (Fadly et al., 2021).

CONCLUSION

Sorghum bicolor has been shown to have low productivity in Indonesia, despite having beneficial properties such as being rich in both micro and macronutrients. In particular, the high contents of proteins and fibers, along with being gluten-free and having a low glycemic index, are preferable to fulfill a more diverse consumer need. These properties contribute to health benefits upon consumption. As such, the Indonesian government is attempting to boost local sorghum production and consumption for food diversity and security. Sorghum itself could be derived into a multitude of products, such as syrup, sweet soy sauce, and plant-based milk, through the utilization of the different parts of the plant. For instance, the grains could act as a rice substitute and further be processed into gluten-free flour and popcorn, while sugar and syrup are derived from the stalk. Therefore, with the benefits of sorghum mentioned, along with the diverse utilization of the plant worldwide, the implementation of sorghum in Indonesia could be further optimized.

ACKNOWLEDGMENT

The authors would like to thank Dr. Siti Muslimatun as the Head of Department of Food Science and Nutrition.

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