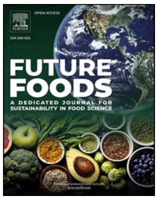
Future Foods 13 (2026) 101012

Contents lists available at ScienceDirect

Future Foods

journal homepage: www.elsevier.com/locate/fufo



Impact of processing on the nutritional, bioactive compounds and rheological behavior of sorghum in tropical climates for food applications

Nurul Farhanah Mohd Aluwi [a], Radhiah Shukri [a,*], Wan Zunairah Wan Ibadullah [b], Rabiha Sulaiman [a], Nor Afizah Mustapha [a], Roseliza Kadir Basha [c], Barakatun Nisak Mohd Yusof [d]

[a] *Department of Food Technology, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[b] *Department of Food Science, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[c] *Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[d] *Department of Dietetics, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

ARTICLE INFO

Keywords:
Sorghum flour
Milling
Grain processing
Flour-based products
Tropical food security

ABSTRACT

Background: Sorghum, agronomically adapted to tropical climates, is a key climate-resilient opportunity crop and a nutritious alternative to imported wheat, crucial for tropical food security. However, the successful integration of sorghum flour is fundamentally limited by a lack of standardized processing methods, a limited understanding of processing impacts on final quality and a substantial lack of optimized application guidelines for specific sorghum flour-based products in tropical climates.

Scope and approach: This review addresses critical gaps by systematically synthesizing findings from recent primary studies (2020–2025) on sorghum flour derived from sorghum cultivated in tropical climates. The study first establishes a comprehensive baseline for key properties (nutritional composition, bioactive compounds and rheological behavior). It subsequently evaluates the impact of various processing techniques (pre-treatment, milling, decortication, biological and thermal) on functional attributes, considering the variety's tannin classification. The final analysis examines optimal sorghum grain processing methods for maximizing textural quality, consumer acceptance and health advantages, before identifying key success factors for industrial commercialization, product innovation and favourable food policy.

Key findings and conclusions: This synthesis provides the first definitive data baseline for tropical sorghum flour, identifying optimal grain processing strategies and yielding a necessary set of standardized recommendations to guide future research and high-quality commercialization. Successful commercialization is justified by its advantageous attributes, but requires a coordinated, integrated approach driven by research, industry and national policy. With this collective approach, the outlook for sorghum flour as a viable wheat alternative in tropical climates is positive.

1. Introduction

Flour-based products are consumed extensively worldwide and are critical to global food security, providing primary nutrition for billions in both developing and developed nations, with wheat being a primary ingredient (Sheng et al., 2025; Wahjuningsih, 2022). Many nations with tropical climates, however, face significant food security vulnerabilities due to their reliance on imported wheat flour, a dependency necessitated by climates unsuitable for local wheat cultivation (Gunawan et al., 2022; Yulviatun et al., 2024). This reliance exposes populations to severe food disruptions during global crises such as climate change (Endalamaw et al., 2025; Ndlovu et al., 2024), rapid population growth (Bahlawan et al., 2025), pandemics (Ariningsih et al., 2023) and wars (Jagtap et al., 2022), thereby intensifying malnutrition and food insecurity in regions where these are already persistent challenges (Ariningsih et al., 2023).

Among these crises, climate change is severely threatening global food security by disrupting agricultural productivity through drought and heat stress, negatively impacting the yield and quality of principal grains such as wheat (Endalamaw et al., 2025). Research indicates that

---

* Corresponding author.
E-mail address: radhiah@upm.edu.my (R. Shukri).

https://doi.org/10.1016/j.fufo.2026.101012
Received 26 December 2025; Received in revised form 5 March 2026; Accepted 7 April 2026

global surface temperatures are expected to rise by 3.7–4.8 °C in the 21st century (Ndlovu et al., 2024). This impact is particularly severe in tropical agroecosystems, where crops already persist near their physiological thermal limits. A recent comprehensive analysis of 30 major food crops encompassing cereals, starchy roots, pulses, oil crops and fruits across global warming levels of 1.5–4 °C identifies sorghum as the most resilient, exhibiting the least reduction among all tested crops and the highest suitability gain among major cereals. While essential tropical staples such as rice, maize and yams are projected to lose 40–60% of their safe climatic space, and major temperate grains including wheat face losses of 35–40% under severe warming of 4 °C, sorghum's unique physiological hardiness underscores why it is a critical, climate-resilient alternative for future tropical food applications (Heikonen et al., 2025).

Consequently, replacing wheat flour with locally produced cereal flours is necessary, as this economic diversification helps reduce the need for expensive wheat imports while promoting the agriculture sector in tropical countries (Vilanculos and Svanberg, 2021). This necessity aligns with the strategy advocated by the FAO since 2008, which promotes the use of available local resources for partial or total flour substitution to reduce import dependence (Bah et al., 2024). This urgency drives the exploration of sorghum (*Sorghum bicolor* L. Moench), a globally significant crop that emerges as a critical strategy to overcome malnutrition and rectify supply shortfalls (Bah et al., 2024). As the world's fifth most important cereal (FAOSTAT, 2023), sorghum presents a logical and sustainable solution. This C$_4$ crop (Farha et al., 2025) is inherently climate-resilient, demonstrating efficient water utilization and tolerance to drought (Joseph et al., 2025; Souza et al., 2025) and high temperatures (Medina Martinez et al., 2020). Importantly, researchers indicate that under drought stress, sorghum exhibits higher growth, yield and better nutritional value compared to other cereals (Ussembayeva et al., 2024). Its robust nature extends to a tolerance for high levels of O$_3$ pollution in tropical field conditions (Farha et al., 2025) and adaptability to grow in poor-nutrient soils (Bahlawan et al., 2023), making it vital in many semi-arid tropical regions across Africa, Asia and Latin America where other staples like wheat, rice or maize cannot be sustainably cultivated (Farha et al., 2025).

Major organizations such as the Vision for Adapted Crops and Soils (VACS) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have identified sorghum as a key climate-resilient opportunity crop, further underscored by its established role as food aid in crisis-affected regions (Joseph et al., 2024). Moreover, the majority of the world's top ten sorghum-producing nations possess tropical climates. However, with 123 countries in the tropical zone and only 76 currently cultivating it (FAOSTAT, 2023), there is a substantial, unexploited potential to reduce import dependency (Bah et al., 2024; Vilanculos and Svanberg, 2021).

In addition to its strong agronomic resilience, sorghum's nutritional profile confirms its role as a "climate-smart" grain (Rumler et al., 2021). Furthermore, its enhanced nutritional profile confers considerable health benefits and physiological effects compared to conventional wheat flour consumption (Fig. 1). Additionally, sorghum provides economic benefits as a cost-effective, non-genetically modified substitute that is readily available in developing countries (Joseph et al., 2025). This increasing global interest further underscores sorghum's potential. For instance, in Brazil, there is increased scientific interest in using sorghum for human nutrition (Bianco-Gomes et al., 2022). Furthermore, national initiatives like the Indonesian President's sorghum roadmap encourage production (Kristanti et al., 2023) and developed countries such as Germany are exploring its cultivation as a climate change adaptation strategy (Hajjarpoor et al., 2023).

However, despite its advantages, sorghum flour remains significantly underutilized in the global food industry due to low public awareness and underdeveloped, unstandardized milling technologies (Ervina et al., 2023; Wang et al., 2020) compared to major cereals like wheat, rice and maize (Yoganandan et al., 2021). Traditional milling methods often result in coarser sorghum flour, high endosperm loss and inconsistent

NUTRITIONAL COMPOSITION AND PHYSIOLOGICAL EFFECTS OF SORGHUM FLOUR AS A WHEAT FLOUR ALTERNATIVE

Nutritional Metrics	Sorghum Flour vs. Wheat Flour	References
Dietary Fiber	2.1× Higher	Ussembayeva et al. (2024); Xu et al. (2021)
Beneficial Lipids	2.6× Higher	
Lysine	1.5× Higher	
Threonine	1.5× Higher	
Essential Minerals	Higher: Ca (7.3×), Fe (2×), K (5×), Zn (4×), Mn (4×), Cu (56×)	
Vitamins (B)	1.3× – 6× Higher	
Vitamin C	2.68 mg/100 g vs. Traces	
Antioxidant Capacity	High (104.48–123 µMol TE/g) vs. Low (15 µMol TE/g)	Aisha & Kurniasih (2024)
Glycemic Index (GI)	Low GI (36–46.8) vs. High GI (60–75)	Djou et al. (2024); Lal et al. (2021); Naveed et al. (2024); Setyowati et al. (2023)
Resistant Starch (RS)	High RS (27.5–65.7 g/100 g) vs. Low RS (0.1–2.5 g/100 g)	Jia et al. (2025); Lal et al. (2021); Taylor & Duodu (2022)

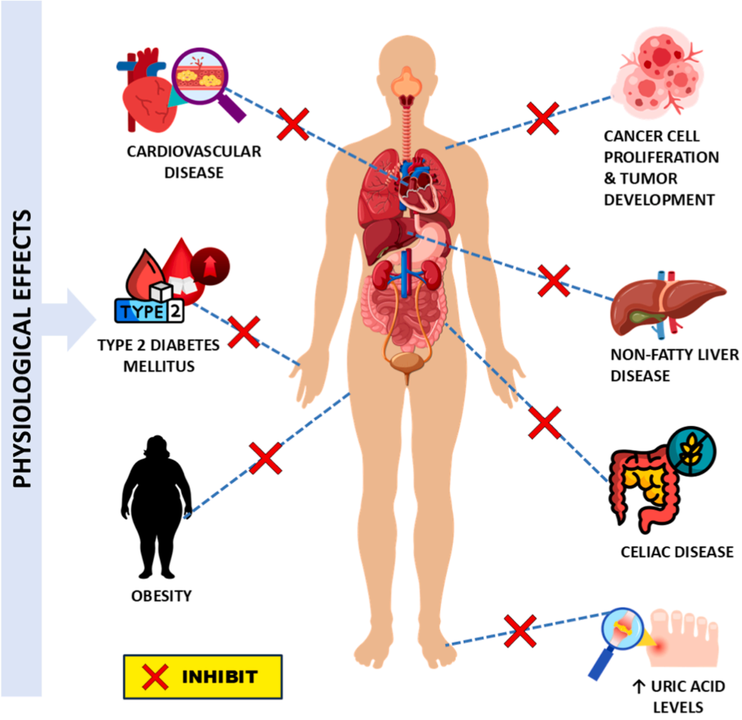


Fig. 1. A comparative overview of the nutritional composition of sorghum and wheat flours, highlighting the physiological mechanisms of sorghum flour as a future food for tropical food security. Illustration of physiological effects was conceptualized and synthesized from Achalu et al. (2025); Aisha and Kurniasih (2024); Djou et al. (2024); Jia et al. (2025); Lal et al. (2021); Medina Martinez et al. (2020, 2021); Naveed et al. (2024); Pinheiro et al. (2021); Ussembayeva et al. (2024).

quality, complicating its use in scalable industrial applications (Ariningsih et al., 2023; Yoganandan et al., 2021). Additionally, inherent limitations of sorghum flour quality, such as a gritty texture, lack of gluten for dough viscoelasticity and potential astringency from polyphenolic compounds, negatively impact consumer acceptability, making various processing methods essential to enhance the flour's palatability (Antarlina et al., 2021) and safety (Bahlawan et al., 2025). This market gap is further compounded by a research disparity that predominantly focuses on raw sorghum grain nutrition and end-product formulation rather than fundamental milling and flour functionality (Yoganandan et al., 2021). This oversight is critical, as processing methods can negatively affect the antioxidant profile, colour and texture of the final sorghum flour-based products. It is therefore necessary to choose an optimal processing method to maximize both health benefits and consumer acceptance (Tadeu da Veiga Correia et al., 2022; Wang et al., 2020).

Furthermore, the reliance on US-centric databases (e.g., USDA, 2019), which predominantly feature tannin-free varieties (Palacios et al., 2021), is insufficient to represent the full varietal diversity of tropical regions cultivating both high-tannin and non-tannin types. Crucially, no comprehensive, large-scale data synthesis for these tropical sorghum varieties currently exists; even recent reviews (e.g., Majzoub et al., 2023) remain preliminary, deriving findings from limited primary studies in the semi-arid tropics.

To address this critical gap, this review systematically synthesizes data from recent primary studies (2020–2025) on the processing and application of sorghum cultivated across tropical climates globally. To establish the first definitive, climate-specific baseline for the field, 116 independent experimental observations were extracted to characterize the nutritional composition, bioactive compounds and rheological behavior of tropical sorghum flour. Building upon this fundamental baseline, this work systematically evaluates the impact of common milling techniques and assesses the efficacy of various postharvest pre-treatment, biological and thermal processing methods. By analyzing these properties alongside their subsequent food applications, this review proposes a set of standardized, optimized processing recommendations intended to guide industrial and household applications.

2. Review methodology

2.1. Search strategy and scope

To provide a comprehensive data synthesis for sorghum flour research in tropical climates, a systematic search was conducted on June 28, 2025, using the Scopus database. This review was structured and reported in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. Scopus was selected as the sole database due to its broader coverage of food science journals compared to other databases (Thelwall, 2018), as well as its extensive, multidisciplinary indexing of peer-reviewed literature (George et al., 2022). The search was limited to a five-year period (2020–2025) to ensure the inclusion of the most recent advancements in sorghum grain science and processing. Search terms included combinations of: 'sorghum', 'sorghum flour', 'grain processing' and 'milling'. To be included in the synthesis, articles were required to be original, peer-reviewed research published in English. Review articles, book chapters and patents were excluded.

2.2. Inclusion and screening criteria

A critical inclusion criterion was the explicit reporting of quantitative data on sorghum varieties specifically cultivated in tropical regions. For studies from partially tropical countries (e.g., Brazil, India), a manual screening of the methodology section was performed to ensure the cultivation area was located within a recognized tropical zone (e.g., Tamil Nadu in India). Furthermore, as a critical screening criterion applied to generate the baseline data, independent experimental observations were only included if the flour was produced by direct milling without any preceding pre-treatment (such as soaking, germination, fermentation or thermal processing). The impact of these specific pre-treatments, which significantly modify flour properties, is analysed separately in Section 4. Following the PRISMA framework (Fig. 2), a final dataset of 69 primary studies was obtained through this multi-stage screening process. To generate the baseline data, 116 independence experimental observations were extracted, comprising 100 for whole grain sorghum flour ($n = 100$) and 16 for refined sorghum flour ($n = 16$).

2.3. Data extraction, classification and synthesis

A standardized data extraction form was created to compile all relevant metrics from the selected studies. This required a multi-level data sorting process. First, data were categorized as either 'whole grain sorghum flour' or 'refined sorghum flour' based on the authors' reported procedures (e.g., the presence or absence of "decortication," "dehulling" or "polishing"). A notable limitation is the inherent variability in this classification across primary studies, as the descriptions provided by the original authors often lacked a standardized milling procedure regarding extraction rates or the specific inclusion of bran and germ fractions. Consequently, this heterogeneity may contribute to some variability in the reported nutritional, bioactive and rheological outcomes.

Second data were sub-categorized based on the sorghum variety's tannin content, extracted from authors' descriptions, into three groups: 'tannin-present', 'tannin-absent' and 'unspecified tannin'. All nutritional metrics were standardized to a dry matter (DM) basis for comparability. Across the 116 independent experimental observations, the evaluated sorghum was cultivated and processed in tropical climates. Under these geographic conditions, milled sorghum naturally equilibrates to a consistent ambient moisture range that prevents microbial spoilage (Célia et al., 2024). Crucially, this typical tropical moisture range safely complies with the Codex Alimentarius Commission (2023a), which mandates a maximum moisture limit of 15% for commercial refined sorghum flour. This climatic and regulatory consistency ensures a negligible margin of error when standardizing the nutritional and bioactive profiles across the dataset.

Given the absence of variance measures (e.g., standard deviations) in a subset of the primary studies, a formal meta-analysis or weighted approach was not mathematically viable. To maximize data inclusion without statistical distortion, the 'Synthesized Findings' represent the compiled range (minimum–maximum) and the calculated unweighted arithmetic mean. To ensure a comprehensive representation of this data range, no formal outlier screening was conducted; extreme upper and lower bounds were specifically retained because these values reflect inherent biological diversity (e.g., specific high-tannin genotypes) and technological heterogeneity (e.g., milling parameters) across the literature, rather than experimental errors. Despite the non-reporting of variance, the extracted mean values were derived from rigorous experimental designs with confirmed statistically significant differences ($p < 0.05$), as demonstrated by primary studies such as Mukkun et al. (2021) and Tasie and Gebreyes (2020).

