Development of Sorghum-Based Food Products

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Due to the increasing interest in sorghum for human nutrition, recent literature reviews highlight its nutrient and bioactive contents, potential health benefits and its ‘gluten-free’ feature. Moreover, a current view of research advances on sorghum-based food products is needed to help both food scientists and industry identify current trends and forward-looking approaches. Studies on homemade processing are still scarce.

gluten-free Sorghum bicolor L. Moench whole grain

1. Introduction

Sorghum (*Sorghum bicolor* L. *Moench*) is the fifth most produced cereal and, in most countries, is mainly used as animal feed. However, due to the interesting nutritional content of this cereal, it can be successfully used to improve the nutritional content of starch-based products that are commonly developed with non-wholemeal flours like wheat, rice and corn [1][2].

The increase in whole grain consumption has been correlated to the decrease in the incidence of non-communicable chronic diseases, a fact that has increasingly aroused the interest of researchers in the study of cereals such as sorghum [3][4]. Studies indicate sorghum to diversify the diet and promote human health through its nutritional composition and potential as a functional food. Among the physiological effects already investigated, sorghum shows good antioxidant activity, lower glycemic response and greater benefits to the intestinal microbiota when compared to other cereal grains [5][6][7][8]. However, despite the human health benefits of sorghum consumption, its cultivation in some countries is still primarily intended for animal feed [9].

Over the last ten years, there has been growing interest among researchers in the health benefits of sorghum consumption [10][11][12] and the use of this grain to develop healthier food products [13][14][15]. Sorghum flour usually presents a high content of dietary fiber, fat and protein in addition to some micronutrients and several bioactive compounds that can contribute to improving the nutritional quality of cereal-based products for human consumption [11][13]. Another advantage of sorghum is that it is gluten-free (GF), making it an ingredient of great interest for those who seek to improve the quality of GF foods. These GF products often have poor nutritional quality since they are neither enriched nor fortified. They also present low technological and sensory quality and do not look or taste good [16][17].

Some researchers evidence the high glycemic index of wheat-based and GF bakery products, and so, the substitution of common cereals with sorghum flour can contribute to the development of products with a lower glycemic index due to the dietary fiber and resistant starch contents of sorghum [6][12]. Also, some genotypes contain tannins in the composition, which have already shown a positive relationship with a decrease in the glycemic rate [10][18].

Due to the increasing interest in sorghum for human nutrition, recent literature reviews highlight its nutrient and bioactive content as well as its potential health benefits [6][10][12] and focus on the milling, malting, fermentation and thermal processing of sorghum to be consumed or used as a food ingredient [11]. Moreover, a current view of recent research into sorghum-based food products is needed to help both food scientists and industry identify current trends and forward-looking approaches as well as to design strategies to diminish the challenges regarding the use of sorghum for human nutrition, including the commercialization of sorghum-based food products.

2. Sorghum-Based Food Products

Based on the inclusion criteria, 451 original articles were selected and used to create the bibliometric map based on research about sorghum-based food products (**Figure 1**).

