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REVIEW ARTICLE

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Climate-Resilient Crops as Gluten-Free Substitutes: A Systematic Review of the Nutritional, Technofunctional, and Rheological Properties of Sorghum, Pearl Millet, and Amaranth

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ABSTRACT

Background: Gluten-free flours are essential alternatives for individuals with gluten intolerance, providing various nutritional benefits. Despite the increasing prevalence of gluten intolerance, there is limited systematic research on the potential of drought-tolerant grains like sorghum, pearl millet, and amaranth as gluten-free flour substitutes.

Aims: This study aims to review the nutritional, functional, and baking properties of gluten-free flours derived from red and white sorghum, pearl millet, and amaranth, assessing their viability as alternatives to wheat for gluten-intolerant individuals.

Methods: A systematic review was conducted following PRISMA guidelines, analyzing 30 peer-reviewed articles published between 2015 and 2024, primarily from Asia and Africa.

Results: White sorghum flour had the highest zinc concentration (13.20 mg/g), while red sorghum had the highest iron levels (28.93 mg/g). Amaranth flour demonstrated the highest protein content (25.5%) and crude fiber (15.9%). In contrast, pearl millet had the lowest iron (0.11 mg/g) and crude fiber content (0.6%). Among functional properties, pearl millet showed the highest water absorption capacity (359.33% ± 1.45), whereas white sorghum had the lowest (1.07% ± 0.04). Amaranth exhibited the highest oil absorption capacity (1.88 g/g ± 0.01), while pearl millet had the highest swelling index (8.17 mL/mL ± 0.01). In terms of baking properties, specific volume was the most frequently analyzed parameter, with pearl millet presenting the highest specific volume (4.87 cm^3/g). Amaranth flour was identified as the best gluten-free option, excelling in loaf volume, porosity, and firmness.

Conclusion: The study suggests that utilizing traditional grains can help meet the growing demand for gluten-free products, highlighting their significant potential in the gluten-free market. Future research should focus on optimizing flour blends to enhance nutritional value and baking performance by incorporating conventional ingredients and innovative techniques to replicate the gluten network.

Keywords: Gluten-Free; Climate-Resilient Grains; Baking Technology; Nutritional Composition; Sorghum; Pearl Millet; Amaranth.

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1 INTRODUCTION

Global wheat production is currently on the rise, accompanied by a diverse array of derived products including bread, biscuits, pasta, noodles, and porridge (Tadesse *et al.*, 2018). Among these, bread and baked products represent a crucial component of the daily diet for numerous individuals. Wheat, along with other grains such as rye and barley, contains gluten— a specific class of storage proteins. It is estimated that approximately 1–2% of the global population (roughly 79.5 million people) suffers from gluten intolerance (Di Cairano *et al.*, 2018). Gluten intolerance is categorized as a common autoimmune enteropathy that occurs in genetically predisposed individuals and is triggered by the ingestion of gluten specifically, the protein present in wheat, rye, and barley (Alkalay, 2022). Furthermore, gluten consumption has been associated with a range of so-called "gluten-related disorders," which include non-celiac gluten sensitivity, dermatitis herpetiformis, gluten ataxia, and wheat allergy (Barbaro *et al.*, 2020). The ingestion of gluten-containing food products by individuals with gluten intolerance can lead to significant health complications, including inflammation and damage to the intestinal epithelium. This damage impairs nutrient absorption and culminates in a condition known as celiac disease (Sharma *et al.*, 2020). In pediatric populations, malabsorption stemming from intestinal injury may impede growth and development, in addition to eliciting symptoms commonly observed in adults, such as abdominal bloating, diarrhea, constipation, and vomiting (Lamacchia *et al.*, 2014).

Consequently, gluten-free diets have gained substantial popularity (Raiteri *et al.*, 2022). At present, the sole effective treatment for celiac disease is adherence to a strict gluten-free diet, which enables individuals to manage symptoms and foster intestinal recovery (Lebwohl *et al.*, 2018). Given the prevalence of gluten sensitivity disorders, there has been a marked increase in demand for gluten-free products not only among individuals seeking to avoid gluten consumption but also among those pursuing healthier dietary options. Therefore, it is imperative to expand and diversify the food industry, focusing on advancements in ingredients and formulations, along with the production of gluten-free food items (Culetu *et al.*, 2021).

The increasing prevalence of allergic diseases in Zimbabwe, particularly gluten intolerance, constitutes a significant public health concern (Ndlovu *et al.*, 2025). Mathematical models project that food and inhalant allergies are likely to become endemic within the country (Mushayi *et al.*, 2021) thereby necessitating heightened attention to allergy care and management. Research indicates that nearly half (47%) of symptomatic individuals exhibit reactions to one or multiple allergen sources (Sibanda, 2012), with recent findings emphasizing a persistent rise in allergies, including gluten intolerance (Mushayi *et al.*, 2021). This trend is especially concerning in light of Zimbabwe's increasing dependence on wheat as a staple food, which is propelled by rapid urbanization, population growth, and shifting dietary preferences toward convenient wheat-based products such as bread, biscuits, pasta, and noodles. Consequently, the increasing demand for wheat, in conjunction with rising rates of gluten intolerance, highlights the urgent need for alternative, locally available, and drought-tolerant sources of gluten-free flour. The global incidence of gluten intolerance is also on the rise, reflecting an escalating demand for gluten-free diets (Taraghikhah *et al.*, 2020).