Finally, a qualitative thematic synthesis was performed to identify optimized processing parameters and food application implications using an inductive and data-driven approach. For Section 4, data were stratified by processing technology (pre-treatment, milling, biological and advanced thermal) to correlate specific variables with their nutritional, bioactive and rheological impacts. Optimal parameters were derived by identifying ranges that maximized nutrient retention while minimizing anti-nutritional factors. In Section 6, studies were categorized by sorghum flour-based product type to evaluate the techno-functional feasibility of sorghum substitution and its subsequent impacts on metabolic health. This synthesis identifies optimal inclusion levels that maximize nutritional benefits without adversely affecting

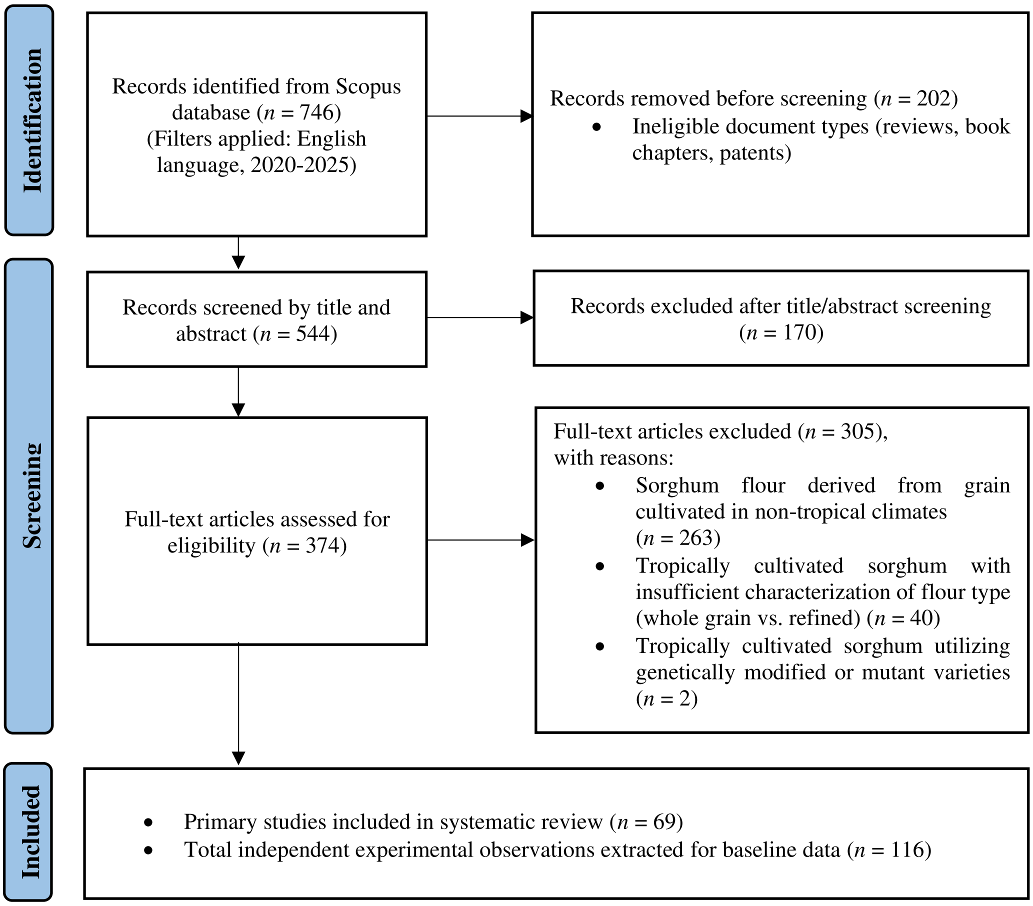


Fig. 2. PRISMA 2020 flow diagram illustrating the identification, screening, and inclusion of primary studies and independent experimental observations.
Note: From the 69 included primary studies, a subset of 39 studies was utilized to establish the nutritional, bioactive and rheological baselines for tropical sorghum flour. This yielded 116 independent experimental observations (100 for whole grain and 16 for refined flour), because distinct sorghum varieties (tannin-present, tannin-absent and unspecified tannin) or processing technologies within a single primary study were treated as separate cases (*n*). The remaining primary studies were utilized for the qualitative synthesis of processing and food applications. Detailed data sources, including the number of primary studies and independent experimental observations used, are provided in the footnotes of the respective tables.

sensory acceptability. These technical findings were then synthesized into actionable ‘Key Success Factors’ for industry commercialization and policy implementation.

3. Synthesized findings on sorghum flour properties in tropical climates

To provide a comprehensive comparative analysis of sorghum flour quality, global standards must be referenced alongside primary data. This section synthesizes the quantitative data for two distinct flour categories. Table 1 presents the nutritional profile of whole grain sorghum flour derived from tropical regions, benchmarked against the established reference values from the United States Department of Agriculture (USDA). This comparison is vital for validating the nutritional stability of tropical sorghum varieties under high-temperature growth conditions, thereby establishing a globally recognized compositional baseline for these regional varieties. Surpassing the USDA reference values indicates that these varieties exhibit exceptional nutritional resilience, maintaining or even enhancing their accumulation of essential macro- and micronutrients despite exposure to environmental stress. This highlights the potential of tropical sorghum as a high-value gluten-free alternative and an important source of essential minerals.

For the purpose of comparative analysis, Table 2 focuses on refined sorghum flour, which is essential for assessing compliance with international trade parameters. The global quality standard for this product is established by the Codex Alimentarius International Food Standards, a joint FAO/WHO body. The standard 'Sorghum Flour (CXS 173-1989),' most recently amended in 2023, specifically applies to refined sorghum flour obtained by removing the seed coat and most of the germ during industrial milling. Consequently, adherence to these standards is a prerequisite for integrating tropical sorghum into global supply chains (Orr et al., 2020), ensuring that regional processing capabilities align with international safety and quality specifications. Therefore, Table 2 presents a direct comparison of the tropical sourced data against the mandatory minimum and maximum limits set by the Codex Alimentarius Commission (2023a). This evaluation is crucial for assessing international trade quality, particularly regarding factors such as ash, crude fat and tannin content.

3.1. Nutritional composition

The nutritional content and chemical composition of sorghum flour are highly variable. This variation is primarily influenced by genetic factors, particularly genotypes and cultivars (A’yunin et al., 2022; Usman et al., 2024), as well as environmental conditions (e.g., agroecology, climate, temperature, soil fertility) (Indrianingsih et al., 2023; Tasie and Gebreyes, 2020), degree of maturity of the sorghum grain (Indrianingsih et al., 2023; Shinda et al., 2022) and post-harvest factors like the milling system (Usman et al., 2024). A comparative analysis, synthesizing findings from 116 independent experimental observations (2020–2025), indicates that refined sorghum flour (Table 2) meets the

Table 1
Nutritional composition of whole grain sorghum flour from various varieties: A comparative synthesis of findings from tropical regions (2020–2025), review literature and USDA data.

Components		Synthesized Findings: Tropical Regions (2020–2025)			Recent Review article (Majzoub et al., 2023) Semi-Arid Africa		USDA (2019)	
		(*n*)[a]	Range Value (100 g)	Mean Value (100 g)	(*n*)[b]	Range Value (100 g)	Standard Range Value (100 g)	Standard Reference Value
Macronutrients	Moisture (g)	94	3.32–14.45	10.68	n/a	n/a	9.04–11.40	10.30
	Protein (g)	100	4.17–16.48	10.04	2	4.00–21.00	6.75–10.80	8.43
	Total lipid (fat) (g)	95	0.54–5.43	3.14	2	2.00–7.00	3.01–3.61	3.34
	Ash (g)	86	0.68–3.38	1.64	2	1.00–3.00	1.22–1.40	1.32
	Carbohydrate (g)	92	62.14–88.04	74.32	n/a	n/a	n/a	76.60
	Fiber, total dietary (g)	8	6.23–35.20	14.61	2	1.00–3.00	4.40–8.20	6.60
	Starch (g)	24	47.72–99.76	71.66	2	55.00–75.00	n/a	68.00
	Amylose (g)	34	7.29–26.48	18.54	2	20.00–30.00	n/a	n/a
Minerals	Fe (mg)	12	0.02–26.10	10.89	2	1.00–20.00	2.48–3.90	3.14
	Zn (mg)	12	0.22–7.80	4.04	n/a	n/a	1.25–2.36	1.63
Vitamins	Niacin (mg)	1	3.14	3.14	2	3.00–6.00	3.63–5.62	4.50
	Folate, total (μg)	1	50.00	50.00	n/a	n/a	11.00–43.00	25.00
	α-tocopherol (E) (mg)	4	0.90–3.40	1.90	n/a	n/a	0.40–0.61	0.50

Data Source: The findings were synthesized from a subset of 31 primary studies out of the 69 total included primary studies that specifically reported direct-milling baseline metrics. Specific details for each finding, including the varieties (tannin-present, tannin-absent and unspecified tannin), tropical countries and references, are provided in Tables 3 and 5.
(*n*)[a]: Number of independent experimental observations extracted from the primary studies for each specific parameter.
(*n*)[b]: A recent literature review provided a range of values for whole grain sorghum flour, citing two primary studies.
Range Value: The primary indicator of variability across the synthesized findings, a method necessitated by the absence of variance measures (e.g., standard deviations) in a subset of the primary data.
n/a: Data not available.
Abbreviations: Fe: iron; Zn: zinc.

Table 2
Chemical composition of refined sorghum flour from various varieties: Synthesized findings from tropical regions (2020–2025) benchmarked against the Codex Alimentarius Commission (2023a).

Components	Synthesized Findings: Tropical Regions (2020–2025)			Codex Standard Limits (CXS 173-1989, 2023 Amendment) (% DM) Codex Alimentarius Commission (2023a).
	(*n*)	Range Value (% DM)	Mean Value (% DM)	
Moisture (% m/m)	13	5.76–10.41	8.83	Max 15.00
Protein	16	6.35–10.50	8.21	Min 8.50
Crude fat	16	0.32–2.86	1.63	Min 2.20–Max 4.70
Ash	16	0.44–1.50	1.03	Min 0.90–Max 1.50
Crude Fiber	4	0.48–3.62	1.27	Max 1.80
Tannin	4	0.05–6.16	1.59	Max 0.30

Data Source: The findings were synthesized from a subset of 5 primary studies out of the 69 total included primary studies that specifically reported baseline metrics for refined flour. Specific details for each finding, including the varieties (tannin-present, tannin-absent and unspecified tannin), tropical countries and references, are provided in Tables 3 and 4.
(*n*): Number of independent experimental observations extracted from the primary studies for each specific parameter.
% DM: Percentage on a dry matter basis. All synthesized values in these columns, except for moisture content, have been calculated or confirmed on a dry matter basis to ensure direct comparability with the Codex Standard (CXS 173-1989).
Statistical Limitation: Parameters with a low number of independent experimental observations, specifically crude fiber ($n = 4$) and tannin ($n = 4$), possess limited statistical robustness. Derived from a restricted dataset within the 5 primary studies, these specific synthesized ranges may not comprehensively represent the broader processing variability across all tropical regions.

standard quality parameters set by the CXS 173-1989 (Codex Alimentarius Commission, 2023a). Meanwhile, whole grain sorghum flour (Table 1) consistently demonstrates an enhanced nutritional profile compared to USDA standards, highlighting the potential of regional varieties both before and after the refining process.

The fundamental composition of sorghum flour originates from the mature sorghum kernel, which is composed of three main parts, with proportions varying by genetic background and environment, namely the endosperm (storage tissue $\approx$ 80%), the germ (embryo $\approx$ 10%) and the pericarp (seed coat $\approx$ 8%). In the context of flour production, the pericarp is concentrated with non-starch polysaccharides and polyphenolic compounds, including tannins and 3-deoxyanthocyanidins (which impact the final flour's colour) (Shinda et al., 2022). The germ contributes B-group vitamins (thiamine, niacin, riboflavin), minerals (ash) and lipids to the flour, while the endosperm primarily consists of starch granules and storage proteins.

Sorghum flour's carbohydrates and starch are a crucial energy source in global diets (Tasie and Gebreyes, 2020). The general starch content in sorghum is known to range broadly, typically between 32.1–72.5 g/100 g (Shinda et al., 2022). The average total carbohydrate content for whole grain sorghum flour is reported at 74.32 g/100 g ($n = 92$); with starch content specifically averaging 71.66 g/100 g ($n = 24$) across tropical whole grain varieties (Table 1). Starch, the main carbohydrate component, exists as water insoluble semi-crystalline granules composed mainly of amylose and amylopectin (81.0–96.5%) (Kurniadi et al., 2021; Shinda et al., 2022). The literature reports an amylose content range of 3.5–19.0%, with the present synthesized findings (Table 1) showing an average of 18.54% within this upper limit (Shinda et al., 2022). The ratio of these two components is a primary determinant of functional applications. Specifically, this intermediate amylose level favours the retrogradation required for rigid products like noodles (Saeed Omer et al., 2025), though it may present challenges for bakery goods, such as cakes and breads (Petri et al., 2026). Beyond functionality, this ratio also affects digestibility and GI (Irondi et al., 2022; Shinda et al., 2022). Starch is nutritionally classified into rapidly digestible starch (RDS), slowly digestible starch (SDS) and RS. RS formation in the sorghum flour is enhanced by factors such as starch–protein interactions, processing methods and the presence of tannins, which form insoluble complexes (A'yunin et al., 2022; Paes et al., 2024).

Sorghum flour is an important source of dietary fiber. The average total dietary fiber (TDF) is 14.61 g/100 g, synthesized from eight independent experimental observations ($n = 8$) (Table 3) in tropical varieties, which, while falling within the USDA's established range,

Table 3
Nutritional composition of sorghum flour in tropical climates (2020–2025): A comparative synthesis of data stratified by tannin content for whole grain and refined flours.

Properties	Sorghum variety	Whole grain flour					Refined flour				
		Range of values	Mean value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References*	Range of Values	Mean Value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References*
Nutritional Composition											
Moisture (g/100 g)	Tannin Present	3.32–14.21	9.89	48	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas), Ethiopia, Indonesia, Kenya and Nigeria	[g, i, j, s, t, u, v, w, aa, cc, ff, hh]	5.76	5.76	1	Indonesia	[v]
	Tannin Absent	10.11–14.45	11.73	13	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia and Nigeria	[b, g, u, hh]	n/a				
	Unspecified Tannin	3.06–14.16	11.40	33	Brazil (Tropical Area Goiás & EMBRAPA Sete Lagoas), Burkina Faso, Ethiopia, Ghana, India (Tropical Area Patancheru & Tamil Nadu), Indonesia, Thailand and Uganda	[a, d, f, h, l, m, n, o, p, r, ee, gg]	6.59–10.41	9.09	12	India (Tropical Area Hyderabad) and Indonesia	[e, k, z]
Ash (g/100 g)	Tannin Present	0.87–2.29	1.57	41	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas), Ethiopia, Indonesia, Kenya and Nigeria	[g, i, j, s, t, u, v, w, aa, ff, hh]	1.00–1.50	1.22	4	Indonesia	[q, v]
	Tannin Absent	1.19–2.10	1.57	13	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia and Nigeria	[b, g, u, hh]	n/a				
	Unspecified Tannin	0.68–3.38	1.76	32	Brazil (Tropical Area Goiás & EMBRAPA Sete Lagoas), Burkina Faso, Ethiopia, Ghana, India (Tropical Area Hyderabad, Patancheru & Tamil Nadu), Indonesia and Uganda	[a, c, d, f, h, n, o, p, r, bb, ee, gg]	0.44–1.42	0.96	12	India (Tropical Area Hyderabad) and Indonesia	[e, k, z]
Protein (g/100 g)	Tannin Present	4.17–16.48	10.51	53	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas), Ethiopia, Indonesia, Kenya, Nigeria and Sudan	[g, i, j, t, u, v, w, x, y, aa, cc, ff, hh]	8.90–10.50	9.63	4	Indonesia	[q, v]
	Tannin Absent	8.43–13.65	11.56	13	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia and Nigeria	[b, g, u, hh]	n/a				
	Unspecified Tannin	5.09–13.43	8.73	34	Brazil (Tropical Area Goiás & EMBRAPA Sete Lagoas), Burkina Faso, Ethiopia, Ghana, India (Tropical Area Hyderabad, Patancheru & Tamil Nadu), Indonesia and Uganda	[a, c, d, f, h, m, n, o, r, bb, ee, gg]	6.35–9.80	7.74	12	India (Tropical Area Hyderabad) and Indonesia	[e, k, z]
Fat (g/100 g)	Tannin Present	1.30–4.60	3.03	48	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas), Ethiopia, Indonesia, Kenya and Nigeria	[g, i, j, s, t, u, v, w, aa, cc, ff, hh]	1.00–2.86	1.74	4	Indonesia	[q, v]
	Tannin Absent	1.95–5.43	3.72	13	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia and Nigeria	[b, g, u, hh]	n/a				
	Unspecified Tannin	0.54–5.06	3.06	34	Brazil (Tropical Area Goiás & EMBRAPA Sete Lagoas), Burkina Faso, Ethiopia, Ghana, India	[a, c, d, f, h, m, n, o, p, r, bb, ee, gg]	0.32–2.08	1.59	12	India (Tropical Area Hyderabad) and Indonesia	[e, k, z]