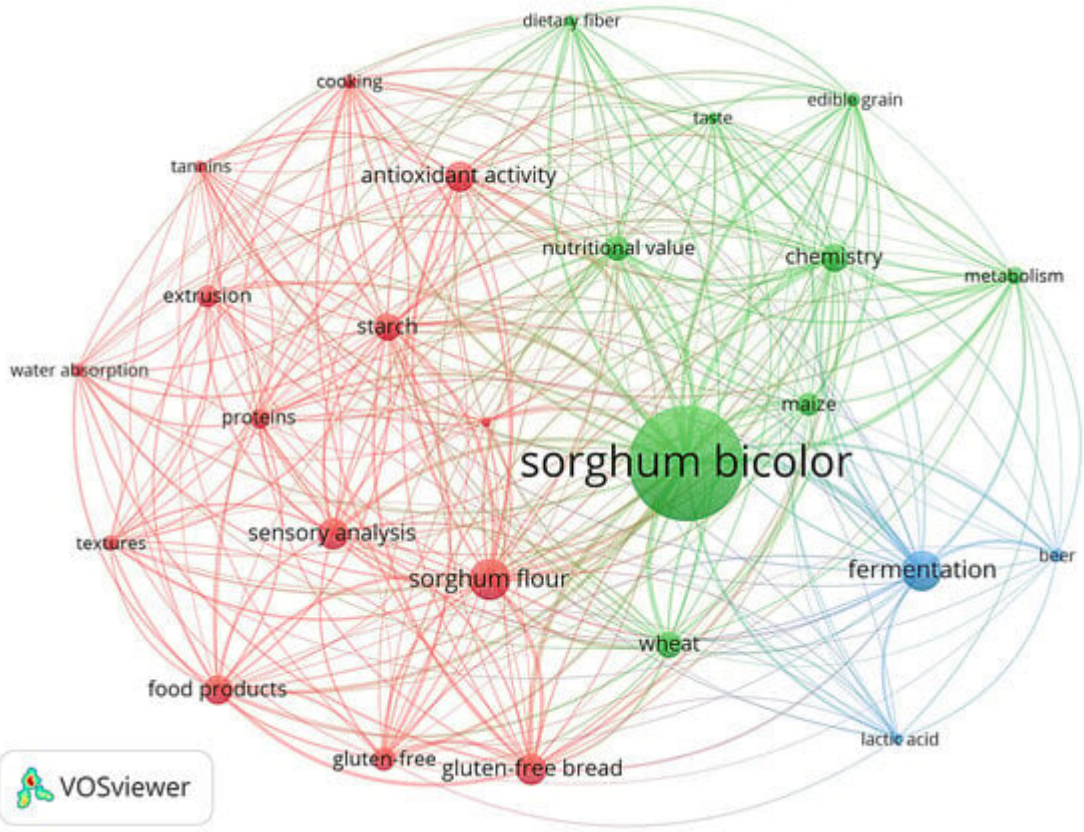

Figure 1. Keyword co-occurrence network from original articles regarding sorghum-based products. Size of the bubbles represents more frequently used terms, while thicker connectors correspond to more frequent co-

occurrence of terms. Source: Scopus database (2012–2022). A minimum of 20 occurrences was adopted to integrate keywords analysis using the VOSviewer software.

Figure 1 shows the 26 most used keywords in the original articles regarding sorghum-based products arranged into three clusters (**Figure 1**). The red cluster is composed of 14 keywords that are related to the development of new food products and draw attention mainly to GF products, especially the GF bread developed with sorghum flour, analyzing product characteristics through sensory analysis, nutrient content and antioxidant activity. The extrusion and cooking processes are also included in this cluster. The green cluster that contains 10 items represents a common research approach to sorghum flour in combination with common ingredients, such as maize or wheat flour, showing the differences in nutritional value, metabolism and the taste of these products. The blue cluster (three items) illustrates the studies about the fermentation process of lactic acid and its relationship with beer development. The figure lays out the research about sorghum used to developed GF products for human consumption, showing that this ancestral cereal is a good option to substitute common cereals, like wheat, rice and corn.

The 451 original articles were also analyzed according to the authors and country co-occurrence as shown in **Figure 2**. In descending order, India (12.6%), Nigeria (10%), the United States (9.7%), South Africa (9%), Brazil (8%) and China (8%) are the main countries of origin of the selected studies, while for the authors, the main researchers are from institutes in Brazil, South Africa and the United States. Among them, there is scientific cooperation between the United States and South Africa or Brazil; collaboration between Brazil and South Africa should be further stimulated.

Country	Authors	Articles*
Brazil	Queiroz, V.A.V.	15
South Africa	Taylor, J.R.N.	11
USA	Alavi, S.	9
Brazil	Ascheri, J.L.R.	9
Australia	Johson, S.K.	8

*Number of articles published between 2012-2022 about sorghum-based products.

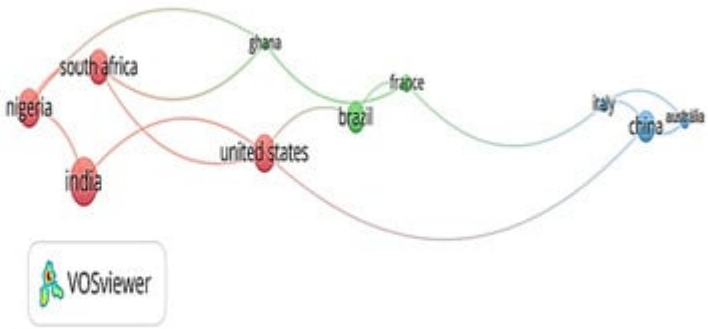

Figure 2. Country co-occurrence network and main authors from original articles regarding sorghum-based products. Size of the bubbles represents more frequently used terms, while thicker connectors correspond to more frequent co-occurrence of terms. Source: Scopus database (2012–2022). A total of 14 articles was adopted as the minimum number of documents to include a country in the analysis using the VOSviewer software.