Sources of Gluten-Free Flours

Gluten-free cereals (GFC) are defined as cereals that do not contain gluten or contain gluten at levels less than 20 parts per million (ppm) (Selladurai *et al.*, 2023). Such flours serve as vital alternatives for individuals diagnosed with celiac disease or gluten intolerance, offering a variety of nutritional benefits. Table 1 presents a selection of some most frequent sources of gluten-free flour on a global scale. Sorghum (*Sorghum bicolor*) flour is abundant in antioxidants, dietary fiber, and essential minerals, rendering it an appropriate substitute for wheat (Takeuchi *et al.*, 2025; de Oliveira, de Orlandin, *et al.*, 2022). Millet (*Pennisetum glaucum*), recognized for its drought resistance, serves as a nutritious source of gluten-free flour, providing magnesium and phosphorus, which are important for metabolic and bone health (Ojha *et al.*, 2022). Amaranth (*Amaranthus* spp.) flour is notably high in protein and contains lysine, an essential amino acid frequently deficient in several cereal grains (Carmona-Garcia *et al.*, 2022).

Table 1. Sources of Gluten-Free Flour

Grain	Reference
Sorghum	Khairuddin & Lasekan, (2021); Nakatani and Tanaka, (2023); Célia *et al.*, (2022); de Oliveira *et al.*, (2022)
Millet	Gomaa, (2022); Ojha *et al.*, (2022); Mudau *et al.*, (2022); Urubkov *et al.*, (2022).
Amaranth	Dabija *et al.*, (2022); Aguiar *et al.*, (2022); Carmona-Garcia *et al.*, (2022); Rybicka *et al.*, (2015); Urubkov *et al.*, (2022).
Teff	Barretto *et al.*, (2021); Nyachoti *et al.*, (2021)
Soy	Lemes, (2023); Egea *et al.*, (2023); Liu *et al.*, (2019); Ogunbusola *et al.*, (2021).
Rice	de Oliveira *et al.*, (2022); Ronie *et al.*, (2023); Rybicka *et al.*, (2015); Urubkov *et al.*, (2022); Ogunbusola *et al.*, (2021).
Quinoa	Bian *et al.*, (2023); Aguiar *et al.*, (2022); Rybicka *et al.*, (2015); Urubkov *et al.*, (2022).
Oats	Šmídová & Rysová, (2022); Smulders *et al.*, (2018); Rybicka *et al.*, (2015).
Buckwheat	Yeşil & Levent, (2022); Ojha *et al.*, (2022); Aguiar *et al.*, (2022); Urubkov *et al.*, (2022).

Teff (*Eragrostis tef*), a staple grain in Ethiopia, yields a fine flour rich in iron and calcium, which are beneficial for anemia prevention (Barretto *et al.*, 2021). Additionally, soy (*Glycine max*) flour is characterized by its high protein content and the presence of isoflavones, which are recognized for their potential role in supporting hormonal balance. Rice (*Oryza sativa*) flour is widely employed in gluten-free baking due to its digestibility and its contribution of B vitamins (Ogunbusola *et al.*, 2021). According to Bian *et al.*, (2023) and Aguiar *et al.*, (2022), quinoa (*Chenopodium quinoa*) flour possesses a complete protein profile, positioning it as a valuable grain alternative to wheat flour. Oats (*Avena sativa*) represent an additional notable source of gluten-free flour, distinguished by their richness in beta-glucan (Smulders *et al.*, 2018). Furthermore, buckwheat (*Fagopyrum esculentum*) flour serves as an additional gluten-free option. The cereals listed in Table 1 also play a significant role in traditional diets, characterized as the eating habits and food patterns inherent to specific cultures or regions, habitually transmitted through generations, across various regions and provide an array of vital micronutrients, including vitamins, iron, calcium, and phosphorus. Table 1 indicates the most common grain crops that produce gluten-free flour.

In the context of Zimbabwe, sorghum, pearl millet, and amaranth have emerged as viable alternatives to wheat, particularly due to their adaptation to the country's semi-arid conditions. These crops not only serve as staple foods for rural communities but also offer significant nutritional benefits, rendering them valuable assets for food security and dietary diversity (Siwela, 2024). Amaranth, traditionally cultivated in Zimbabwe, is gaining recognition as a highly nutritious, gluten-free grain with exceptional resilience to harsh environmental conditions (de la Barca *et al.*, 2010; Liu *et al.*, 2019). Historically utilized by rural populations, amaranth is now transitioning from an underutilized crop to a crucial component of food security initiatives (Yadav & Yadav, 2024; Mazike *et al.*, 2023; Mazike *et al.*, 2025). Research indicates that amaranth flour constitutes a rich source of high-quality protein, particularly lysine, which is frequently deficient in cereal grains. Additionally, amaranth contains bioactive compounds with antioxidant properties, enhancing its role in promoting health and preventing malnutrition-related diseases (Sarkar *et al.*, 2023). With regard to sorghum and millets, these grains are already integral to Zimbabwean agriculture and diets. They are not only drought-tolerant but also require minimal inputs, making them well-suited for smallholder farmers operating in resource-constrained environments. From a nutritional standpoint, both sorghum and pearl millet are rich in essential micronutrients, including iron, zinc, and magnesium, which are critical for addressing widespread micronutrient deficiencies in Zimbabwe (Mawouma *et al.*, 2022).