(*continued on next page*)

Table 3 (*continued*)

Properties	Sorghum variety	Whole grain flour					Refined flour				
		Range of values	Mean value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References*	Range of Values	Mean Value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References *
					(Tropical Area Hyderabad, Patancheru & Tamil Nadu), Indonesia and Uganda						
Total Dietary Fiber (TDF) (g/100 g)	Tannin Present	10.81–20.45	15.34	3	Brazil (Tropical Area EMBRAPA Sete Lagoas)	[g, aa, ff]	11.40–15.70	13.07	3	Indonesia	[q]
	Tannin Absent	10.09	10.09	1	Brazil (Tropical area EMBRAPA Sete Lagoas)	[g]	n/a				
	Unspecified Tannin	6.23–35.20	28.80	4	Ethiopia, India (Tropical Area Hyderabad), Indonesia and Uganda	[c, h, p, ee]	n/a				
Crude Fiber (g/100 g)	Tannin Present	n/a					3.62	3.62	1	Indonesia	[v]
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	n/a					0.48– 0.49	0.48	3	India (Tropical Area Hyderabad)	[e]
Total CHO (g/100 g)	Tannin Present	62.14 –85.68	73.83	47	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas), Ethiopia, Indonesia and Kenya	[g, j, s, t, u, v, w, aa, cc, ff, hh]	76.80–86.00	80.05	4	Indonesia	[q, v]
	Tannin Absent	68.60 –76.00	71.42	13	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia and Nigeria	[b, g, u, hh]	n/a				
	Unspecified Tannin	70.11–88.04	76.22	32	Brazil (Tropical Area EMBRAPA Sete Lagoas), Burkina Faso, Ethiopia, Ghana, India (Tropical Area Patancheru & Tamil Nadu), Indonesia and Uganda	[a, c, f, h, m, n, o, p, r, bb, gg]	78.06–87.06	81.07	12	India (Tropical Area Hyderabad) and Indonesia	[e, k, z]
Iron (Fe) (mg/100 g)	Tannin Present	0.02–26.1	12.47	8	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia, Nigeria and Sudan	[i, j, x, aa]	n/a				
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	2.39 –13.81	7.73	4	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia, India (Tropical Area Karnataka) and Indonesia	[c, p, gg]	n/a				
Zinc (Zn) (mg/100 g)	Tannin Present	0.22 –7.80	4.48	8	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia, Nigeria and Sudan	[i, j, x, aa]	n/a				
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	1.57–4.62	3.16	4	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia, India (Tropical Area Karnataka) and Indonesia	[c, p, gg]	n/a				
Vitamin B3 (Niacin) (mg/100 g)	Tannin Present	n/a					n/a				
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	3.14	3.14	1	Indonesia	[p]	n/a				
Vitamin B9 (Folate) (mg/100 g)	Tannin Present	n/a					n/a				
	Tannin Absent	n/a					n/a				

(*continued on next page*)

Table 3 (*continued*)

Properties	Sorghum variety	Whole grain flour					Refined flour				
		Range of values	Mean value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References*	Range of Values	Mean Value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References *
	Unspecified Tannin	0.05	0.05	1	Indonesia	[p]	n/a				
Vitamin E (α-tocopherol) (mg/ 100 g)	Tannin Present	0.90 –3.40	1.8	3	Indonesia	[p]	n/a				
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	2.22	2.22	1	Brazil (Tropical Area EMBRAPA Sete Lagoas)	[dd]	n/a				

Data Source: The findings were synthesized from a subset of 34 primary studies out of the 69 total included primary studies.
(*n*): Number of independent experimental observations extracted from the primary studies for each specific parameter.
n/a: Data not available.

[*] **References:** [a] Achalu et al. (2025); [b] Adeyanju et al. (2025); [c] Souza et al. (2025); [d] Célia et al. (2024); [e] Dhanya et al. (2024); [f] Gebremedihin and Abera (2024); [g] Paes et al. (2024); [h] Ronoh et al. (2024a); [i] Sobowale et al. (2024); [j] Suraj et al. (2024); [k] Usman et al. (2024); [l] Adzqia et al. (2023); [m] Bahlawan et al. (2023); [n] Bazié et al. (2023); [o] Indrianingsih et al. (2023); [p] Winarti et al. (2023); [q] A'yunin et al. (2022); [r] Atuna et al. (2022); [s] Bahlawan et al. (2022); [t] Bianco-Gomes et al. (2022); [u] de Oliveira et al. (2022); [v] Gunawan et al. (2022); [w] Shinda et al. (2022); [x] Abdelhalim et al. (2021); [y] Almaiman et al. (2021); [z] Antarlina et al. (2021); [aa] Comettant-Rabanal et al. (2021); [bb] Lavanya et al. (2021); [cc] Mukkun et al. (2021); [dd] Pinheiro et al. (2021); [ee] Sruthi et al. (2021); [ff] Medina Martinez et al. (2020); [gg] Rebellato et al. (2020); [hh] Tasie and Gebreyes (2020).

represents a mean value more than double the USDA benchmark (Table 1). Dietary fiber (consisting of soluble and insoluble fractions) is generally located in the pericarp of the sorghum grain. The insoluble fraction (mainly cellulose and water-insoluble hemicellulose) constitutes the majority (75–90%) of the total fiber content (Mohamed et al., 2022). Functionally, this fraction provides the physical bulk essential for promoting gut motility and bowel regularity. In contrast, soluble fiber (ß-glucans and arabinoxylans), though less abundant (10–25%), plays a crucial role in metabolic health, particularly in lowering cholesterol levels (Tanwar et al., 2023). In terms of functional properties, fiber is critical in product development as its water- and oil-holding capacities (WHC and OHC) improve yield, modify texture and enhance viscosity in products requiring hydration (Tasie and Gebreyes, 2020). Additionally, dietary fiber in sorghum flour can help lower blood glucose levels by inhibiting glucose absorption (Probosari et al., 2025). However, high levels of crude fiber may bind minerals, potentially leading to essential mineral imbalance (Tasie and Gebreyes, 2020).

Consequently, the dietary fiber composition of the final sorghum flour depends entirely on the degree of pericarp removal during the milling or extraction process. A detailed analysis of the eight independent experimental observations ($n = 8$) indicates that three involved tannin-present sorghum, one was tannin-free and four were unspecified. The observed higher fiber levels in tannin-containing varieties suggest that dietary fiber's major location in the pericarp, often associated with tannins, plays a critical role in this elevation. Given that the USDA standard primarily reflects the 99% tannin-free sorghum crops grown in the United States (Palacios et al., 2021), this is in contrast to high-tannin varieties commonly cultivated in global regions like Africa. Refined sorghum flour is therefore expected to show a significant reduction in fiber (detailed in Table 2). As Table 2 reports crude fiber to align with the (Codex Alimentarius Commission, 2023a), and Table 1 reports dietary fiber, this inherent methodological difference demonstrates the loss of the nutritional value of the whole grain, even though it meets the minimal quality standard.

As a cost-effective protein source (Tasie and Gebreyes, 2020), tropical whole grain sorghum flour averages a high protein content of 10.04 g/100 g ($n = 100$), reflecting the enhanced genetic quality of regional varieties (Table 1). Sorghum protein is divided into storage proteins (prolamin or kafirin) and non-prolamin proteins (globulin and albumin) (Probosari et al., 2025). The bulk of the protein is located in the endosperm; consequently, the protein content in refined flour often shows only minor variation compared to whole grain flour (Table 2). Protein levels are, instead, heavily influenced by genotype, environmental conditions (including temperature and water availability) and soil fertility during the growth of the sorghum grain (Hatmi et al., 2021).

Whole grain sorghum flour possesses a relatively high total lipid (fat) content, averaging 3.14 g/100 g ($n = 95$, Table 1). The grain's large germ fraction contributes to this high content (Xu et al., 2021), which includes essential fatty acids like omega-6, oleic acid and palmitic acids (Yulviatun et al., 2024). This synthesized tropical average aligns closely with specific regional primary studies, such as the 3.34% total fat content reported for Indonesian sorghum flour (Yulviatun et al., 2024). Although this value is based on the tropical-specific data, it still falls within the broader range reported by the USDA and a recent review focused on semi-arid Africa (Majzoub et al., 2023). This high fat content is substantially reduced in refined flour due to germ removal (values in Table 2), a necessary step as higher fat levels in whole grain products can negatively impact flour shelf-life (Indrianingsih et al., 2023) by increasing the risk of oxidative rancidity (Xu et al., 2021).

Moisture content in whole grain sorghum flour, averaging 10.68 g/100 g ($n = 94$), is a crucial quality parameter for its durability and storage (Antarlina et al., 2021). Lower sorghum flour moisture levels (e.g., below 9–10%) are recommended for baked products and prolong shelf-life by inhibiting microbial growth (Adu et al., 2024) and reducing water activity (Antarlina et al., 2021; Xu et al., 2021). Moisture levels are influenced by factors such as sorghum starch content (due to the highly hydrophilic nature of starch) and the drying process (Bahlawan et al., 2022).

Sorghum flour contains a wide array essential functional nutrient, including β–carotene (a precursor to vitamin A), anthocyanin and other minerals, iron (Fe) (Shinda et al., 2022). Ash content, which serves as an index of total inorganic mineral material in sorghum flour (Antarlina et al., 2021), averages 1.64 g/100 g (Table 1) and shows variability attributed to agroecology (Tasie and Gebreyes, 2020). This micronutrient density, established in the present synthesized findings on sorghum flour from over 100 independent experimental observations (2020–2025), is reflected in the highly elevated levels of essential nutrients in whole grain flour (Table 1), where folate averages 50.00 μg/100 g (double the USDA standard) and Vitamin E averages 1.90 mg/100 g (nearly four-fold higher than the USDA standard). This includes other key vitamins like niacin (averaging 3.14 mg/100 g) and minerals such as Fe (averaging 10.89 mg/100 g (over three-fold higher than the USDA standard) and zinc (Zn), averaging 4.04 mg/100 g (over two-fold higher). Critically, this micronutrient density is significantly reduced in refined sorghum flour due to the loss of the germ and pericarp, which is quantitatively evidenced by the reduction in ash content in Table 2, emphasizing the importance of biofortification (Abdelhalim et al., 2021).

3.2. Bioactive compounds

Sorghum flour is recognized as a significant food source of bioactive compounds and antioxidants, largely due to the presence of phenolic components, alongside dietary fibers like RS and *β*-glucan (Abdelhalim et al., 2021; Probosari et al., 2025) . The bioactive profile of sorghum flour includes phenolic acids, flavonoids, condensed tannins (CT) (Bianco-Gomes et al., 2022; D'Almeida et al., 2021), anthocyanins, phytosterols, policosanols and the carotenoids lutein and zeaxanthin (Abdelhalim et al., 2021; Irondi et al., 2022). These phenolic components are primarily responsible for the high antioxidant activity of sorghum, which is strongly correlated with its α–glucosidase inhibitory effect (Indrianingsih et al., 2023) and overall health benefits. The phenolic compounds in sorghum flour are derived from the grain's structure and are predominantly concentrated in the outer layers, specifically the pericarp (dos Reis Gallo et al., 2021), testa (D'Almeida et al., 2021) and bran (A'yunin et al., 2022).

Comparative analysis of whole grain sorghum flours from tropical regions clearly demonstrates the impact of tannins on bioactive content (Table 4). To rigorously differentiate between the high bioactive potential of specific genotypes and the nutritional baseline, while addressing methodological variations in reporting, data were stratified into tannin-present, tannin-absent and unspecified categories (Tables 3–6). This distinction is fundamental, as 'tannin-present' comprises genotypes containing CT (typically with a pigmented testa), whereas 'tannin-absent' refers to tannin-free varieties. The 'unspecified' category encompasses primary studies where the specific genotype or tannin status was not characterized. Crucially, this stratification has significant implications for storage stability, particularly in tropical climates where environmental stress accelerates physicochemical degradation.

Quantitative analysis establishes the baseline vulnerability of whole grain sorghum flour under tropical ambient temperature (29.06 °C; 57.57% relative humidity), where significant oxidative degradation occurs. Célia et al. (2024) reported that while whole grain sorghum flour remained viable throughout 12 months of storage across various packaging types (paper, polyethylene, vacuum polyethylene and polypropylene), its nutritional quality was significantly degraded. Specifically, antioxidant activity exhibited a marked decline (from 57.52% to 12.27%) alongside a reduction in lipid content (from 2.58% to 2.17%), a decline driven by oxidative reactions responsible for bitter and rancid flavours. Mechanistically, the concurrent loss of antioxidant activity results from the oxidation and polymerization of polyphenols, which reduce the number of free hydroxyl groups, a process accelerated by oxygen, high temperature and humidity. This quantitative evidence underscores the functional necessity of the high-tannin varieties identified in Table 4, as their higher initial bioactive capacity is essential to mitigate such rapid oxidative deterioration. Consequently, practical preservation strategies in such environments must prioritize vacuum polyethylene packaging to minimize water vapor transmission and oxygen exposure. While paper packaging can offer higher protection against light-induced antioxidant degradation due to its opacity, its porosity renders it unsuitable for moisture control in humid tropical climates; therefore, vacuum sealing combined with storage in dark conditions remains the most efficacious strategy for ensuring overall stability. Furthermore, this classification is critical because the presence of CT significantly affects processing outcomes, nutritional bioavailability and the rheological behavior of the resulting flour.

The mean total phenolic content (TPC) for tannin-present varieties is significantly higher at 28.50 mg/g GAE (range 3.71–83.11 mg/g GAE) across 12 independent experimental observations ($n = 12$). This contrasts sharply with the mean TPC of 1.96 mg/g GAE (range 1.54–2.39 mg/g GAE) reported for tannin-absent varieties ($n = 4$). Furthermore, unspecified tannin varieties show a high degree of variability, with a mean of 10.80 mg/g GAE (range 0.58–568.10 mg/g GAE) across a substantial number of independent experimental observations ($n = 68$). The wide disparity in TPC is suggested to be affected by variables such as genotype, cultivar, growing conditions, cultivation place, harvest handling and storage (Indrianingsih et al., 2023). This high content is driven by CT, where the mean content for tannin-present whole grain flour is 9.24 mg CE/g (range 0.04–27.11 mg CE/g) ($n = 3$) (Table 4). These data empirically confirm that coloured, tannin-containing sorghum genotypes possess a higher concentration of phenolics (A'yunin et al., 2022; Shinda et al., 2022) and a greater antioxidant capacity than white or tannin-free varieties (dos Reis Gallo et al., 2021).

Sorghum flour is suitable for patients with T2DM due to its phenolic compounds, fiber and a low-GI (Probosari et al., 2025), with reported values as low as 36 (Setyowati et al., 2023). The primary antidiabetic mechanism involves the sorghum flour's phenols and flavonoids acting as α–glucosidase inhibitors (Dwipajati et al., 2022), which delays carbohydrate digestion and glucose absorption. This inhibitory strength is notable even in refined sorghum flour, which has an IC_{50} range of 4.64–11.87 µg/mL ($n = 6$); however, the whole grain form demonstrates significantly higher functional efficacy, showing an average inhibition of 96.37% (range 95.30 to 97.43%) of α–glucosidase activity (Table 4). This suggests a near-complete inhibitory effect, highlighting the critical role of the bran or pericarp layer. Furthermore, this functional benefit is enhanced by the significant presence of RS in the whole grain, particularly in tannin-present varieties which average 25.68 g/100 g ($n = 3$) (Table 5). These RS fractions act as dietary fiber, resisting enzyme hydrolysis in the small intestine (Shinda et al., 2022) and contributing significantly to the low-GI. Importantly, cultural preferences for processing different grain varieties significantly affect their carbohydrate availability and GI (A'yunin et al., 2022).