The African continent is responsible for more than 22% of sorghum research, being the main continent to contribute with studies about sorghum for human nutrition. However, India is the country that produced the most research about sorghum (12.6%), while France, South Africa and the United States (USA), compared with all 84

countries that produced some of the selected articles of sorghum, were regarded as the leaders for research collaboration with other countries. This scientific cooperation between the different countries is essential to investigate all sorghum genotypes and traditional and novel food processes and to contribute to a greater inclusion of sorghum in human food.

Even though the sorghum grain is one of the main grain crops planted in Brazil, and Brazilian researchers are responsible for the largest number of studies on sorghum-based products for human consumption, sorghum continues to be produced mainly for animal feed, while in Asian and African countries, its cultivation is largely intended for human consumption, playing an important role in the food security of these populations and showing the potential of the grain for use in food for human consumption [1][2][19]. Until now, no research collaboration between Brazil and South Africa or India was noticed. This scientific cooperation is important to provide a better knowledge of traditional African and Asian uses of sorghum, allowing for its adaptation to the western diet as well as different countries' and regions' food products and preparations.

Sorghum is indicated as a cereal with high potential to be used in the development of various starchy-based food products for human consumption, such as bakery products, extruded products, beverages and porridges, being very appropriate for the development of GF products [13][14][15]. **Figure 3** shows the total scientific production of original articles about different sorghum-based products (2012–2022), showing the categories of these products.

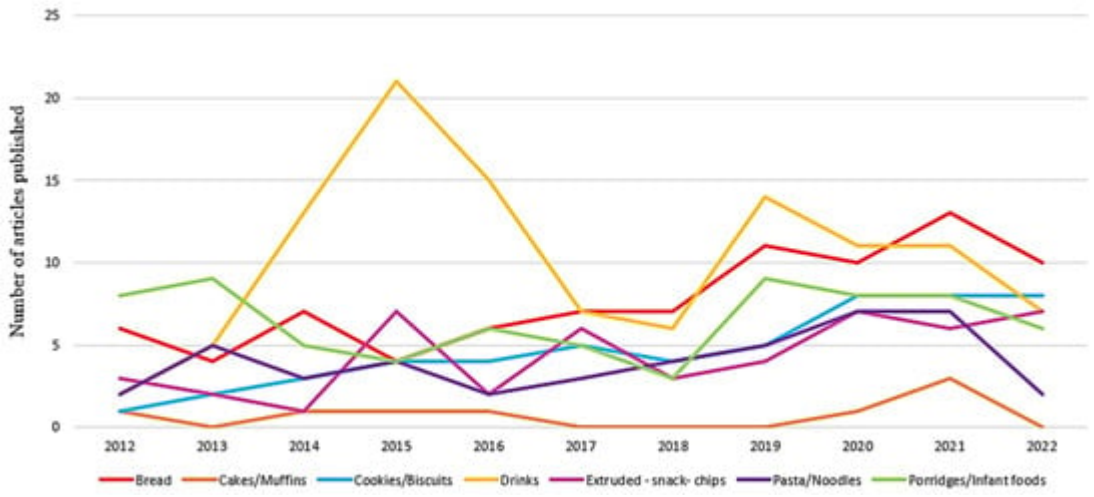

Figure 3. Comparison of total scientific production of original articles about different sorghum-based products in terms of title, abstract and keywords registered in Elsevier Scopus database (2012–2022).

2.1. Beverages and Syrup

Beverages used to be the most researched sorghum-based products with beer as the main type of drink as it is commonly produced and consumed in Africa and China. Davana and Revanna [20] developed beers using different proportions of sorghum with barley (40%, 60% and 100% of each cereal), and the 60% sorghum beer received the highest score based on the mouth feel. From the organoleptic evaluation, as observed in **Table 1**, the sorghum beer was comparable to commercial beer made with barley, demonstrating the potential of sorghum as an

alternative cereal in beer production, especially in GF beers that benefit people who do not tolerate gluten, and having an advantage from the economic point of view due to the lower planting cost of sorghum.