There have been increasing calls for the production of sorghum, pearl millet and amaranth instead of maize production to enhance food security against the background of climate change in Zimbabwe (Makuchete *et al.*, 2024). However, their production and market availability remain inconsistent, due to limited processing capacity, weak value chains and consumer preferences shift towards wheat products (Deribe and Kassa 2020). Among these grains, amaranth had been recognized nutritionally superior but not yet commercially established in Zimbabwe and is mainly cultivated on a small scale by urban and peri- urban farmers (Mabhaudhi *et al.*, 2019). As such, these grains are recognized for their high nutritional, product development of gluten-free products, their full utilization will depend on local availability, affordability, and market development. To full utilize the benefits of these crops, the investments targeted for farmers training, seed systems, and the agro- processing infrastructure are required to integrate traditional grains into national food and nutrition strategies (Massawe *et al.*, 2016).

Despite the rising prevalence of gluten intolerance in Zimbabwe, there remains a lack of systematic research assessing the potential of common drought-tolerant grains, such as sorghum, pearl millet, and amaranth, as viable gluten-free flour alternatives. While these traditional grains are well adapted to the local climate and have been historically cultivated for their nutritional benefits, their potential role in meeting the gluten-free dietary needs of an increasing allergic population remains underexplored. A comprehensive review is necessary to evaluate the suitability of these three grains as substitutes for wheat in terms of nutritional composition, functional properties, and baking characteristics. Addressing this research gap will provide crucial insights into promoting sustainable, locally available, and nutritionally rich gluten-free flour alternatives, thereby reducing dependency on wheat imports and supporting food security and public health initiatives in Zimbabwe. The objective of this review is to identify and analyze published scientific literature to gain an understanding of the nutritional composition, functional properties, and baking characteristics of the examined gluten-free flours.

2 METHODS

A comprehensive literature search was conducted to identify published literature from various regions worldwide that aligned with the objective of this review. This systematic review adhered to the guidelines outlined in the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) Statement (Moher *et al.*, 2009). The search employed keywords such as "traditional grains," "sorghum," "amaranth," "pearl millet," "climate-resilient crops," "nutrition analysis," "baking properties," and "functional properties." Only peer-reviewed articles published in reputable journals were included in the literature selection. The search was executed across multiple databases, including: Web of Science, Scopus, PubMed, and Google Scholar.

The inclusion criteria for this review encompassed experimental papers published in English between January 1, 2015 (the earliest article sourced via the search engines), and May 30, 2024. Initially, 2,153 papers were identified. After the removal of duplicate articles, 480 were excluded from consideration. A preliminary screening of the abstracts of the remaining 480 papers further reduced the number to 122. During this screening process, review papers, outdated papers, and those not specific to the type of sorghum (red or white sorghum) were excluded. Additionally, papers based on titles, keywords, and written in languages other than English were excluded for relevance with respect to the objectives of the review. The selection of red and white sorghum, pearl millet, and amaranth for this study was based on their gluten-free status, rendering them suitable alternatives for individuals with celiac disease and gluten intolerance. Furthermore, these grains possess significant nutritional and agronomic value, contributing to food security and dietary diversity, particularly in regions characterized by poor soils and intermittent droughts. Their resilience to harsh environmental conditions further highlights their potential as sustainable and climate-smart alternatives to conventional gluten-containing grains. Following a thorough review of the full articles, 30 articles were selected.

Figure 1 indicates a concise overview of the inclusion and exclusion criteria. Data from the selected studies were extracted from figures, tables, and text. The pertinent data from each included study was subsequently summarized in thematic tables and graphs.

3 RESULTS AND DISCUSSION

Thirty (30) relevant scientific articles were identified and are presented in this section. The results discussed herein include the number of articles published during the review period from 1 January 2015 to 30 May 2024 (Figure 2), the distribution of articles by continent, the distribution of articles by grain type, and the number of articles per thematic area, specifically nutritional profile, functional properties, and baking properties.