Tannins (Bahlawan et al., 2022) and phytic acid (Joseph et al., 2025) are the primary antinutritional factors in sorghum flour. The quantitative findings on these factors and their effects on mineral content are comprehensively summarized in Table 4. As a high-molecular-weight polyphenol, tannin preferentially binds to proteins, reducing their digestibility *in vivo* (A'yunin et al., 2022; Paes et al., 2024) and imparting an undesirable astringent taste (A'yunin et al., 2022; Tasie and Gebreyes, 2020). The concentration of CT in untreated sorghum seeds can be very high, reportedly reaching up to 10.66% in certain varieties (Bahlawan et al., 2023). As shown in Table 4, whole grain sorghum flour can contain high CT, up to 27.11 mg CE/g, driven by red sorghum varieties from tropical areas like EMBRAPA, Sete Lagoas in Brazil (D'Almeida et al., 2021). These high concentrations substantiate the grain's anti-nutrient classification and significantly reduce consumer acceptability due to the pronounced tartness (Bahlawan et al., 2023). For food safety and quality, the FAO suggests a maximum safe concentration of only 0.3% for tannin in sorghum flour (Codex Alimentarius Commission, 2023a). Consequently, to meet the established standards of organizations like the FAO/WHO (via Codex Alimentarius International Food Standards), the bran and pericarp of the sorghum grain must be removed. This necessity to reduce high tannin levels is the primary reason the commercial standard for sorghum flour is refined flour rather than whole grain flour. It is noteworthy, however, that the retention of tannins at very low concentrations (specifically below 0.3% of total composition) still provides significant health benefits, including enhanced antioxidant and radical scavenging function, along with documented anticancer, anti-inflammatory, immunomodulatory, cardioprotective and antithrombotic effects (Bahlawan et al., 2022).

Phytic acid is a primary concern regarding mineral bioavailability. The phytic acid content in tannin-present whole grain flour averages 4.54 g/100 g ($n = 3$). The lower range limit of 0.00 g/100 g highlights that phytic acid can be virtually absent in specific whole grain samples, even in the presence of tannins. In contrast, refined sorghum flours can retain high concentrations of phytic acid, exemplified by a finding of 11.9 g/100 g ($n = 1$) in a high-tannin brown sorghum variety from

Table 4
Bioactive compounds of sorghum flour in tropical climates (2020–2025): A comparative synthesis of data stratified by tannin content for whole grain and refined flours.

Properties	Sorghum Variety	Whole Grain Flour					Refined Flour				
		Range of Values	Mean Value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References	Range of Values	Mean Value	(*n*)	Tropical Country/ Area of Sorghum Cultivation	References
Bioactive Compounds											
Total Phenolic (TPC) (mg/g GAE)	Tannin Present	3.71–83.11	28.50	12	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas), Ethiopia, Indonesia, Nigeria and Sudan	Abdelhalim et al. (2021); Almaiman et al. (2021); Bianco-Gomes et al. (2022); D'Almeida et al. (2021); de Oliveira et al. (2022); Irondi et al. (2022); Suraj et al. (2024)	n/a				
	Tannin Absent	1.54–2.39	1.96	4	Brazil (Tropical Area EMBRAPA Sete Lagoas)	D'Almeida et al. (2021); de Oliveira et al. (2022)	n/a				
	Unspecified Tannin	0.58–568. 10	10.80	68	Brazil (Tropical Area Goiás), Ethiopia, India (Tropical Area Hyderabad, Patancheru & Tamil Nadu) and Indonesia	Bhukya et al. (2020); Célia et al. (2024); Indrianingsih et al. (2023); Lavanya et al. (2021); Souza et al. (2025)	n/a				
Total Flavonoid (mg CE/g)	Tannin Present	5.21–46.20	27.74	6	Brazil (Tropical Area EMBRAPA Sete Lagoas) and Sudan	Abdelhalim et al. (2021); D'Almeida et al. (2021)	n/a				
	Tannin Absent	0.21	0.21	1	Brazil (Tropical Area EMBRAPA Sete Lagoas)	D'Almeida et al. (2021)	n/a				
	Unspecified Tannin	7.05–11.60	8.69	5	India (Tropical Area Patancheru & Tamil Nadu)	Lavanya et al. (2021)	n/a				
Condensed Tannin (mg CE/g)	Tannin Present	0.04–27.11	9.24	3	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia and Indonesia	D'Almeida et al. (2021); Medina Martinez et al. (2020); Suraj et al. (2024)	n/a				
	Tannin Absent	0.83	0.83	1	Brazil (Tropical Area EMBRAPA Sete Lagoas)	D'Almeida et al. (2021)	n/a				
	Unspecified Tannin	5.43	5.43	1	India (Tropical Area Hyderabad)	Sruthi et al. (2021)	n/a				
Total Tannin Content (mg TAE/g)	Tannin Present	0.00–6.73	2.52	3	Indonesia and Nigeria	Gunawan et al. (2022); Irondi et al. (2022); Sobowale et al. (2024)	0.05– 6.16	1.59	4	Indonesia	A'yunin et al. (2022); Gunawan et al. (2022)
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	n/a					n/a				
Phytic Acid (g/100 g)	Tannin Present	0.00–13.50	4.54	3	Ethiopia, Indonesia and Nigeria	Gunawan et al. (2022); Sobowale et al.	11.9	11.9	1	Indonesia	Gunawan et al. (2022)

(continued on next page)

Table 4 (*continued*)

Properties	Sorghum Variety	Whole Grain Flour					Refined Flour				
		Range of Values	Mean Value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References	Range of Values	Mean Value	(*n*)	Tropical Country/ Area of Sorghum Cultivation	References
						(2024); Suraj et al. (2024)					
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	1.15–4.01	2.30	3	Brazil (Tropical Area EMBRAPA Sete Lagoas) and Ghana	Atuna et al. (2022); Rebellato et al. (2020)	n/a				
Antioxidant Activity (DPPH) (mg/ kg AAE)	Tannin Present	n/a					n/a				
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	555.73–20,174.40	3859.64	75	Burkina Faso and India (Tropical Area Hyderabad)	Bazié et al. (2023); Bhukya et al. (2020)	n/a				
α-glucosidase inhibitory activity (Whole grain: % Inhibition; Refined: IC_{50}, μg/mL)	Tannin Present	n/a					6.27–11.87	8.40	4	India (Tropical Area Hyderabad)	Kumari et al. (2021)
	Tannin Absent	n/a					4.64–5.16	4.90	2	India (Tropical Area Hyderabad)	Kumari et al. (2021)
	Unspecified Tannin	95.30–97.43	96.37	2	Indonesia	Indrianingsih et al. (2023)	n/a				

Data Source: The findings were synthesized from a subset of 21 primary studies out of the 69 total included primary studies.
(*n*): Number of independent experimental observations extracted from the primary studies for each specific parameter.
n/a: Data not available.

Indonesia (Gunawan et al., 2022; Table 4). This variation suggests that specific tannin profiles, varietal origin and milling technique significantly affect residual phytic acid content, indicating that decortication alone is frequently insufficient for its elimination. This is a critical nutritional factor because phytic acid carries a strong negative charge and facilitates the chelation of polyvalent cations (Rebellato et al., 2020). This process primarily involves specific metal ions such as Zn (Zn^{2+}), Fe (Fe^{2+}), magnesium (Mg^{2+}) and calcium (Ca^{2+}) (Samtiya et al., 2020). The resulting interaction leads to the formation of insoluble and non-digestible complexes within the digestive tract, effectively preventing these essential ions from being absorbed by the body (Gunawan et al., 2022). Consequently, this reduces the overall bioavailability of essential minerals, particularly Fe (Joseph et al., 2025) and Zn (Tasie and Gebreyes, 2020). Notwithstanding this limitation, tannin-present whole grain sorghum flour shows high average Fe levels of 12.47 mg/100 g ($n = 8$) and Zn levels of 4.48 mg/100 g ($n = 8$) (Table 3), emphasizing the need for processing to maximize the absorption of these beneficial micronutrients.

3.3. *Rheological behavior*

The rheological and pasting profile of sorghum flour is a critical determinant of its functionality, as these properties control viscosity behavior during processing and storage (Usman et al., 2024), which directly determines the texture, digestibility and final product quality of food systems (Achalu et al., 2025). Determined by the behavior of starch and other components during hydrothermal treatment, this profile is essential for predicting the flour's performance. Fundamentally, the rheological behavior of sorghum flour is directed by its starch composition, specifically the ratio of amylose to amylopectin, which affects solubility and the degree of gelatinization (Hatmi et al., 2021). Sorghum varieties with high-amylose starches, typically exhibit lower peak viscosity (PV) (Souza et al., 2025) but higher final viscosity (FV), making them suitable for forming the strong gels required for products like films and vermicelli (Antarlina et al., 2021). In contrast, a higher proportion of amylopectin in the sorghum starch, which has a larger granule size, contributes to a softer texture (Hatmi et al., 2021) and lower FV, ideal for applications requiring thickening agents (Antarlina et al., 2021).

The transformation from raw sorghum flour to a viscous paste occurs through gelatinization and pasting. This process involves the swelling of sorghum starch granules, amylose leaching, the formation of a three-dimensional network and interactions between leached amylose and granule remnants (Irondi et al., 2022). The pasting temperature (PT), which indicates the minimum temperature needed for gelatinization (Adzqia et al., 2023), is the point where viscosity begins to rise as granules swell. PV, the maximum viscosity achieved, indicates the WHC of the sorghum flour and is correlated with final product quality (Atuna et al., 2022). It reflects the extent of granule swelling before physical breakdown (Irondi et al., 2022; Xu et al., 2021). Following this peak, breakdown viscosity (BV) measures the paste's stability during continuous heating and shearing; a lower BV value (Atuna et al., 2022) signifies greater resistance of the sorghum starch granules to disintegration (Xu et al., 2021). Finally, setback viscosity (SV) describes the tendency of the sorghum starch paste to retrograde (Xu et al., 2021) or re-associate upon cooling (Antarlina et al., 2021; Atuna et al., 2022). A high SV value is indicative of a greater tendency for retrogradation and syneresis (Adepehin, 2020; Atuna et al., 2022), while a lower value suggests better stability against gelling and water separation during storage (Antarlina et al., 2021).

A defining characteristic of sorghum rheology is the significant influence of its non-starch components. The strong, hydrophobic protein matrix, primarily composed of kafirins, encapsulates starch granules, restricting their ability to absorb water and swell (Adzqia et al., 2023; Souza et al., 2025). This encapsulation, along with the presence of

Table 5
Starch properties of sorghum flour in tropical climates (2020–2025): A comparative synthesis of data stratified by tannin content for whole grain and refined flours.

Properties	Sorghum variety	Whole grain flour					Refined flour				
		Range of Values	Mean Value	(*n*)	Tropical Country/ Area of Sorghum Cultivation	References	Range of Values	Mean Value	(*n*)	Tropical Country/Area of Sorghum Cultivation	References
Starch Properties											
Total Starch (g/100 g)	Tannin Present	47.72–99.76	89.22	8	Indonesia and Nigeria	Irondi et al. (2022); Mukkun et al. (2021)	n/a				
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	54.19–73.86	62.89	16	Burkina Faso and Indonesia	Bazié et al. (2023); Winarti et al. (2023)	n/a				
Amylose (g/ 100 g)	Tannin Present	7.29–22.75	17.12	10	Brazil (Tropical Area EMBRAPA Sete Lagoas), Indonesia and Nigeria	de Oliveira et al. (2022); Irondi et al. (2022); Mukkun et al. (2021)	21.35	21.35	1	Indonesia	Gunawan et al. (2022)
	Tannin Absent	11.50–19.25	15.91	3	Brazil (Tropical Area EMBRAPA Sete Lagoas)	de Oliveira et al. (2022)	n/a				
	Unspecified Tannin	15.38–26.48	19.59	21	Burkina Faso, India (Tropical Area Patancheru & Tamil Nadu) and Indonesia	Bazié et al. (2023); Winarti et al. (2023); Lavanya et al. (2021)	11.24–28.16	22.15	8	Indonesia	Antarlina et al. (2021)
Amylopectin (g/100 g)	Tannin Present	77.34–92.71	83.11	8	Indonesia and Nigeria	Irondi et al. (2022); Mukkun et al. (2021)	57.03	57.03	1	Indonesia	Gunawan et al. (2022)
	Tannin Absent	n/a					n/a				
	Unspecified Tannin	38.81–50.44	43.73	16	Burkina Faso and Indonesia	Bazié et al. (2023); Winarti et al. (2023)	n/a				
Resistant Starch (RS) (g/100 g)	Tannin Present	0.39–41.35	25.68	3	Brazil (Tropical Area EMBRAPA Sete Lagoas)	de Oliveira et al. (2022); Paes et al. (2024)	6.70–10.20	8.5	3	Indonesia	A'yunin et al. (2022)
	Tannin Absent	0.00–7.40	2.30	4	Brazil (Tropical Area EMBRAPA Sete Lagoas)	de Oliveira et al. (2022); Paes et al. (2024)	n/a				
	Unspecified Tannin	n/a					n/a				

Data Source: The findings were synthesized from a subset of 10 primary studies out of the 69 total included primary studies.
(*n*): Number of independent experimental observations extracted from the primary studies for each specific parameter.
n/a: Data not available.

tannins, is a primary reason why sorghum starch often requires higher transition and gelatinization temperatures compared to other cereals. Endogenous lipids (Irondi et al., 2022) and fiber (Adzqia et al., 2023) in the sorghum grain further contribute to this effect by limiting starch swelling and competing for water, thereby restricting gelatinization. Consequently, while these components can increase overall paste viscosity, their matrix-forming properties hinder the full gelatinization potential of the starch (Curti et al., 2021). This complex interplay is also dependent on sorghum genotype, growing climates and location conditions and processing methods such as milling; for instance, smaller flour particle sizes (< 100 µm) have been shown to increase PV (Xu et al., 2021).

A comparative analysis of data from tropical regions (Table 6) reveals that the rheological properties of sorghum flour are profoundly influenced by tannin content. This is particularly evident when comparing different whole grain sorghum varieties from Nigeria. Red, tannin-present sorghum flour exhibits a very high PV (2165.04 cP), indicating significant swelling capacity, but also an extremely high BV (863.52 cP), which suggests poor paste stability under heat and shear (Irondi et al., 2022; Xu et al., 2021). In sharp contrast, tannin-absent whole grain sorghum flour shows a much lower PV (953.10 cP) and a remarkably low BV (30.99 cP), indicative of a highly stable paste (Adeyanju et al., 2025). This suggests that while tannins in red sorghum varieties contribute to high initial viscosity, they may create a less stable granular structure during processing.

For sorghum varieties where tannin content is unspecified, rheological behavior varies widely based on flour type. Refined sorghum flour exhibits a significantly higher and wider range of SV (1232.50–4331.70 cP) ($n = 8$) compared to whole grain sorghum flours (877–2362 cP) ($n = 4$). This suggests that the removal of the bran and germ, which contain lipids and fiber, facilitates greater amylose retrogradation and result in a firmer, more rigid final gel (Antarlina et al., 2021). PV in these whole grain sorghum flours also shows extreme variation across different tropical regions, likely due to genetics and local growing conditions, with values reported from 861.67 cP ($n = 1$) in Ghana to 3340.00 cP ($n = 1$) in India.

Processing methods that involve enzymatic activity, such as fermentation and malting, significantly modify these properties. Fermented sorghum flour, for example, shows a low PV (865.33 cP) but is uniquely characterized by a remarkably low BV (16.33 cP) and moderate SV (900.33 cP), indicating a paste with high stability under heat and shear. Malted sorghum flour, however, exhibits the most substantial

Table 6

Pasting properties of sorghum flour in tropical climates (2020–2025): A comparative synthesis of data stratified by tannin content and grain processing (whole grain, refined, fermented and malted).