Besides the beer, sorghum is also interesting for juice development. Sharma et al. [21] developed a juice using sweet sorghum. The juice was extracted using a mechanical extractor, sterilized by heating at 90 °C for 15 min and then centrifugated for 10 min at 6000 RPM to remove the insoluble particles. [21] converted the fermentable sugars present in the juice into functional carbohydrate molecules, producing a well-accepted functional beverage that was rich in prebiotic oligosaccharides, which can contribute to gut health. This demonstrates the potential of sweet sorghum juice as a low-cost raw material for producing new beverages with functional appeal.

Cséfalvay and Bakacsi [22] and Mazumdar et al. [23] investigated the use of sweet-sorghum juice to produce a syrup with improved nutritional quality that was also well accepted by the consumers. Sorghum syrup is an interesting product because it can be used by the industry as an alternative sugar to sweeten different food products. The cited authors drew attention to the fact that the syrup, which is made from the sweet-sorghum juice, has the potential to be used in developing commercial beverages since they can be further fortified or blended with other fruit juices or concentrates. They can also be with protein concentrates or other beverages, allowing for the development of products with an improved nutritional quality and with good acceptance by the nutraceutical segment due to the health benefits provided by the sorghum [10][11][12].

2.2. Porridge

Figure 2 shows that, like beer, sorghum porridge used to be the most developed product in research. Rashwan et al. [15] reviewed various technological processing methods, such as soaking, germination, fermentation, thermal processes and irradiation that could contribute to improving the nutritional quality of sorghum porridges, and the authors indicated fermentation as the principal treatment to benefit the nutritional value of sorghum-based products, using some other combined treatments such as soaking, germination and nixtamalization (soaking and cooking in limewater), demonstrating the contribution to producing sorghum-based foods with a higher nutritional value.

Makame et al. [24] investigated the oral texture properties of some complementary indigenous porridges, indicating the sorghum-based porridge as “not easy to swallow even with low solids content”, presenting a viscosity higher than that indicated for children up to 3 years old. The difficulty in swallowing the porridge can limit food and nutrient intake, perpetuating protein and energy malnutrition in infants that rely on these types of food. These data call attention to the necessity of research involving different techniques to reduce the viscosity of sorghum-based porridges, which may contribute to easier consumption by children under 3 years of age.

Adebowale et al. [25] microwaved sorghum grains, which resulted in a lower viscosity of the porridges made, with these treated grains being more adequate for infant feeding. The authors highlight the necessity to evaluate the porridge acceptance with children, since they have different chewing, bolus formation and swallowing process from

adults. However, the economic viability of microwave treatment needs to be evaluated to validate its applicability in an industrial production line.

2.3. Bakery Products

Since 2014, there has been an increase in research about sorghum-based bakery product development, mainly GF bread. Aguiar et al. [17] showed that, during the last ten years, commercial gluten containing (GC) (n = 7122) and GF (n = 3153) food products have been investigated and compared worldwide. The label evaluation of GF bread (n = 935) reveals that this product is composed of multiple raw ingredients and additives, resulting in a high variability in the carbohydrate (14 to 84%), fat (1 to 19%), protein (0 to 11%), sugar (0 to 24%) and dietary fiber (0 to 17%) contents. These GF products continue to be recognized as high in fat, low in protein and, in some cases, low in dietary fiber. The use of sorghum to produce GF breads can improve not just the nutritional content but also the physical and sensory properties, as reported by some authors like Centeno et al. [14] who developed well-accepted GF bread using up to 75% of white sorghum flour (BRS501 genotype without tannins) combined with 25% potato starch or using 100% of bronze sorghum flour (BRS332 genotype containing tannins).

Khoddami et al. [11] reported lower sensory acceptance of sorghum-based products when compared to other cereal products. In fact, as pointed out by de Oliveira et al. [26] who investigated the acceptance of GF bread developed with different sorghum types and flours, the presence of tannins and other phenolics in sorghum-based bread may contribute to a negative effect on the acceptance. However, the authors draw attention to the need to indicate the most suitable product for each sorghum hybrid, since GF bread developed with the red sorghum BRS 332 flour was well-accepted.