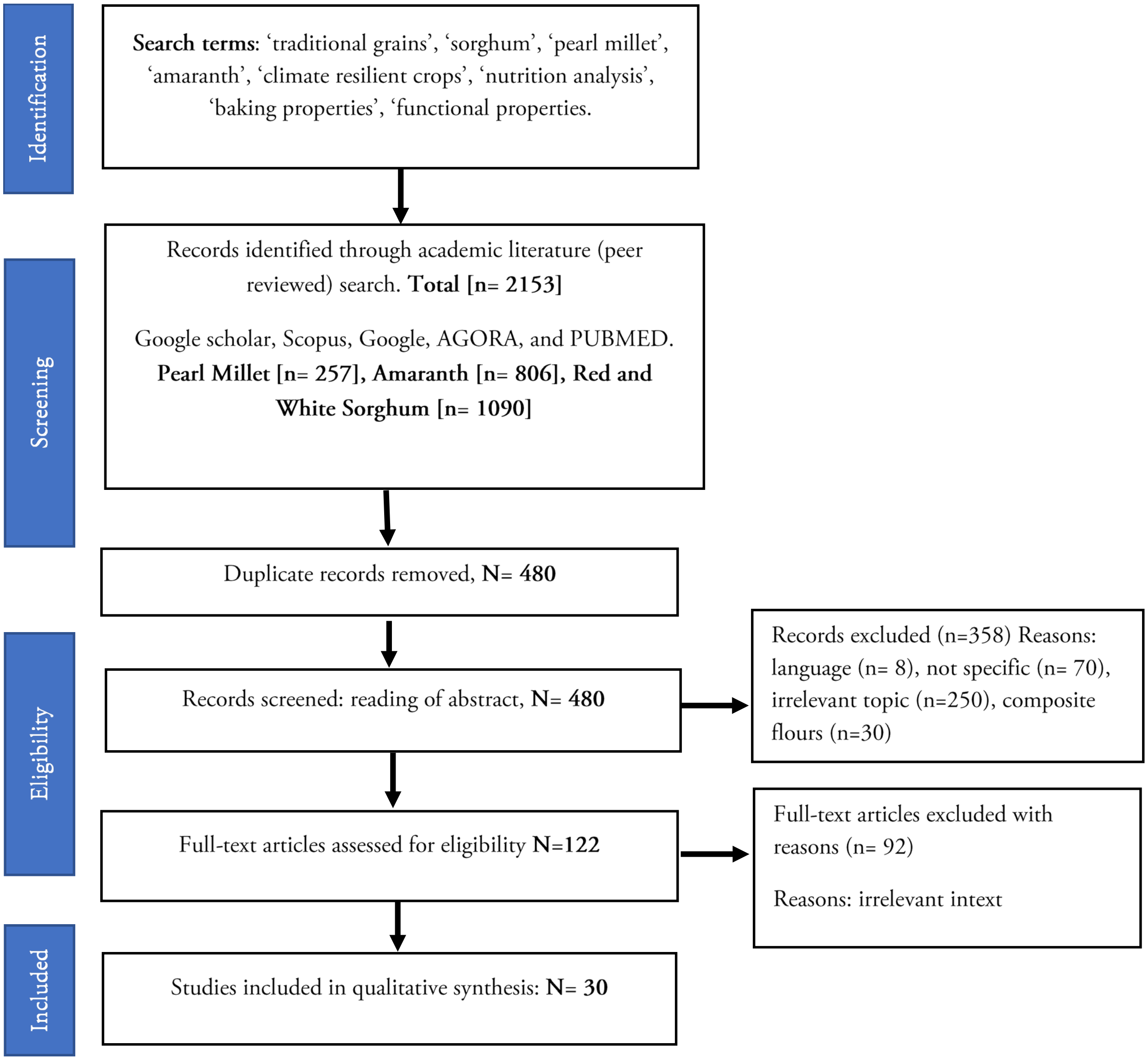

Figure 1. PRISMA Flow Diagram of Study Selection Process

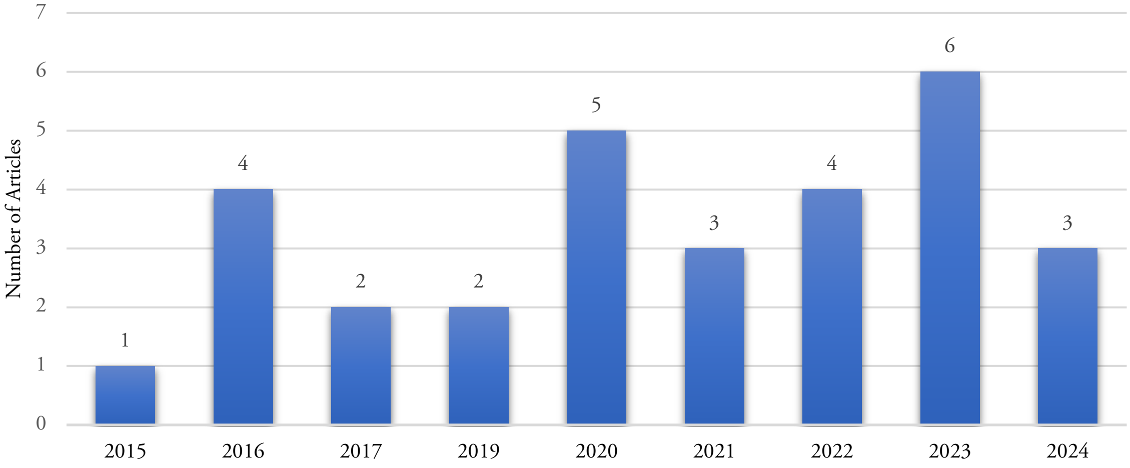

Figure 2. Distribution of Reviewed Articles between 2015 and 2024 (n=30)