Type of flour	Tropical Country/Area of Sorghum Cultivation	PT (°C)		PV (cP)		BV (cP)		FV (cP)		SV (cP)		References
		Range of Values	Mean Value	Range of Values	Mean Value	Range of Values	Mean Value	Range Of Values	Mean Value	Range Of Values	Mean Value	
Tannin Present												
Whole grain	Nigeria	80.83	(n = 1) 80.83	2165.04	(n = 1) 2165.04	863.52	(n = 1) 863.52	2624.04	(n = 1) 2624.04	1322.52	(n = 1) 1322.52	Irondi et al. (2022)
Tannin Absent												
Whole grain	Nigeria	n/a		953.10	(n = 1) 953.10	30.99	(n = 1) 30.99	1027.75	(n = 1) 1027.75	995.45	(n = 1) 995.45	Adeyanju et al. (2025)
Unspecified Tannin												
Whole grain	Ethiopia	78.20–92.95	(n = 2) 85.58	900.50–956.00	(n = 2) 928.25	119.00–204.50	(n = 2) 161.75	696.00 – 3199.00	(n = 2) 1947.50	2362.00	(n = 1) 2362.00	Achalu et al. (2025); Gebremedihin and Abera (2024)
	Ghana	n/a		861.67	(n = 1) 861.67	18.33	(n = 1) 18.33	2845.00	(n = 1) 2845.00	2001.67	(n = 1) 2001.67	Atuna et al. (2022)
	India (Tropical Area Mumbai)	72.50	(n = 1) 72.50	3340.00	(n = 1) 3340.00	3166.00	(n = 1) 3166.00	1051.00	(n = 1) 1051.00	877.00	(n = 1) 877.00	Patil et al. (2020)
	Thailand	87.40	(n = 1) 87.40	1498.50	(n = 1) 1498.50	69.30	(n = 1) 69.30	2619.20	(n = 1) 2619.20	1190.00	(n = 1) 1190.00	Adzqia et al. (2023)
Refined	Indonesia	n/a		n/a		n/a		n/a		1232.50–4331.70	(n = 8) 2140.00	Antarlina et al. (2021)
Fermented	Ghana	n/a		865.33	(n = 1) 865.33	16.33	(n = 1) 16.33	1749.67	(n = 1) 1749.67	900.33	(n = 1) 900.33	Atuna et al. (2022)
Malted	Ghana	n/a		103.67	(n = 1) 103.67	67.33	(n = 1) 67.33	84.67	(n = 1) 84.67	48.33	(n = 1) 48.33	Atuna et al. (2022)

Data Source: The findings were synthesized from a subset of 8 primary studies out of the 69 total included primary studies.

(*n*): Number of independent experimental observations extracted from the primary studies for each specific parameter.

n/a: Data not available.

Abbreviations: BV: breakdown viscosity; FV: final viscosity; PT: pasting temperature; PV: peak viscosity; SV: setback viscosity.

changes, with its PV (103.67 cP) and gelling capacity (48.33 cP) almost completely eliminated, demonstrating a more fundamental deconstruction of the starch structure suitable for thin porridges or beverages (Atuna et al., 2022).

4. Synthesized findings on the impact of milling and grain processing on sorghum flour properties

Despite sorghum's nutritional and agronomic advantages, its commercialization is significantly limited by milling technologies that lack the standardization of major cereals (Yoganandan et al., 2021). This challenge is further complicated by trace phenolic acids (Yulviatun et al., 2024) and anti-nutritional compounds like CT that impart undesirable bitterness and astringency (Bahlawan et al., 2022). Techniques such as dehulling, soaking, pressure cooking, germination, extrusion and fermentation have been proven effective in significantly reducing the levels of tannins and other anti-nutrients like phytic acid (Shinda et al., 2022). For example, treatments like malting and fermentation can improve the bio-accessibility of crucial minerals such as Fe and Zn (Atuna et al., 2022). However, a critical challenge remains in optimizing these processes to effectively remove anti-nutrients without compromising the grain's valuable nutritional content, particularly proteins and amino acids (Bahlawan et al., 2025; Shinda et al., 2022). Furthermore, these techniques inevitably influence starch and protein digestibility as well as the overall physicochemical properties of the resulting sorghum flour, impacting its final application (A'yunin et al., 2022). Therefore, the key to achieving broader commercialization for sorghum flour, especially in tropical countries, lies in optimizing these methods. The goal is to produce a high-quality, uniform sorghum flour that not only meets industrial demands for a stable supply and competitive pricing but also preserves its nutritional value to adhere to international standards, such as those established by the Codex Alimentarius Commission (2023a) (Fig. 3). The key findings from recent primary studies (2020–2025) from tropical climates and recommended processing conditions aimed at achieving this balance are synthesized in Table 7. However, the details synthesized in Table 7 are limited to primary studies from tropical climates. This limitation is particularly evident for the milling section, as these regions often feature limited technologies and a smaller volume of research compared to non-tropical countries, especially developed nations with more extensive research programs. Notwithstanding this constraint, the subsections incorporate key principles and established methods from other countries to explain the overall concept for each processing.

4.1. *Pre-treatment and its effects*

4.1.1. *Moisture adjustment (Preconditioning)*

Moisture adjustment is a fundamental pre-treatment step for sorghum determined by two primary objectives specifically ensuring safe storage in high-humidity tropical climates and optimizing the sorghum grain for efficient milling and desirable rheological properties. In high-humidity tropical regions, such as Indonesia, sorghum grain is often harvested with high moisture levels (up to 18–20%) (Pujiharti et al., 2022). The initial adjustment step involves drying the sorghum grain to a maximum of 10–12% moisture content to prevent spoilage, fungal contamination and mold growth, thereby preserving seed quality (Ariningsih et al., 2023; Mukkun et al., 2021). This is generally lower than the maximum standard of 14.5% set by the CXS 172-1989 for sorghum grains, with lower limits being necessary depending on climate, transport and storage duration (Codex Alimentarius Commission, 2023b).

While the primary goal of initial drying is to ensure food safety and

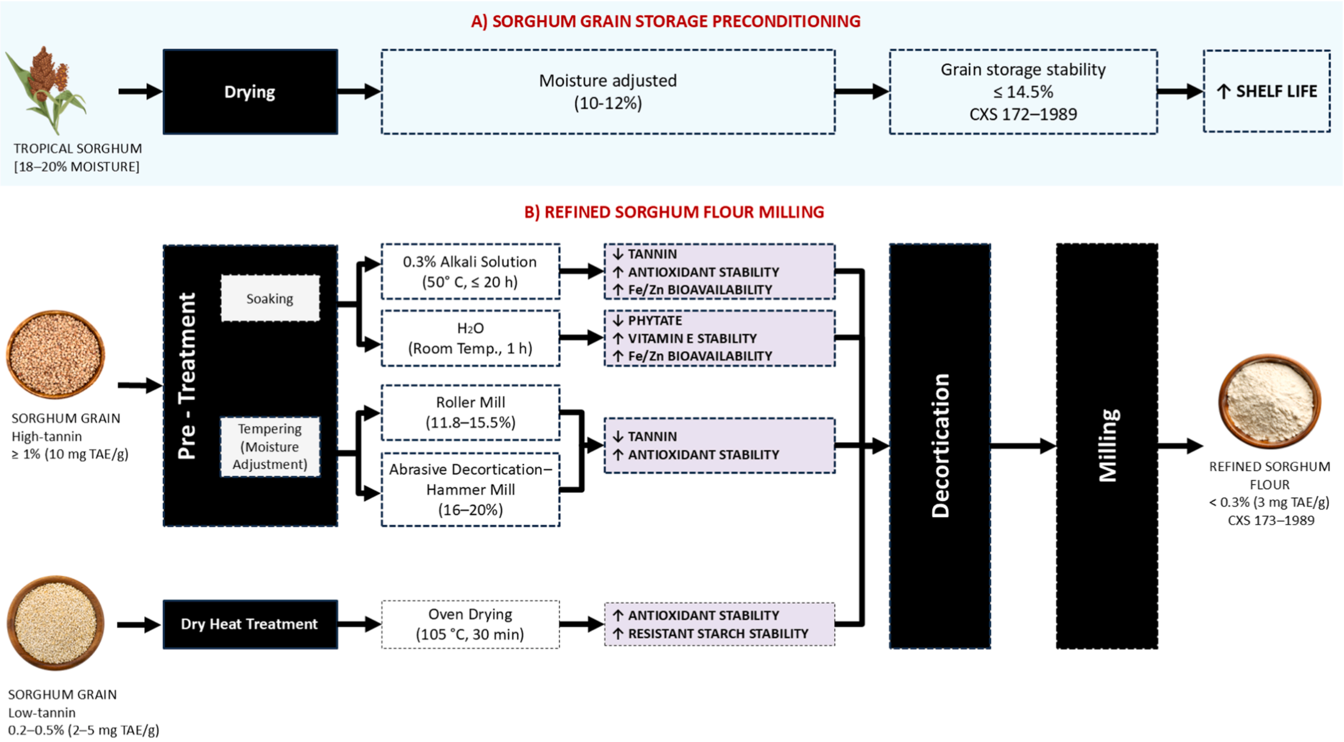


Fig. 3. (A) Tropical sorghum grain storage preconditioning. Moisture content must be adjusted to a maximum of 14.5% (m/m) following Codex Standard CXS 172–1989 (Codex Alimentarius Commission, 2023b). Lower moisture limits may be required for specific destinations depending on climate (e.g., 10–12% for tropical zones), transport duration and storage conditions. (B) Refined sorghum flour milling process producing standard sorghum flour in accordance with Codex Alimentarius Standard CXS 173–1989 (Codex Alimentarius Commission, 2023a). As defined by this standard, refined flour is produced from *Sorghum bicolor* (L.) Moench by eliminating the seed coat and germ, yielding an endosperm that is milled to the required granularity. The milling process is categorized by initial tannin content of grain, stratified into Type III (high-tannin > 1.0%) and Type II (low-tannin 0.2–0.5%), to ensure the final flour meets the standard tannin limit of < 0.3% on a dry matter basis.

Table 7
Impact of milling and grain processing technologies on sorghum flour properties in tropical climates (2020–2025): A qualitative synthesis.

Processing Technology	Key Findings on Property Impact	Optimized/Recommended Processing Conditions (Actionable Synthesis)	Geographical Context (Tropical Region)	References
Pre-treatment				
Moisture adjustment (Preconditioning) (Sorghum grain)	• Preconditioning to 16–20% facilitates optimal decortication • The combined pre-treatment process ensures the complete removal of tannins from whole grain sorghum, yielding highly refined tannin-free flour.	Recommendations: 1. Sorghum Grain Storage: 10–12% Moisture content 2. Optimal Decortication: 16–20% Moisture content	Indonesia	Ariningsih et al. (2023); Mukkun et al. (2021); Widowati and Luna (2022)
Soaking (Sorghum grain)	• Nutritional Profile: Whole grain soaking improves nutritional quality by significantly increasing crude fiber while concurrently reducing ash, fat and amylose. • Bioactive Compound Management & Anti-nutrients: Efficacy is determined by the soaking medium: 1. Alkali: Maximizes tannin reduction (≤ 86%), improves protein content and stabilizes antioxidants. 2. Water: Stabilizes α–tocopherol/ flavonoids. 3. All types enhance Fe/Zn bioavailability and maintain α-glucosidase inhibitory activity. • Functional Properties: Post-dehulling soaking is a critical step, as it enhances gelatinization temperature and pasting stability, which is essential for achieving a desirable low-GI product.	Recommendations: 1. Antioxidant/Antidiabetic Stability: Soaking duration < 20 h 2. Improved Fe/Zn Bioavailability: Water soaking (1 h) 3. Tannin Reduction: 0.3% Alkali solution at 50 °C 4. Low-GI and Pasting Stability: Post-dehulling soaking 5. Increased Mg Content: Soaking in 4% citric acid solution	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia, Indonesia and Mozambique (Tropical Area Massinga)	Antarlina et al. (2021); Bahlawan et al. (2022, 2024, 2025); Indrianingsih et al. (2023); Pinheiro et al. (2021); Tasie and Gebreyes (2020); Widowati and Luna (2022)
Dry heat treatment (Sorghum grain)	• Protein and Composition: Dry heat treatment (before milling) increases total protein content in the resulting flour due to the reduction in moisture content. • Stability and Bioactive: This treatment are effectives in maintaining high stability of critical components, including antioxidants, TPC and RS.	Recommendation: 1. Maximum Antioxidant, Phenolic, RS Stability and Increased Protein: Oven at 105 °C for 30 min (before milling)	Brazil (Tropical Area Espírito Santo & EMBRAPA Sete Lagoas) and Indonesia	Bianco-Gomes et al. (2022); Medina Martinez et al. (2020, 2021); Yulviatun et al. (2024)
Turmeric addition (Sorghum flour)	• Bioactive Enhancement: Turmeric addition significantly increases phenolic compounds and antioxidant activity in sorghum flour. • Anti-nutrient and Sensory Improvement: Turmeric acts as a multi-functional agent, reducing anti-nutritional factors while simultaneously improving sensory appeal by softening the astringent flavour. • Functional Compatibility: Crucially, this treatment achieves all benefits without negatively impacting protein solubility, ensuring functional compatibility for food applications.	Recommendation: 1. Maximum Anti-nutrient Reduction, Sensory and Antioxidants: Add 3% turmeric powder to the sorghum flour before extrusion	Brazil (Tropical Area EMBRAPA Sete Lagoas)	D'Almeida et al. (2021)
Conventional Milling Techniques				
Whole grain flour milling (Sorghum grain)	• Composition and Nutrition: Whole grain milling retains high crude fiber while increasing the total energy content (calorific value). • Functional Properties: Milled flour is often coarse, making it unsuitable for some bakery products.	Recommendations: 1. High Fiber Stability: Hammer mill 2. Smaller Particle Size Flour: Ball mill	Brazil (Tropical Area EMBRAPA Sete Lagoas) and Indonesia	Antarlina et al. (2021); A'yunin et al. (2022); D'Almeida et al. (2021)
Refined flour milling (Decorticated sorghum grain)	• Anti-nutrient & Sensory Impact: Polishing significantly reduces anti-nutrients by removing the outer layers, drastically lowers tannin content (79–92%) and removes other compounds like phenolics, crude fiber, and wax, which in turn reduces bitterness and improves sensory appeal. • Nutritional Profile: Significantly reduces fat (improving shelf-life), crude fiber, ash and minerals. This process also increases the relative starch concentration and improves bioavailability, although the net impact on protein content is variable. • Rheological Properties: Polishing results in a higher PT and decreased WAC and solubility.	Recommendations: 1. Highest Degree Refinement: Decortication, polishing and milling 2. Efficient Removal of Anti-nutrients: Mechanical dehulling (abrasive-type machine) 3. Reduce Tannin in High-tannin Varieties: 2–3 polishing cycles	Burkina Faso, Indonesia and Kenya	Antarlina et al. (2021); A'yunin et al. (2022); Bahlawan et al. (2024,2025); Kurniadi et al. (2021); Shinda et al. (2022); Sustriawan et al. (2021); Wang et al. (2020)

(continued on next page)

Table 7 (*continued*)

Processing Technology	Key Findings on Property Impact	Optimized/Recommended Processing Conditions (Actionable Synthesis)	Geographical Context (Tropical Region)	References
Biological Treatment				
Fermentation (Sorghum flour)	• Nutritional and Compositional Enhancement: Fermentation significantly increases crude protein and mineral bioavailability (Fe, Zn) due to low pH. Concurrently, the process reduces moisture, ash and crude fiber while decreasing starch and amylopectin. • Anti-nutrient Reduction: Effectively reduces anti-nutritional factors, including tannins ($\leq$ 35% reduction), phytic acid and oxalate. • Rheological Modification: Increased amylose modifies the rheology, resulting in higher PV but lower SV and BV, modifying pasting characteristics.	Recommendations: 1. LAB Type/Duration: *L. bulgaricus* ($\leq$ 48 h) for maximum crude protein and minimum phytic acid 2. Tannin Reduction Agent: Yeast fermentation ($\leq$ 35% reduction) 3. High-tannin Pre-treatment: NaOH submersion followed by fermentation (e.g., brown sorghum) 4. High Carbohydrate: Extend fermentation ($\geq$ 72 h)	Ethiopia. Indonesia, Kenya and Nigeria	Adepehin (2020); Bahlawan et al. (2022, 2024, 2025); Gunawan et al. (2022); Sobowale et al. (2024); Souza et al. (2025); Wahyuni et al. (2021); Yulviatun et al. (2024)
Germination (Sorghum grain)	• Nutritional and Digestibility Profile: Germination increases energy density, essential amino acids and minerals, but concurrently leads to a reduction in protein, fiber, flavonoid compounds and total Vitamin E content. • Anti-nutrient Reduction and Bio-accessibility: The process effectively reduces anti-nutrients (tannin, phytate, oxalate) and significantly enhances Fe/Zn bio-accessibility (up to 30%). • Functional and Rheological Impact: Amylase degradation decreases all pasting properties (PV, BV, FV and SV), but simultaneously improves WAC/OAC, swelling power and solubility.	Recommendations: 1. High Carbohydrate and Less Fat: Malt $\leq$ 2 days 2. Low-viscosity Paste / Minimized Retrogradation: Malt 96 h at 27–31 °C, 72–78% relative humidity	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ethiopia, Ghana and Indonesia	Adu et al. (2024); Atuna et al. (2022); Keyata et al. (2021, 2023); Kristanti et al. (2023); Pinheiro et al. (2021)
Enzymatic treatment (Sorghum flour)	• Targeted Anti-nutrient Removal and Mineral Bio-accessibility: Enzymatic treatment with phytase targets the anti-nutrient phytate (IP6), leading to a significant increase in the bioaccessibility of essential minerals, specifically Fe (up to 150%) and Zn (up to 266%)	Recommendations: 1. Phytase-treated Sorghum Flour: pH 4–6 2. *myo*-Inositol Phosphate Fractions: Target IP6	Brazil (Tropical Area EMBRAPA Sete Lagoas), Ghana and Nigeria	Atuna et al. (2022); Rebellato et al. (2020); Sobowale et al. (2024)
Advanced Thermal Treatments				
Roasting (Sorghum grain)	• Compositional and Physical Changes: Roasting significantly increases protein (+6.9%) and crude ash (+7.4%). Physically, it reduces bulk density and increases OAC. • Improved Rheological Stability: Leads to a low overall viscosity and an almost 40% decline in BV, indicating a paste that is more stable under hot conditions and shear stress. • Anti-nutrient Inactivation: Roasting at 70–80 °C can inactivate endogenous phytase, resulting in minimal or no reduction of phytic acid.	Recommendations: 1. Increase Protein and Paste Stability: Roast sorghum grains at 110–120 °C before milling 2. Phytic Acid Reduction: Roast sorghum grains at 110–120 °C followed by fermentation	Ghana	Atuna et al. (2022)
Toasting (Sorghum flour)	• Flour Stability and Nutritional Preservation: Toasting significantly reduces moisture content ($<$ 2%) for improved storage stability. The process maintains proximate composition, preserving high levels of RS and TDF. • Functional Modification: The dry heat partially denatures kafirin proteins, resulting in a crucial increased WAC. • *In Vivo* Health Benefits: Consumption of toasted flour has been shown *in vivo* to reduce oxidative stress, improve lipid profiles and promote liver protection.	Recommendation: 1. Toast sorghum flour at 200 °C for 6 min	Brazil (Tropical Area EMBRAPA Sete Lagoas)	Paes et al. (2024); Silva et al. (2020)