For the development of cakes with no color impact, the sorghum with the white pericarp can easily be used to substitute for flours like wheat and rice, while for products that contain chocolate, it also possible to use the brown and red genotypes, which contribute to a darker product that has a positive impact on the physical appearance [14][27][28].

Sorghum contributes to good physical characteristics of cakes and also provides an improvement in the nutritional quality and high acceptance from the consumers, indicating the cakes made with sorghum are very similar in terms of flavor, odor, texture and color to those traditional products made with wheat or rice flour [29]. Cayres et al. [30] developed GF cakes that contained 87.8% red sorghum wholegrain flour (flour basis), demonstrating that sorghum can be used as the main ingredient for this food product. The authors draw attention to the fact that, when questioned, the Brazilian consumers stated that they did not know about sorghum, so its use has the potential to be offered as a novelty on the market.

Cookies and biscuits are products that can also benefit when developed with sorghum because both the GC and the GF versions can use this ingredient to improve their nutritional quality. Yu et al. [27] developed biscuits that contained wheat flour (WF) enriched with whole sorghum flour and extruded sorghum flour (ESF). The use of 80% of ESF with WF biscuits was indicated to improve the resistant starch content of these products with this sample

obtaining a higher sensory acceptance than the control sample prepared with 100% WF. Cervini et al. [31] developed GF biscuits enriched with a novel resistant starch ingredient obtained from annealed white sorghum starch. The use of resistant starch is interesting because the partial substitution of flours like the WF for this ingredient can be a great alternative to the commercially developed products containing starches with low digestible properties, containing a higher fiber content. However, even with a positive effect on the nutritional quality, the biscuits made with the resistant starch presented a low texture score and low overall acceptance, being harder when compared to the control sample made with 100% of commercial GF flour mixture.

One of the principal challenges in the production of GF foods is the low acceptance of texture because the lack of gluten directly impacts the hardness. Consequently, products developed for their health appeal need to focus on the sensory acceptance since, despite so much research about GF products, they are still not very satisfactory in terms of sensory characteristics, mainly flavor and texture, for both celiac and non-celiac GF consumers [16][32].

2.4. Pasta Products

Regarding pasta products, the literature reports the use of sorghum in high quantities without a negative impact on the sensory acceptance. Johnson et al. [28] found that the use of up to 75% of black sorghum flour combined with WF can be used to produce noodles with improved nutritional quality, increasing the total polyphenolic content and presenting a higher antioxidant capacity as well as a sensory acceptance comparable to the standard sample produced with 100% WF. De Oliveira et al. [26] investigated the use of sorghum to develop GF pasta using 24.4% white (commercial and CMSXS 180), red (BRS 330 and BRS 332) or brown (BRS 305 and 1167048) sorghum flour. In the sensory analysis, the authors observed that there was no significant difference in the preference for a specific pasta color. However, the samples developed with the BRS 305 (brown color and rich in tannins) were the least acceptable samples, receiving a lower acceptance for the flavor attribute with a higher astringency and a sandy sensation in the mouth. This could be related to the high tannin content of this sorghum genotype and the endosperm characteristic that was more farinaceous.

2.5. Sorghum-Based Ingredients

The literature shows a high use of sorghum as flour for developing new products but also calls attention to the extraction of the starch from the grain, which is also an interesting ingredient due to its high content of resistant starch that can be used to formulate food products with less glycemic impact. This is because products with this sorghum starch present a high dietary fiber content and properties of slowly digestible starch without affecting the sensory attributes [31].

There has been an increase in research about sorghum grain extruded products (**Figure 3**), like snacks and breakfast cereals, along with extruded sorghum flour, which is used as an ingredient in cakes, breads and beverages. The use of the extruded flour instead of the raw sorghum flour can contribute to better digestion of sorghum. However, this process can reduce the content of some biocomponents that are interesting to human health [27][33][34]. According to Xu, Wang and Zhao [10], the extrusion process affected the total phenolic content and

total flavonoids of sorghum, which are related to the loss of the biological functions of the phenolic components in sorghum. Other studies are needed to define the process conditions that maintain the phenolic content and its biological activity and, also, processes that help reduce the anti-nutritional factors in sorghum, improving nutrient digestion.

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