a. Distribution of Reviewed Articles

The selected scientific articles were organized chronologically from the oldest to the most recent, as illustrated in Table 2. The reviewed articles encompass various types of traditional grain flour, including red sorghum, white sorghum, pearl millet, and amaranth grain flours. Cereal crops such as wheat and maize, which are common sources of flour, have been adversely affected by drought conditions, leading to poor harvest yields (Bharambe *et al.*, 2023; Kim and Lee, 2023). Consequently, several rural communities in Asia and Africa have shifted towards the cultivation of small (traditional) grains as an adaptive strategy to climate change (Chadalavada *et al.*, 2021; Chakauya *et al.*, 2023; Mthethwa *et al.*, 2022). This transition towards traditional grains such as sorghum, pearl millet, and finger millet has also led to an increase in research focused on gluten-free flours derived from these grains. The shift from maize to traditional grains has further stimulated funding and collaborative research efforts concerning gluten-free flours.

Geographical distribution of the published articles

The results presented in Figure 3 indicate that the majority of the studies investigating the potential of traditional grains as sources of gluten-free flours were conducted in Europe (8), followed by Asia (9), Africa (7), America (5), and Australia (1). Among the nine publications originating from Asia, India accounted for the highest number (6), while the seven publications from Africa originated from different countries: Ethiopia (1), Tunisia (1), Egypt (1), South Africa (1), and Nigeria (3). The substantial number of publications from India may be attributable to its status as the largest producer of traditional grains, which have been cultivated for centuries and are often referred to as super grains due to their high nutritional value (Anal *et al.*, 2024).

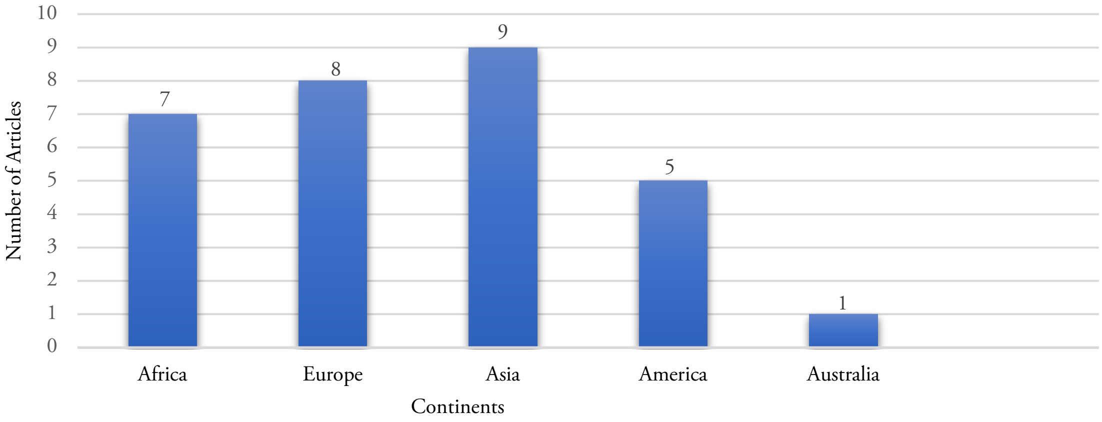

Figure 3. Distribution of Articles by Continents

Table 2. Distribution of identified articles on traditional grain flours

	Article	Year	Country	Red Sorghum	White Sorghum	Amaranth	Pearl Millet
1	Chauhan *et al.*	2015	India	+	+	+	
2	Chauhan *et al.*	2016	India			+	
3	Maktouf *et al.*	2016	Tunisia	+			+
4	Adeyeye *et al.*	2016	Nigeria	+			+
5	Taylor *et al.*	2016	Australia	+	+		
6	Abolaji *et al.*	2017	Nigeria	+			+
7	Filipčev *et al.*	2017	Serbia			+	
8	Bian *et al.*	2019	Argentina			+	
9	Liu *et al.*	2019	USA				
10	Apostol *et al.*	2020	Russia			+	
11	Gebreil *et al.*	2020	Egypt			+	
12	Nasir *et al.*	2020	India			+	
13	Nieto-Mazzocco *et al.*	2020	Mexico			+	
14	Pezzali *et al.*	2020	USA	+	+		
15	Culetu *et al.*	2021	Romania			+	
16	De Bock *et al.*	2021	Denmark			+	
17	Tadesse *et al.*	2021	Ethiopia	+			
18	Coţovanu & Mironeasa	2022	Romania			+	
19	de Oliveira *et al.*	2022	Brazil	+			
20	Irondi *et al.*	2022	Nigeria				+
21	Turk Aslan & Isik	2022	Turkey			+	
22	Hamzehpour & Dastgerdi	2023	Iran			+	
23	Sharanagat & Nema	2023	India			+	
24	Rumler *et al.*	2023	Austria	+	+	+	
25	Sharanagat & Nema	2023	India	+			
26	Coţovanu *et al.*	2023	Romania			+	
27	Adzqia *et al.*	2023	Thailand		+		
28	Alizadeh *et al.*	2024	Iran			+	
29	Sibanda *et al.*	2024	South Africa				+
30	Wilson *et al.*	2024	India	+			+

Moreover, Europe has emerged as the leading contributor to the publication of articles in this field, a trend likely correlated with the increase gluten sensitivity and celiac disease (Cabanillas, 2020; Caio *et al.*, 2020;). This rise in gluten-related illnesses has heightened consumer demand for gluten-free products, motivating researchers and food producers to explore traditional grains as viable substitutes for wheat (Babio *et al.*, 2020; Montemurro *et al.*, 2021; Wang and Jian, 2022).