(*continued on next page*)

Table 7 (*continued*)

Processing Technology	Key Findings on Property Impact	Optimized/Recommended Processing Conditions (Actionable Synthesis)	Geographical Context (Tropical Region)	References
Extrusion (Sorghum flour)	• Nutritional and Functional Enhancement: Significantly improves starch digestibility, protein availability and viscosity control. Compositionally, it increases fiber and carbohydrates while decreasing lipids. • Bioactive Management and Sensory Appeal: The process enhance free phenolic compounds (improving accessibility) and reduces tannins, thus improving palatability. • Compound Trade-off: Extrusion can lead to the instability or degradation of sensitive compounds like flavonoids.	Recommendations: 1. Viscosity Controller (sauce/soup): Extrusion at 20–30% feed moisture with α-amylase addition 2. Bulky/Thickening Agent: Extrusion at 35% feed moisture with α-amylase addition 3.Phenolic Accessibility: Add 3% turmeric powder to the sorghum flour before extrusion	Brazil (Tropical Area EMBRAPA Sete Lagoas) and Indonesia	A'yunin et al. (2022); D'Almeida et al. (2021); Tadeu da Veiga Correia et al. (2022); Usman et al. (2024)
Advanced Thermal Treatments				
Microwave processing (Sorghum grain)	• Protein Integrity vs. Functionality: While protein content and digestibility are maintained, microwave treatment causes significant reduction in protein solubility and emulsifying/foaming capacity due to denaturation. • Enhanced Foam Stability: The treatment dramatically improves foam stability, with the highest level (93.2%) achieved under optimal conditions (500 W for 45 s). • Bioactive Enhancement: Significantly reduces total tannins ($\leq$ 77%) while concurrently increasing TPC and antioxidant activity.	Recommendations: 1. Desirable Emulsifying Properties: Microwave sorghum grains at 350, 300 W for 15 s before milling 2. Tannin Reduction, Highest Foaming Stability and Increased Antioxidant Activity: Microwave sorghum grains at 350, 500 W for $\leq$ 45 s before milling	Sudan	Almaiman et al. (2021)
Hydrothermal treatment (Boiling) (Sorghum grain/ sorghum flour)	• Starch and Protein Trade-offs: Starch gelatinization improves digestibility; however, protein denaturation and aggregation form less digestible protein–starch complexes, thereby reducing *in vitro* protein digestibility. • Drastic Loss of Functional Components: Wet heat drastically lowers RS (retaining $\approx$ 7%) and overall carbohydrate content. • Severe Bioactive Degradation: Substantially reduces TPC and antioxidant capacity as CT are highly vulnerable (average reduction $\geq$ 50%).	Recommendations: 1. Maximum CT Reduction: pH 8 at 60–120 min 2. TPC Stability: pH 5 or 7 for 2 h	Brazil (Tropical Area Espírito Santo), Mexico (Tropical Area Puerto Vallarta) and Uganda	Bianco-Gomes et al. (2022); Peterson et al. (2024); Ronoh et al. (2024b)
Autoclaving/ pressure cooker (Sorghum grain)	• Mineral Enhancement and Compositional Shift: Significantly increases moisture content and yields the highest percentage of essential minerals in the flour. • Protein and Bioactive Loss: Generally, leads to a reduction in protein and a significant decrease in TPC and antioxidant activity. • Carbohydrate Retention: Despite the losses, carbohydrate content is higher than standard boiling due to shorter processing time and lower water usage.	Recommendation: 1. Pressure cook sorghum grains at a 20 g:500 ml (grain-to-water) ratio for 15 min	Brazil (Tropical Area Espírito Santo)	Bianco-Gomes et al. (2022)

Data Source: The findings were qualitatively synthesized from a subset of 38 primary studies (out of 69 total). This subset encompasses both milling and advanced processing technologies, with several studies contributing to both the baseline and qualitative dataset.

Abbreviations: BV: breakdown viscosity; CT: condensed tannin; Fe: iron; FV: final viscosity; GI: glycemic index; LAB: lactic acid bacteria; Mg: magnesium; OAC: oil absorption capacity; PT: pasting temperature; PV: peak viscosity, RS: resistant starch; SV: setback viscosity; TPC: total phenolic content; WAC: water absorption capacity; Zn: zinc.

prevent spoilage at moisture levels below 12%, a significantly different moisture content is required when the sorghum grain undergoes milling to produce flour. This second adjustment, known as tempering (or preconditioning), involves carefully adjusting moisture to promote the efficient size reduction and separation of the sorghum endosperm during milling. Tempering toughens the sorghum bran, making it more flexible and easier to separate, while simultaneously softening the endosperm (Curti et al., 2022). It has been shown to positively affect the sorghum flour extraction rate and the critical particle size distribution from abrasive decortication–hammer milling (Yoganandan et al., 2021).

Non-tropical tempering studies, such as the research by Curti et al. (2022) on sorghum cultivated in Argentina investigated the influence of tempering moisture on roller milling yield, evaluating a range of levels including low (8.2%), medium (11.8%) and high (15.5%). The study demonstrated that while high moisture is necessary to toughen the sorghum bran for cleaner separation, exceeding the optimal level (e.g., 15.5%) over-softens the endosperm leading to flour loss that sticks to the sorghum bran and significantly lowers yields. Consequently, successful tempering necessitates achieving a critical equilibrium between maximizing refined sorghum flour extraction yield and minimizing final sorghum bran contamination.

In contrast to the 11.8% to 15.5% range optimal for roller milling, moisture adjustment for decortication often requires significantly higher levels, particularly to reduce anti-nutritional factors like tannins. For example, according to Widowati and Luna (2022), conditioning sorghum grains at 18–20% water content has been shown to increase the final refined flour yield from decortication. Furthermore, an optimal conditioning water content of 16% was found to improve decortication quality and facilitate tannin removal in high-tannin sorghum varieties. Decorticating dry sorghum (<12% moisture) negatively impacts both yield and quality of refined sorghum flour.

Tempering sorghum grain at a high moisture content (e.g., 15.5%) significantly enhanced the pasting viscosity of both whole grain and refined sorghum flours. The viscosity increase is attributed to a dual mechanism, encompassing the concentration of available starch due to efficient external layer removal and the subsequent swelling and amylose leaching of starch granules. These factors, combined with leached amylose and molecular reorganization during paste formation, influence the FV and consequently induce gel formation (Curti et al., 2022). The high pasting viscosity of sorghum is a desirable quality for gluten-free baked products, such as cakes and bread, because it allows for better retention of air bubbles and CO_2 (Curti et al., 2021). While tempering moisture content or time did not affect the protein content of white sorghum variety, the total starch content was significantly impacted by different tempering methods, such as room temperature, hot water and steam tempering (Yoganandan et al., 2021).

4.1.2. *Soaking*

Multi-functional soaking is a pre-treatment whose efficacy is highly dependent on process variables such as duration, temperature and soaking medium. The use of alkali solutions such as 0.3% NaOH (Bahlawan et al., 2022), 0.3% Na_2CO_3 (Widowati and Luna, 2022), 0.15% $Ca(OH)_2$ (Bahlawan et al., 2024,2025) and 0.15% KOH (Bahlawan et al., 2024) is the most effective method for reducing CT in whole grain sorghum flour compared to using water alone, achieving up to an 86% reduction. This efficiency is attributed to the high solubility of phenolic groups in alkali (Bahlawan et al., 2022), driven by the increased availability of hydroxide ions (OH^-) which effectively cleave tannin–protein and tannin–starch complexes, thus freeing the tannins for solubilization (Bahlawan et al., 2025) while successfully retaining the antioxidant function of whole grain sorghum flour (Widowati and Luna, 2022). A higher temperature during dissolution of sorghum grain leads to a greater concentration of dissolved tannins, with the optimal being approximately 50 °C (Bahlawan et al., 2024). Meanwhile, the soaking process in water effectively targets phytate in the sorghum bran (Tasie and Gebreyes, 2020), leading to 39% solubilization in 1 h (Vilanculos and Svanberg, 2021) and improving the *in vitro* bioavailability of Fe and Zn (Tasie and Gebreyes, 2020).

Furthermore, the soaking process of sorghum grain significantly impacts rheological properties, provided the temperature remains below the starch gelatinization range (64–95 °C) to prevent structural degradation (Bahlawan et al., 2024). For refined sorghum flour, the processing sequence of soaking relative to dehulling is crucial. Soaking the sorghum seeds in water post-dehulling consistently yields refined flour with significantly higher gelatinization temperatures and enhanced pasting stability compared to soaking pre-dehulling. This thermal advantage is evident across all soaking durations, including 12 h (Post: 89.25–92.15 °C vs. Pre: 76.88–81.00 °C); 24 h (Post: 87.80–92.25 °C vs. Pre: 76.62–80.13 °C); 36 h (Post: 88.70–91.45 °C vs. Pre: 78.57–81.83 °C); and 48 h (Post: 89.55–92.75 °C vs. Pre: 75.14–80.23 °C) (Antarlina et al., 2021). The observed increase in pasting temperature is primarily attributed to molecular reorganization facilitated by soaking, which enhances the interaction between starch molecules (Li et al., 2024). This delayed gelatinization onset is associated with the enhanced thermal stability of the starch structure (annealing). Consequently, this structural modification appears to be the primary driver for high SDS content and low-GI, as SDS is closely linked to the degree of gelatinization and directly influences the GI of refined sorghum flour (Cesbron-Lavau et al., 2021). Additionally, the presence of lipids in sorghum flour has been found to limit starch gelatinization (Souza et al., 2025).

In terms of proximate composition, soaking causes a decrease in ash, fat, carbohydrate and protein content of refined sorghum flour, particularly with longer durations and smaller particle sizes (Antarlina et al., 2021). However, a contrasting effect has been noted where soaking and drying may soften the hull, leading to an increased concentration of fat in the endosperm fraction (Adu et al., 2024). The soaking process in sorghum seeds can also reduce the soluble protein content in the resulting refined sorghum flour because protein bonds are released, allowing the protein components to dissolve in water (Sustriawan et al., 2021). This reduction in ash content is due to mineral leaching, which is enhanced when sorghum seeds are soaked after dehulling (Antarlina et al., 2021). In addition, water soaking at 50 °C for 2 h increases crude fiber while decreasing total carbohydrates in whole grain sorghum flour, likely via starch degradation or leaching (Indrianingsih et al., 2023). Nevertheless, the soaking treatment did not significantly affect the biological activity of whole grain sorghum flour, showing stability for phenol and flavonoid content during soaking (Pinheiro et al., 2021). This is supported by findings from Indrianingsih et al. (2023), where whole grain sorghum flour from the white and red variety, with or without soaking treatment, showed a higher antioxidant activity, higher TPC and higher antidiabetic activity using an α-glucosidase inhibitor assay. However, prolonged aqueous soaking (20 h) causes a total reduction of phenolic and flavonoid compounds (Antarlina et al., 2021).

4.1.3. *Dry heat treatment*

Dry heat treatment of sorghum grain is a highly efficient pre-milling strategy, demonstrated to be more effective than wet heat processing in maintaining levels of antioxidants and RS in sorghum flour (Medina Martinez et al., 2021). In a comparative analysis, the TPC in sorghum subjected to wet heat (e.g., cooking) was found to be at least 6.5 times lower compared to dry-heat treated or untreated grain. Interestingly, even with significant TPC variations between the dry-heat treated and the control group (non-dry heat), their antioxidant activity did not vary ($p > 0.05$). This result can be explained by the concentration of bioactive compounds in the food matrix promoted by the reduction in humidity, as well as by the exposure of fat-soluble vitamins, such as vitamin E (present in the germ) and greater accessibility to carotenoids (Bianco-Gomes et al., 2022).

Optimal dry heat processing often involves exposing the sorghum grains to 105 °C in an air circulating oven for 30 min before milling (Medina Martinez et al., 2020). The dehydration not only concentrates these native components but also results in observed higher levels of protein, carbohydrate and ash (minerals) in the dry heat-treated sorghum flour (Bianco-Gomes et al., 2022). In addition to simple concentration, heat treatment has also shown promising results in lowering anti-nutrients like phytates. This reduction is critical as it improves mineral bio-accessibility, for instance by increasing Fe solubility through the mitigation of Fe–phytate complex formation (Joseph et al., 2025). This aligns with a broader goal in cereal processing, where techniques including heat treatment are employed specifically to minimize the phytate effect (Rebellato et al., 2020). In contrast, the thermal process can negatively impact the starch, potentially reducing overall carbohydrate content in whole grain sorghum flour due to leaching or damage (Yulviatun et al., 2024). Therefore, utilizing dry heat processing is the most appropriate strategy for maximizing TPC and antioxidant activity, as it preserves and concentrates these compounds more efficiently (Bianco-Gomes et al., 2022).

4.2. *Conventional milling techniques*

4.2.1. *Whole grain flour milling*

Milling is a critical step in sorghum flour production, where mechanical energy and frictional heat modify the structural properties of the sorghum starch. This process influences the final particle size and functionality of the sorghum flour (Myers et al., 2023). The choice of equipment, such as a ball mill to achieve smaller particles (D'Almeida et al., 2021) or an impact mill, is determinant. For example, impact–milled sorghum flour has been shown to exhibit a bimodal particle distribution from 25 μm to 500 μm (Curti et al., 2022).

The use of different milling methods, specifically a hammer mill, explains the finding that whole grain sorghum flour exhibits a higher particle size for the fine fraction flour and a lower particle size for the coarse fraction flour when compared to refined sorghum flour. This phenomenon is attributed to several factors inherent in the hammer milling system. The particles resulting from ground cellulose-containing materials exhibit greater length than their diameter. Moreover, the forces of the hammer or air blowing drive material through a screen and facilitate the movement of elongated particles through the hammer mill screen nearly perpendicular to the screen surface. With the particles' long axis parallel to airflow and perpendicular to the screen opening, this orientation offers the least resistance to airflow. Furthermore, hammer mills may not be perfectly sealed at the seams holding the sieves. Critically, the diagonal length of the sieve, which is calculated to be 445.48 μm by the Pythagorean theorem, is sufficient for particles with a diameter greater than the nominal screen opening of 315 μm to pass through (Joseph et al., 2024).

Milling sorghum has significant nutritional consequences. While grinding grains can increase the total calorific value (A'yunin et al., 2022), milling this sorghum grain, which is characterized by its high fiber content, often produces a coarse sorghum flour that is unsuitable for many bakery products (Antarlina et al., 2021). This high fiber content can also inhibit the isolation of sorghum protein. The milling method directly impacts protein yields; dry milling sorghum, for example, yields a higher kafirin protein content compared to wet milling (Xiao et al., 2024).