Table 2 illustrates that amaranth grain flour was the most extensively researched gluten-free grain flour, accounting for 17 out of 30 articles reviewed. This preponderance of published studies may be associated with the exceptional nutritional profile of amaranth, particularly its high protein content (Gebreil *et al.*, 2020) as well as its comprehensive amino acid profile, which includes lysine, a nutrient often deficient in other grains (Mătieş *et al.*, 2024). Additionally, formulations of bread incorporating amaranth flour have demonstrated significant enhancements in protein, lipid, and ash content compared to further wheat substitutes, such as quinoa (Gebreil *et al.*, 2020). Research by Coţovanu *et al.*, (2023) indicated that incorporating 7 – 9% of amaranth flour into wheat bread formulations result in increased protein, lipid, and ash content in the bread. The superior attributes of amaranth grain may have significantly contributed to the considerable number of studies focused on its utilization as a wheat substitute in gluten-free product development.

b. Nutritional Profile

This study reviews the literature regarding the nutritional composition of four specific grain flours. Of particular interest are the macro- and micronutrients present in these traditional grain flours. Table 3 indicates that white sorghum flour exhibits the highest concentration of zinc (13.20 mg/g) (Pezzali *et al.*, 2020) followed by amaranth flour at 3.5 mg/g (De Bock *et al.*, 2021). The highest concentration of iron (28.93 mg/g) was recorded in red sorghum flour (Pezzali *et al.*, 2020) whereas pearl millet flour contained the lowest concentration at 0.11 mg/g. Crude fiber content was highest in amaranth flour (15.9%) as reported by Turk Aslan and Isik, (2022) while pearl millet exhibited the lowest crude fibre content at 0.6% (Wilson *et al.*, 2024). Furthermore, red sorghum flour demonstrated the lowest fat content (1.6%) and the highest carbohydrate content (84%), as noted by Taylor (2016). Additionally, the protein content was highest in amaranth flour (25.5%), as reported by Coțovanu & Mironeasa (2022). It is crucial to acknowledge that the nutritional composition of these four grain flours may vary significantly based on environmental conditions and other factors, including genetic variation (Krishnan & Meera, 2018).

The nutritional adequacy of gluten-free diets and their associated products remain a significant concern for consumers, industry stakeholders, and healthcare professionals. While gluten-free diets are recognized for alleviating symptoms and facilitating gastrointestinal recovery in individuals with gluten-related disorders, long-term adherence to such diets may result in nutritional deficiencies. Numerous studies have analyzed the nutritional profiles of gluten-free products as well as the dietary habits of individuals adhering to these diets. According to Do Nascimento *et al.*, (2013), gluten-free products are predominantly issued from raw ingredients such as corn, rice, soy, cassava, and potato, which serve as substitutes for gluten-containing grains such as wheat, rye, and barley in conventional products. In general, gluten-free items tend to exhibit higher levels of fat, sugar, and sodium compared to standard products; however, these trends can vary by product category (Fry *et al.*, 2018). Furthermore, gluten-free products are typically lower in protein and dietary fiber. The glycemic index (GI) of gluten-free items differs based on the types and quality of ingredients utilized, as well as the food processing methods employed during production (Romão *et al.*, 2021). Additionally, because gluten-free products are frequently not fortified or enriched to the same extent as various conventional items, they generally contain lower levels of folate, iron, niacin, thiamin, and riboflavin (Kaur *et al.*, 2024).

c. Functional Properties

In terms of findings related to functional properties, Table 4 indicates that water absorption capacity was the most extensively analyzed functional property, as all eight (8) retrieved articles addressed this attribute. Bulk density followed as the second most analyzed functional property, being examined in six out of eight articles, while solubility was the least analyzed functional property, with only one of the eight articles addressing it (Irondi *et al.*, 2022). The results reveal that pearl millet exhibited the highest water absorption capacity (359.33% ± 1.45) (Abolaji *et al.*, 2017) whereas white sorghum had the lowest, with a water absorption capacity of 1.07% ± 0.04 (Sharanagat & Nema, 2023). Additionally, amaranth flour demonstrated the highest oil absorption capacity (1.88 g/g ± 0.01) (Culetu *et al.* 2021) and pearl millet flour recorded the highest swelling index (8.17 mL/mL ± 0.01) (Irondi *et al.*, 2022). According to Meena *et al.* (2024), the significant water-holding capacity of pearl millet renders it suitable for various food applications, including baking, extrusion, and fortification. Bulk density serves as an indicator of a product's porosity and its wettability (Irondi *et al.*, 2022). The relatively lower values of bulk density observed may be attributed to the lack of complex structures, such as carbohydrates and proteins, in the bran of these grains (Adebo & Kesa, 2023).

d. Baking Properties

Table 5 presents the baking properties of the flours, which include cohesiveness, loaf volume, specific volume, porosity, elasticity, and firmness. The results indicate that specific volume was the most frequently analyzed parameter, with six articles published. Three of these articles (Coțovanu & Mironeasa, 2022; Filipčev *et al.*, 2017; Liu *et al.*, 2019) focused on amaranth flour, while one examined red sorghum (de Oliveira *et al.*, 2022) and another studied pearl millet (Wilson *et al.*, 2024). The highest specific volume of 4.8 cm^3/g was recorded in pearl millet flour (Wilson *et al.*, 2024). The baking properties of pearl millet flour, particularly its specific volume, have gained attention as a potential substitute for wheat flour in bread-making. Research indicates that the incorporation of pearl millet flour into bread formulations can significantly affect dough rheology and the resultant bread quality (Maktouf *et al.*, 2016). Porosity (Coțovanu & Mironeasa, 2022) and firmness (Filipčev *et al.*, 2017) were the least investigated baking properties during the period under review, as only one article reported on these attributes. Porosity is a key factor in determining the texture and overall quality of bread (Protonotariou *et al.*, 2020).

e. Summary on Baking Properties

Based on the literature search and results presented in this paper, the four flours exhibit distinct characteristics. For example, red sorghum flour demonstrates excellent cohesiveness (0.44 ± 0.03), which is critical for the quality and texture of baked goods, influencing their overall appeal and performance. Pearl millet flour possesses the highest specific volume (4.87 ± 0.01), which is essential for achieving light and airy baked products, while amaranth flour has the highest loaf volume (368.54 ± 6.0), which is important for evaluating bread quality. Among the reviewed gluten-free flours, amaranth flour stands out for its superior overall baking properties, including loaf volume, specific volume, porosity, elasticity, and firmness Table 5. These attributes render it a favorable choice for individuals seeking gluten-free alternatives without compromising quality. However, when compared to traditional wheat flour, wheat exhibits the best overall baking properties.

Table 3. Comparative Nutritional Profiles of Sorghum, Pearl Millet, and Amaranth Flours Across Literature Data

Article	Calcium (mg/g)	Zinc (mg/g)	Iron (mg/g)	Sodium (mg/g)	Phosphorus (mg/g)	Crude Fiber (%)	Protein (%)	Ash (%)	Fats (%)	Carbs (%)
Pearl Millet										
Article 3	0.23		0.11	1.33	1.52		16.10±0.02	3.92±0.02	5.1±0.2	43±0.1
Article 4	129.91±2.7		1.78±11.6		26.85±60.1	1.06±0.0	8.38±0.33	1.68±0.1	7.05±0.7	69.44±4.2
Article 6						1.20±0.01	10.99±0.00	4.37±0.01	1.83±0.01	
Article 29	30.8±0.78	2.14±0.16	3.51±0.04	42.8±1.54			11.12±0.30	1.67±0.02	5.28±0.41	
Article 30						0.60±0.02	11.96±0.01	2.6±0.28	6.06±0.2494	49.03±0.03
Red Sorghum										
Article 1							1±0.002	1.5±0.070		
Article 5						3.50±0.12	9.47±0.20	1.33±0.01	1.58±0.38	84
Article 14	0.017±0.006	13.13±2.37	28.93±4.20		0.30±0.02	2.47±0.15	8.22±0.16	1.01±0.20	3.03±0.23	
Article 17						2.48±0.1	11.73±0.04	1.64±0.12	3.00±0.31	71.57±1.03
Article 19						14.9±0.01	11.06±0.19	1.41±0.06	3.6±0.20	69.54±0.09
Article 24						8.49±1.09	6.83±0.36	1.56±0.01	4.28±0.04	49.74±0.23
White Sorghum										
Article 1							22.2±0.007	1.5±0.014		
Article 5						4.09±0.14	11.61±0.12	1.22±0.09	1.69±0.37	81
Article 14	0.017±0.006	13.20±1.28	25.20±1.91		0.38±0.03	2.47±0.15	9.95±0.27	1.26±0.27	2.69±0.36	
Article 24						10.07±0.94	10.15±0.02	1.55±0.02	4.07±0.38	55.15±2.51
Article 25						12.70±0.85	12.55±0.35	3.90±0.99	3.15±0.78	58.50±1.41
Amaranth										
Article 2						3±0.03	15.05±0.05	2.93±0.08	6.68±0.08	
Article 8							12.51±0.12	2.88±0.05	7.78±0.02	
Article 10							26.47	8.08	13.81	
Article 11	687	2.1	2.75	40.34		3.55±0.51	15.38±0.38	2.54±0.10		65.69±1.71
Article 12						4.60±0.21	13.85±0.29	2.83±0.03	6.53±0.33	
Article 13						2.21±0.02	17.14±0.12	3.61±0.05	8.02±0.05	65.71±0.16
Article 15	189.74±1.70	3.02±0.05	7.43±0.06	2.09±0.06	597.93±1.33	9.01±0.12	16.09±0.09	2.45±0.02	6.20 ± 0.03	
Article 16	1930±79	3.5 ±5.5	8.2 ±6.2	75.7±14.6		9.45±2.46	16.0±0.5	2.53±0.20	6.81±0.29	61.0 ± 2.9
Article 18						25.33±0.25	3.54±0.04	8.09±0.04	52.85±0.53	
Article 21	171.7 ± 22.0	1.1 ± 0.2	5.5 ± 1.1			15.99±2.71	15.08±0.34	2.37±0.02	6.69±0.13	
Article 22						14.20±0.60	17.51±0.50	2.82±0.05	6.54±0.02	
Article 23	2040 - 2410	3.4 - 4.2	8.21 - 13.9		4780 - 5650	3	12.34-17.7	1.7-5.1	4.9-9.8	
Article 24						5.47±0.23	17.23±0.65	2.85±0.04	8.63±1.44	45.40±1.09
Article 28						13.32±0.05	15.79±0.08		6.58 ± 0.04	