The milling process also directly influences the rheological behavior of sorghum flour. Starch damage from the mechanical grinding increases the sorghum flour's WHC (Myers et al., 2023). According to Curti et al. (2021), a larger particle size in sorghum flours creates a physical barrier for heat and mass transfer, which is crucial for starch gelatinization. This barrier is associated with a delayed gelatinization peak and lower paste viscosity during the rapid visco analyzer process. This behavior in coarse sorghum flour is attributed to the native protein and cell-wall structures stabilizing the starch paste, which delays granule swelling. Therefore, reducing the particle size of sorghum flour weakens these structural effects, allowing the starch granules to swell faster and facilitating the rupture of the swollen starch granule.

4.2.2. *Refined flour milling (Decortication)*

Refined sorghum flour production is initiated by decortication or dehulling, which are the general processes used to remove the grain's outer layers (pericarp, testa and germ) (Antarlina et al., 2021; Yoganandan et al., 2021). The objective is to purify the endosperm (Joseph et al., 2024). To achieve higher degrees of refinement, this initial step is often followed by pearling or polishing, a specific abrasive technique used for secondary cleaning (A'yunin et al., 2022; Curti et al., 2021). Refined sorghum flour production typically employs either a single-step break roller mill or a two-step process combining partial dehulling (decortication) with subsequent particle size reduction, often using a hammer or impact mill (Curti et al., 2022).

Roller milling is a gradual process that first coarsely breaks the sorghum grain to free the endosperm before using progressively decreasing roller gaps to pulverize the endosperm and separate it from the bran and germ, thereby producing the final particle size (Curti et al., 2022; Rumler et al., 2021). This technique is often favoured for its efficacy in providing a higher production rate of fine-grained sorghum flour, yielding products with greater oil and protein content and reducing ash content. However, roller milling can result in greater bran contamination compared to abrasive decortication–hammer milling (Yoganandan et al., 2021).

Subsequent to pearling, the sorghum endosperm is size-reduced by an impact mill. The impact mill produces refined sorghum flour by shattering the sorghum grains first through the impact of rotating hammers and then by the grains striking the inner surface of the chamber yielding uniform fractures that result in a quite uniform particle size distribution. Importantly, the impact mill's role is limited to particle size reduction as the overall bran removal is achieved solely during the abrasive steps of decortication and pearling. In impact milling the duration of the abrasion step (pearling time) is the primary factor determining sorghum flour yield and ash content while moisture content plays a lesser role (Curti et al., 2022). The dehulling characteristics of sorghum grains can be predicted using the Abrasive Hardness Index (AHI) however, the seed's resistance to splitting, its hardness index and the strong binding strength of the pericarp to the endosperm adversely affect decortication capacity a challenge that remains even after tempering (Yoganandan et al., 2021). Furthermore, the gradual size reduction from milling of refined sorghum flour produces much smaller particles that pass through the sieve horizontally driven primarily by gravitational force (Joseph et al., 2024).

The primary objective of refined milling is to remove the outer layers, a process that significantly modifies the sorghum flour's chemical and nutritional profile and to meet the standard requirements for refined sorghum flour set by Codex Alimentarius Commission (2023a). The abrasive treatment is crucial for endosperm purification, as the resulting reduction in ash content is a key indicator of successful germ and pericarp removal, with lower ash values strongly correlating with increased decortication time (Joseph et al., 2024; Sustriawan et al., 2021). Milling also decreases the content of crude fat which is concentrated in the germ and aleurone, this reduction is significant as high fat content may affect sorghum flour quality during storage and in general, lower fat content contributes to a longer shelf life (A'yunin et al., 2022). The process also removes crude fiber (cellulose) by removing the outer layers (Joseph et al., 2024; Shinda et al., 2022). Consequently, the removal of these fat and protein rich components leads to a relative increase in starch concentration in the final refined sorghum flour, a finding consistent with the positive correlation observed between the level of decortication and starch content as demonstrated by a significant increase in starch from whole grain sorghum flour to refined flour (A'yunin et al., 2022; Joseph et al., 2024).

The removal of the pericarp and testa significantly reduces the concentration of tannins (Bahlawan et al., 2025) and polyphenolic compounds in sorghum, which are responsible for bitter tastes but possess high antioxidant activity (Wang et al., 2020), with decortication capable of reducing tannin content by 75 to 92% (A'yunin et al., 2022; Hatmi et al., 2021). The application of multiple polishing cycles, up to three times, has been identified as an effective method for lowering high-tannin content in sorghum (A'yunin et al., 2022). Phytate in sorghum, which is generally recognized as a monocot, is present in the bran or aleurone layer and must be significantly reduced to increase mineral absorption from foods (Atuna et al., 2022). The efficacy of removing antinutritional factors like phytic acid is highly dependent on the selection of milling technology and the intrinsic characteristics of the grain. Although decortication is generally effective for removing tannins and pericarp layers milder techniques like peeling may leave significantly more phytic acid in the final product due to failure to remove the innermost layers where phytic acid is concentrated particularly in high-tannin sorghum varieties (Gunawan et al., 2022). For example, the high phytic acid retention observed in some refined sorghum flours (up to 11.9 g/100 g, as reported in Table 4) is specifically linked to the use of a peeling process (a surface-level abrasion) combined with a high-tannin brown sorghum variety (Gunawan et al., 2022). This variance demonstrates that the efficiency of antinutritional factor removal is highly dependent on both the intensity of the milling process and the intrinsic characteristics like colour and tannin content of the original sorghum grain. While decortication reduces micronutrients (minerals and vitamins) contained in the bran (Shinda et al., 2022), it may enhance the bio-accessibility of the remaining components (A'yunin et al., 2022).

The compositional changes resulting from refining profoundly impact the sorghum flour's functional and pasting properties. Refined sorghum flour exhibits significantly higher PV and FV compared to whole grain sorghum flour (Curti et al., 2022). This rheological increase is directly attributed to a higher starch concentration available for gelatinization and reduced interference from components like protein and fat, which is confirmed by findings that PV in refined sorghum flour negatively correlates with protein content and positively correlates with carbohydrate content (Curti et al., 2023). Furthermore, the reduction in particle size achieved via high-speed milling amplifies these effects leading to even higher pasting viscosities and noticeable starch breakdown with increased SV values (Curti et al., 2021).

4.3. *Biological treatment*

4.3.1. *Fermentation*

Fermentation (*Lactobacillus* spp. and *Saccharomyces* spp.), a traditional and cost-effective biological treatment particularly relevant in tropical climates for staple food production, profoundly impacts sorghum's nutritional, bioactive (Bahlawan et al., 2022; Indrianingsih et al., 2023) and rheological properties. This process is crucial for creating popular fermented sorghum-based foods common in the tropics, such as *ogi, kisra* or *injera* (Adepehin, 2020). During fermentation, microorganisms produce a range of beneficial metabolites, such as enzymes, organic acids, alcohols, antibiotics and carbohydrates, that are critical for product safety and quality (Antarlina et al., 2021).

Sorghum flour is often subjected to a mixed-culture fermentation dominated by two distinct microbial groups, lactic acid bacteria (LAB) (Antarlina et al., 2021) and yeasts (Handa et al., 2020). LAB are the primary drivers of quality improvement, as they are vital for maintaining and enhancing the quality of nutrition, sensory properties and the safety of the final product (Antarlina et al., 2021). Specific LAB species, such as *Lactobacillus plantarum* (Wahyuni et al., 2021), *Lactobacillus bulgaricus, Lactobacillus casei* and *Lactobacillus brevis,* produce lactic acid to lower the pH and catalyze the degradation of anti-nutritional factors in sorghum flour (Gunawan et al., 2022). They are also crucial for the breakdown and acidification of polysaccharides and fiber, producing enzymes like amylase and glucoamylase to reduce starch and complex carbohydrates (Antarlina et al., 2021). Complementary to LAB, yeasts, primarily *Saccharomyces cerevisiae*, contribute to the fermentation profile through alcoholic fermentation, generating CO_2 for leavening and textural improvement, along with ethanol and flavor compounds (Sawadogo-Lingani et al., 2021).

The fermentation process is highly effective at reducing anti-nutritional factors in whole grain sorghum flour, like phytic acid and tannins, through the microbial production of phytase (Atuna et al., 2022; Sobowale et al., 2024) and tannase enzymes (Gunawan et al., 2022). This enzymatic action is critical for enhancing mineral bioavailability and improves Fe and Zn absorption due to the resulting low pH (Sobowale et al., 2024; Souza et al., 2025). For example, a notable study demonstrated that fermentation using *L. bulgaricus* significantly reduced phytic acid from 13.5% to 0.58% and tannin from 6.73% to 0.36% in whole-grain sorghum flour (Gunawan et al., 2022). However, to meet rigorous standards for sorghum flour, like the Codex Alimentarius Commission (2023a) tannin limit (0.3%), a two-step process combining NaOH submersion and fermentation was utilized, resulting in significantly greater reductions (e.g., tannin to 0.063%) and making the brown sorghum variety, which is known for its high-tannin content, suitable as a wheat alternative (Gunawan et al., 2022). Overall, biological treatment like fermentation can reduce tannin content by up to 30–35% (Bahlawan et al., 2022, 2024).

Fermentation enhances sorghum flour's crude protein percentage (Yulviatun et al., 2024) and frequently its absolute protein quantity, primarily through two mechanisms. First, microorganisms (e.g., LAB and yeasts) generate high-protein single-cell protein (Gunawan et al., 2022) which directly contributes to an increase in total protein. Gunawan et al. (2022) found that fermentation of sorghum increased protein content from 8.75% to 15.58%, 13.59% and 12.48% when fermented with *L. bulgaricus, L. casei* and *L. brevis*, respectively. Second, microbial proteases hydrolyze complex proteins into shorter peptides and free amino acids, significantly improving protein quality and digestibility as these smaller nitrogenous compounds are fully captured in crude protein analysis (Wahyuni et al., 2021). This protein increase is augmented by a concentration effect. Microbial utilization of carbohydrates reduces the sorghum flour's overall dry mass, thereby elevating the final protein percentage relative to total weight (Sobowale et al., 2024). Consequently, protein content is positively correlated with the duration of fermentation and the corresponding microbial growth in sorghum flour (Wahyuni et al., 2021).

Furthermore, fermentation typically reduces moisture, ash and crude fiber (Antarlina et al., 2021) in whole grain sorghum flour. The decreased moisture content in the fermented sorghum flour is caused by microbial enzymatic activity (e.g., amylases) that degrades long starch chains into shorter components. This hydrolysis reduces the starch's overall water-binding capacity, allowing water to be more readily evaporated during the subsequent drying process. Most notably, crude fiber levels decline as LAB hydrolyze complex fibers into simpler monosaccharides (e.g., glucose) for cell metabolism (Wahyuni et al., 2021). However, a significant trade-off can be the depletion of antioxidant activity and TPC under 24 h fermentation conditions (Lohani and Muthukumarappan, 2020; Luzardo-Ocampo et al., 2020). The fermentation duration is a critical process parameter, while the best physicochemical results are often obtained around 48 h, extended periods exceeding this limit ($>$ 48 h) can lead to a depletion of nutrients within the LAB growth media (Wahyuni et al., 2021). As a result, the fermented sorghum flour's nutritional profile features a high protein concentration alongside reduced levels of moisture, ash, fiber and potentially key protective phytochemicals compared to its whole grain sorghum flour.

Besides pasting properties, fermentation also beneficially modifies the sorghum flour's functional attributes, notably reducing bulk density and increasing OAC (Atuna et al., 2022). Starch structure in fermented sorghum flour changes, mediated by amylase and isoamylase, increase amylose content from 21.35% to 36.51% (Gunawan et al., 2022), which beneficially modifies the fermented sorghum flour's rheological behavior which it increases viscosity and PV, while significantly reducing SV and BV (Adepehin, 2020; Wahyuni et al., 2021).

4.3.2. *Germination*

Germination, often referred to as malting or sprouting, is a biological processing technique that significantly modifies and enhances the physicochemical, nutritional, functional and health-enhancing properties of sorghum flour (Adu et al., 2024). The incorporation of malted sorghum grains into complementary foods increases energy density and improves bioactive compound profiles while reducing anti-nutritional factors. These positive changes are beneficial for the gut microbiota and may help lower the risk of chronic diseases, including oxidative stress, diabetes, inflammation and obesity (Keyata et al., 2023).

The primary mechanism of germination involves the activation of intrinsic enzymes such as amylases, proteases, lipases, fiber-degrading enzymes and phytases (Adu et al., 2024). This enzymatic activity improves the digestibility of the sorghum kernel's proteins and carbohydrates by degrading them into simpler molecules. Crucially, germination effectively reduces anti-nutrients like tannin, phytate and oxalate in the sorghum flour, which subsequently improves the bio-accessibility of minerals (Keyata et al., 2021), enhancing *in vitro* Fe (10% to 20%) and Zn (8% to 15%) accessibility (Adu et al., 2024). Germination also generally enhances the bioavailability of bioactive compounds (Chiodetti et al., 2024). However, while the total concentration of Vitamin E is reduced, including α-, γ- and δ-tocotrienols and γ-tocopherol, a significant increase ($p < 0.05$) is observed in β-tocopherol and β-tocotrienol. Furthermore, the malting process substantially reduces flavanone compounds in sorghum flour by between 73% and 87% (Pinheiro et al., 2021).

Sprouting significantly enhances the nutritional quality and digestibility of sorghum by increasing the availability of essential amino acids and raising the ash (mineral) content, indicating a richer source of available organic nutrients and suggesting its utility as a composite flour to combat micronutrient deficiencies. Adu et al. (2024) reported an increase in ash content with increasing malting days. However, there was a significant difference ($p < 0.05$) in the fat contents of the sample, as well as an observed increase in fat with an increasing malting period.

These changes appear to depend on the malting duration. For malted sorghum, a general observation was an increase in ash, fat and energy content, while moisture, fiber, protein and carbohydrate content declined with increasing malting time. The fiber content in malted sorghum flour is typically lower, a reduction primarily driven by the enhanced activity of hydrolytic enzymes, particularly β-glucanase, during malting. These enzymatic actions, combined with the physical softening of the sorghum endosperm tissue, result in a more efficient milling process and a resultant finer, smoother particle size in the final flour. However, the total protein content in malted sorghum flour may decrease due to two main mechanisms, namely protein solubilization and leaching during steeping or the *in situ* utilization of soluble proteins by the germinating embryo during early malting (Adu et al., 2024).

In terms of sorghum flour functionality, germination improves the WAC, OAC, swelling power and solubility (Kristanti et al., 2023). However, the technological properties of the sorghum starch fraction are generally reported to be negatively affected after sprouting. The proteases and amylases act by reducing protein–starch interactions, yet the amylases simultaneously degrade the starch granule structure, thus limiting the granules' ability to gelatinize (Chiodetti et al., 2024). This starch degradation, caused by α- and β-amylase activity (Atuna et al., 2022), is responsible for the significant decrease in all key pasting properties in malted sorghum flour, including PV, BV, FV and SV (Kristanti et al., 2023). The resulting low FV and SV is particularly desirable for sorghum complementary food products, as it yields a low-viscosity paste upon cooking and cooling, which is preferred over a thick gel (Atuna et al., 2022). Furthermore, a low SV value is also helpful when formulating frozen sorghum food products, as it minimizes retrogradation (Kristanti et al., 2023).

4.4. Thermal treatments

4.4.1. Toasting

Toasting or dry heat processing, is a crucial thermal method that primarily impacts the physical state and functional compounds of whole grain sorghum flour. This method significantly reduces the flour's moisture content to below 2%, which is substantially lower than the 10–13% typically observed in whole grain sorghum flour (Paes et al., 2024; Silva et al., 2020). Despite this moisture loss, direct dry heat processing generally results in no major modifications to the overall proximate composition of the flour (Paes et al., 2024). However, dietary fiber and moisture remain the primary exceptions when comparing toasted sorghum flour to its whole grain counterpart (Silva et al., 2020). This method is typically applied to stabilize the sorghum flour for storage and improve its textural characteristics in end products.

Critically, toasting causes partial changes in the starch and protein components, directly affecting the sorghum flour's rheological behavior for food applications. Dry heat treatment, which is similar to toasting, modifies the starch structure by causing partial denaturation of kafirin proteins, leading to an increased WAC of the toasted sorghum flour (Batariuc et al., 2021). Furthermore, this method is effective at maintaining high levels of RS and consequently, TDF, especially when compared to severe wet heat methods (Paes et al., 2024). In particular, tannin-containing toasted sorghum flour exhibited a higher total fiber content, which is attributed to its naturally high RS content (Taylor and Duodu, 2022). In addition to functional changes, *in vivo* studies confirm the significant health benefits provided by toasted sorghum flour. Specifically, rats fed either toasted white variety without tannin (BRS501) or brown variety with tannin (BRS305) sorghum flour from sorghum cultivated in a tropical region in Brazil demonstrated reduced oxidative stress and improved lipid profiles. The thermal modification achieved through toasting is also associated with promoting liver protection by successfully preventing the accumulation of lipids in the liver, confirming its potential as a functional ingredient in clinical nutritional products (Silva et al., 2020).