Table 4. Functional Properties of Red and White Sorghum, Pearl Millet, and Amaranth flours

Article	Solubility	Swelling Index (mL/mL)	Oil Absorption Capacity (g/g)	Foaming	Water Absorption Capacity %	Bulk Density (g/mL)
Pearl Millet						
Taylor *et al.*, (2016)				3.36±0.02	359.33±1.45	1.12±0.02
Irondi *et al.*, (2022)	15.42±0.04	8.17±0.01			105.37±0.72	
Wilson *et al.*, (2024)				2.26±0.24	2.26±0.24	0.58±0.03
Red Sorghum						
Kassa & Emire, (2021)		5.63±0.1	1.40 ±0.2		2.27±0.8	0.61±0.8
White Sorghum						
Sharanagat & Nema, (2023)			0.77±0.02		1.07±0.04	0.76±28
Amaranth						
Culetu *et al.*, (2021)			1.88±0.01		0.96±0.01	0.63±0.01
De Bock *et al.*, (2021)					2.02±0.09	
Coţovanu & Mironeasa, (2022)		4.18±0.10			2.37±0.05	0.76±0.04

Table 5. Baking properties of red and white sorghum, pearl millet, and amaranth flours

Author	Grain Type	Cohesiveness	Loaf volume (cm3)	Specific volume cm3/g	Porosity	Elasticity	Firmness (g)
Filipčev *et al.* (2017)	**Amaranth**		368.54 ± 6.0	4.00 ± 0.1			619.81 ± 107.8
Coțovanu *et al.* (2023)	**Amaranth**			2.47±0.27	67.33 ± 7.28	94.98 ± 2.45	
Liu *et al.* (2019)	**Amaranth**		327.28	1.86			914.61
de Oliveira *et al.* (2022)	**Red Sorghum**	0.44 ±0.03		3.49±0.06		0.98 ±0.01	
Adzqia *et al.*, (2023)	**White sorghum**	0.27 ± 0.03		2.11 ± 0.04			
Wilson *et al.*, (2024)	**Pearl Millet**	0.23 ± 0.07	45.1 ± 0.37	4.87 ± 0.01			

The gluten content of wheat flour provides elasticity and strength that are often lacking in gluten-free flours, leading to denser and less cohesive baked products. In summary, while red sorghum, pearl millet, and amaranth flours present unique advantages in gluten-free baking, wheat flour remains the optimal choice for superior baking performance due to its advantageous structural properties.

4 CONCLUSION

This systematic review elucidates critical insights concerning gluten-free flour sources, revealing a pronounced geographical concentration of research within European and Asian contexts. Among the matrices evaluated, red sorghum exhibited superior rheological cohesiveness, whereas pearl millet flour yielded the highest specific loaf volume. Notably, amaranth flour emerged as the superior gluten-free flour, exhibiting optimal baking properties such as loaf volume, specific volume, porosity, elasticity, and firmness. Furthermore, the bibliometric dominance of amaranth within peer-reviewed literature underlines a robust scientific impetus toward characterizing its nutritional architecture and functional performance in bakery systems.

Ultimately, these findings suggest that harnessing the potential of red sorghum, white sorghum, pearl millet, and amaranth may facilitate the increasing demand for gluten-free products. Future investigative efforts should pivot toward optimizing multi-flour blends to maximize macro- and micronutrient density. Concurrently, research must prioritize advanced formulation strategies, such as the incorporation of hydrocolloids and innovative macromolecular approaches—including enzymatic modifications and alternative biopolymers—to effectively mimic the viscoelastic gluten network and bolster overall baking performance. In conclusion, this systematic synthesis of the literature reveals that these drought-tolerant traditional grains not only serve as sustainable agronomic sources but also possess considerable potential in the gluten-free market. Their inherent climatic resilience, coupled with distinct nutritional profiles, positions them as an essential component of future secure food systems.

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