4.4.2. Extrusion

Extrusion, a high-temperature short-time (HTST) process, delivers intense thermo-mechanical energy that profoundly modifies the functional and nutritional profile of sorghum flour. Nutritionally, it is primarily applied to enhance starch digestibility and protein availability. Concurrently, it modified the macronutrient profile in sorghum cultivated in a tropical area of Brazil (Tadeu da Veiga Correia et al., 2022), fiber content increased (from 11.94% to 17.45%) and total carbohydrates increased (64.67% to 70.76%), while the lipid fraction decreased (3.09% to 1.19%) in both a tannin-free (BRS332 red) and a tannin-containing (SC319 brown) variety.

Regarding bioactive compounds, the process efficiently modifies the phenolic profile of sorghum flour. High temperatures induce the rupture of cell wall matrices and break covalent bonds in high-molecular-weight polyphenol complexes, consequently improving phenolic accessibility and increasing the total content of free phenolic compounds and TPC in extruded sorghum flour (D'Almeida et al., 2021). Extrusion also effectively reduces tannin concentration in extruded sorghum flour, which is attributed to the interaction of CT with carbohydrates and proteins to form insoluble and less extractable complexes. However, this reduction may be linked to decreased nutrient metabolizable energy, though it can improve palatability (Tadeu da Veiga Correia et al., 2022). In contrast, some sensitive compounds, such as flavonoids, may remain unstable during the extrusion process of sorghum flour (A'yunin et al., 2022).

Regarding rheological properties, extrusion is an effective method for modifying pasting properties, primarily by promoting complete starch gelatinization. The intense thermo-mechanical energy breaks down starch molecules to such an extent that, in some cases, no enthalpy or peak gelatinization temperature is observed (Lohani and Muthukumarappan, 2020). In terms of these pasting properties, extruded sorghum flour, especially when combined with enzyme addition and specific moisture content (e.g., feed moisture level of 20% or 30%), is used to control the viscosity of liquid products like sauces and soups (Usman et al., 2024).

4.4.3. Hydrothermal treatment (boiling)

The application of hydrothermal treatments, including boiling (wet cooking) and steaming, to sorghum grain or flour results in significant structural transformations that critically influence both the nutritional and functional profiles of the final product. The primary effects of this treatment are centered on the reorganization of the sorghum grain's macro-components, such as starch, protein and anti-nutritional factors. Physiochemically, the high temperatures in the presence of water promote the gelatinization of sorghum starch granules, a transformation that generally improves starch digestibility of sorghum (Bianco-Gomes et al., 2022). However, the simultaneous heat and moisture drastically affect the highly hydrophobic kafirin storage proteins of sorghum (Taylor and Duodu, 2022). Wet heat induces protein denaturation, aggregation and the formation of stable disulfide and non-disulfide cross-links, often forming less digestible complexes between proteins and starch (Ronoh et al., 2024b). For example, wet cooking has been demonstrated to reduce *in vitro* protein digestibility in non-tannin sorghum flour (Taylor and Duodu, 2022).

Wet heat affects protein content variably based on tannin presence, with boiling reducing protein in white sorghum cooked flours but not in red varieties due to the protective effect of higher CT (18.92 mg CE/g in red and 12.17 mg CE/g in white whole grain sorghum flour) (Cabrera-Ramírez et al., 2020). The observed reduction in protein content in cooked sorghum flour is not attributed to proteins leaching into the cooking water, irrespective of their solubility in alcohol-water solutions, because kafirins are hydrophobic prolamines composed mostly of non-polar amino acids with a greater affinity for hydrophobic solvents. Thus, the change in protein concentration is primarily related to the moisture and dry matter percentage. Dry heat increases protein content due to moisture loss and subsequent concentration of dry matter, while humid heat (wet cooking) promotes a reduction due to moisture uptake (Bianco-Gomes et al., 2022).

The primary and most immediate hydrothermal impact on bioactive compounds are the substantial reduction of TPC in sorghum flour (Luzardo-Ocampo et al., 2020) and its subsequent antioxidant capacity. This is predominantly attributed to the leaching of free phenolic compounds into the cooking water, with some studies reporting TPC as over six times lower in wet-heat treated sorghum compared to dry-heat counterparts (Bianco-Gomes et al., 2022). Furthermore, approximately 60 g/kg of total phenolics in coloured sorghum are highly susceptible to this loss mechanism during boiling (Luzardo-Ocampo et al., 2020).

Quantitatively, prolonged boiling effectively reduces TPC. For instance, 2 h of boiling led to a 32% and 41% loss in low- and high-tannin sorghum varieties, respectively. However, TPC reduction is highly variable, depending on processing time and pH. The TPC of whole grain sorghum flour from brown sorghum with high-tannin and high phenolic content cultivated in a tropical area of Mexico, was in the range of 11.21 to 16.0 mg GAE/g. This content demonstrated pH-dependent stability during subsequent heating. A 10 min cook treatment caused a non-significant decrease in TPC, except at pH 3. TPC was significantly reduced after 30 min, except at pH 8. Overall, TPC stability of cooked sorghum flour was highest at pH 5 and 7 across the 120 min heating period (Peterson et al., 2024).

The stability of CT is also highly sensitive to pH and thermal processing, diverging from the stability observed for TPC. While TPC stability was highest at pH 5 and 7, the initial CT content of whole grain sorghum flour ranging from 29.77 to 39.76 CE (mg/g) significantly decreased by an average of 51.46% after just a 10 min wet heat treatment across all pH groups. Even though whole grain sorghum flour at pH 8 started with the highest CT content, it declined to the lowest level (0.46 mg CE/g) after 120 min of heating, indicating that alkaline pH promotes maximum CT loss over prolonged cooking (Peterson et al., 2024).

Concurrently, carbohydrate content is generally lower in cooked sorghum flour compared to whole grain sorghum flour, although wet pressure cooking retains more carbohydrate than wet boiling due to a lower water volume and shorter cooking time (Bianco-Gomes et al., 2022). Furthermore, wet cooking of sorghum grain or flour significantly reduces the RS content, retaining only approximately 7% of the original amount (Taylor and Duodu, 2022).

5. Synergistic and interdependent effects of variety and processing

The nutritional and bioactive profile of sorghum flour is not determined by variety or processing alone, but rather by their complex interplay. The sorghum genotype fundamentally determines the initial composition, particularly the profile of phenolic compounds, flavonoids and tannins (Palacios et al., 2021). These compounds are primarily concentrated in the outer sorghum grain layers, specifically the pericarp and testa. Pigmented sorghum varieties (red, black and brown) possess a pigmented testa and thus contain significantly higher levels of tannins and total phenolics compared to white pericarp sorghum varieties (A'yunin et al., 2022). This genetic trait in sorghum is controlled by specific genes, such as B_1, B_2, *S*, *Tan1* and *Tan2*, which regulate testa presence and pigmentation (Palacios et al., 2021).

Consequently, antioxidant capacity in sorghum is strongly variety-dependent. Pigmented, high-tannin sorghum genotypes cultivated in a tropical area in Brazil, specifically the brown genotypes SC319 and BR305, consistently demonstrate significantly higher antioxidant activities (DPPH, ABTS). In contrast, non-tannin varieties are reported to exhibit the lowest antioxidant capacity (Luzardo-Ocampo et al., 2020). Sorghum varieties exhibiting this trait, such as cultivated in Ethiopia (e.g., Abshir, Melkam, ESH-1, ESH-3, Teshale, Macia, Gambela-1170, Meko-1), are often preferred for food products due to better sensory attributes and mineral–protein bioavailability (Tasie and Gebreyes, 2020).

Processing methods interact directly with this inherent sorghum varietal chemistry. Mechanical processing of sorghum, such as decortication or increased polishing frequency, is designed to remove the tannin-rich sorghum testa. However, studies indicate that variety remains the dominant factor; the final antioxidant capacity of polished sorghum grains is more heavily influenced by the initial sorghum genotype than by the polishing frequency (A'yunin et al., 2022).

A clear illustration of this synergy was provided by Chiremba et al. (2009) in a study on South African cultivars. Refined sorghum flour (70–90% extraction rate) from the naturally tannin-free PAN 8564/8446 cultivar exhibited significantly higher antioxidant activity (98–107 Trolox equivalents/g, dry basis) compared to refined wheat flour (15 Trolox equivalents/g). This advantage was also evident in baked goods; cookies made from this specific refined sorghum flour (78–94 Trolox equivalents/g) also showed significantly higher antioxidant activity than those made from refined wheat flour (8 Trolox equivalents/g).

In contrast, the PAN 3860 cultivar is a tannin-containing variety, and its whole grain sorghum flour (100% extraction) had a high CT content (7.78 g catechin equivalents/100 g, dry basis). However, abrasive decortication of this cultivar to a 70% extraction rate removed all CT. Despite this complete tannin removal, the resulting decorticated PAN 3860 sorghum flour still retained higher antioxidant activity than refined wheat flour. This demonstrates that processing, specifically decortication, can be optimized to produce a refined sorghum flour that not only meets safety standards, such as the 0.3% maximum tannin level set by Codex Alimentarius Commission (2023a), but also retains high antioxidant activity.

Thermal and wet processing effects are similarly modulated by sorghum variety. Whole sorghum grain flours (both red and white) typically show the highest antioxidant capacity, which is reduced by processing methods like nixtamalization and cooking (Luzardo-Ocampo et al., 2020). However, the high phenolic content of pigmented sorghum varieties appears more resilient; for instance, red sorghum flour, with or without soaking, maintains higher antioxidant capacity and total phenolic content than its white sorghum counterpart (Indrianingsih et al., 2023). This synergy dictates the processing requirements whereby high-tannin sorghum varieties may necessitate fermentation or alkaline submersion to meet Codex Alimentarius Commission (2023a) (0.3% tannin in sorghum flour), whereas low-tannin sorghum varieties may only require simple soaking or decortication (Gunawan et al., 2022).

These interactions extend to sorghum macronutrients. Pigmented sorghum cultivars generally have higher RS due to the formation of insoluble tannin–starch complexes that limit digestibility (A'yunin et al., 2022). A clear example of synergy, as highlighted in the discussion on toasting (Section 4.4.1), is the differential reaction of tannin-containing varieties to thermal processing to achieve greater dietary fiber retention. This advantage persists after processing; toasted tannin-sorghum flour, for example, exhibits higher total fiber content than toasted white sorghum flour, a difference attributed to its higher RS (Paes et al., 2024; Taylor and Duodu, 2022). Protein content in sorghum is also affected differently by processing. Boiling was found to decrease protein content in white sorghum flours but not in red sorghum flours; this protective effect was attributed to the higher concentration of CT in the red sorghum varieties (Cabrera-Ramírez et al., 2020). Extrusion may also improve protein digestibility by modifying proanthocyanidins (CT) and kafirins, but this effect is again strongly sorghum genotype-dependent (D'Almeida et al., 2021).

Finally, these interactions influence bioavailability and bioactivity in sorghum flour-based products. While processing can improve some aspects, it may lead to reduced solubility percentages for Fe in white sorghum variety, likely due to the formation of insoluble complexes with components such as fibers (Rebellato et al., 2020). Interestingly, even with substantial differences in phenolic content and antioxidant capacity, both red and white sorghum varieties, with or without soaking, have demonstrated similar antidiabetic potential via α-glucosidase inhibitory activity (Indrianingsih et al., 2023).

6. Implications for food applications, industry and policy

The unique nutritional and physicochemical profile of sorghum flour present significant implications for food applications and public health policy. Protein is an essential nutrient for human growth, tissue maintenance and repair; a deficiency, therefore, can lead to systemic failures resulting in stunting. Consequently, a high-protein diet incorporating local commodities such as sorghum is an effective alternative for stunting reduction (Winarti et al., 2023), directly supporting global targets for Zero Hunger (SDG 2). The natural richness of sorghum in dietary fiber and tannins makes sorghum flour a highly effective gluten-free alternative (dos Reis Gallo et al., 2021), which holds considerable potential for processing into various healthy food applications, including carbohydrate-controlled diets and contributes to managing human glucose and insulin levels (Dwipajati et al., 2022). These functional properties underscore sorghum’s potential as a key resource for promoting Good Health and Well-being (SDG 3). Due to their role as a functional food, certain tannin containing sorghum genotypes have become consumer attractions, containing key components such as antioxidants, minerals, fibers, oligosaccharides and ß-glucans. Appropriate processing is critical to retain these functional food components in ready-to-eat products (A’yunin et al., 2022), nonetheless a challenge exists because excessive CT in sorghum can negatively affect food quality by causing undesirable bitter flavour and astringent tastes (Bahlawan et al., 2022). This negative effect can be mitigated by effectively reducing the tannin content through polishing the sorghum grains up to three times (A’yunin et al., 2022). Furthermore, crackers produced by polishing white sorghum grain contain high protein content, whereas those made from polishing brown sorghum grain possess high functional beta carotene (Hatmi et al., 2021).

The rheological behavior of sorghum flour is a key determinant of final product texture. The protein content in a sorghum flour-based product is directly linked to the formed texture, as protein helps in water absorption and binding during dough preparation (Indrianingsih et al., 2023). In contrast, the starch granules in sorghum flour are encapsulated by kafirin, a hydrophobic protein that is more inert than gluten; this hydrophobic exterior may impede moisture absorption and retention by the starch in the sorghum flour, contributing to a lower moisture content in final products like cookies (Myers et al., 2023). In terms of viscosity, a greater proportion of sorghum flour in the formula is correlated with a higher PV value, such as that observed in noodle formulas (Wahjuningsih, 2022). FV is a commonly used quality index for sorghum flour intended as complementary food, as it reflects the starch’s stability during cooking (Adepehin, 2020) and its capacity to form a viscous paste or gel after cooling (Atuna et al., 2022; Xu et al., 2021). However, for whole grain sorghum flour, higher FV and SV upon cooling indicate increased starch retrogradation and syneresis rates, which can negatively affect the softness and texture of bread after baking and during storage (Adzqia et al., 2023).

From an industrial perspective, processing sorghum into flour is often more profitable, as it provides a practical and convenient base for manufacturing various snack products (Sustriawan et al., 2021), thereby driving local economic growth and industrial innovation (SDGs 8 and 9). Furthermore, the substitution of imported wheat with indigenous sorghum flours specifically in clinical formulas and bakery applications promotes the efficient use of natural resources, directly aligning with Responsible Consumption and Production (SDG 12). Enhancing the physicochemical characteristics of sorghum flour often requires modifying food processing techniques to improve shelf life, palatability, digestibility and nutritional value for specific applications such as muffin-based products (Suarni and Sulistyaningrum, 2023). While gluten-free bread research has focused on formulation, final quality is more dependent on milling properties like particle size and ash content, as well as the sorghum flour's WAC during dough formation, all of which are determined by the milling technique, as previous studies identified roller milling as efficient for extracting sorghum flour with good baking characteristics (Yoganandan et al., 2021). Furthermore, a higher proportion of white sorghum flour affects the fiber content by increasing sulphate groups to maximize water penetration (Patty et al., 2023). Fermentation is another key technique that improves sorghum flour quality by reducing fiber content to increase whiteness and enhancing the product texture by minimizing hardness, dryness, crumbs and grittiness in cookies and cakes (Antarlina et al., 2021). Finally, pregelatinization is a modification that disrupts the crystalline structure of native sorghum starch, significantly increasing the sorghum flour’s WAC and enabling instant cold-water dissolution, which contributes a desirable crunchy texture to food products (Suarni and Sulistyaningrum, 2023).

The practical application of these modified nutritional and processing strategies results in the successful development of viable sorghum food products with direct public health and industry relevance. Specifically, these applications advance the UN Sustainable Development Goals (SDGs) by linking agricultural processing to poverty reduction and health outcomes. A detailed summary of the impact of sorghum flour, its processing and product formulation on final food quality, alongside the resulting key success factors for industry and policy, is presented in Table 8. This table synthesizes the outcomes of using sorghum flour in various end products, drawing from recent primary studies (2020–2025) on sorghum cultivated in tropical climates, ranging from energy-dense thick porridge for toddlers (Cisse et al., 2025) to low-GI, gluten-free bread designed for diabetic and celiac dietary management (dos Reis Gallo et al., 2021). The findings demonstrate how tailored processing, such as optimized soaking, crushing and sieving used to maximize the quality of couscous (Laya et al., 2022) and fine milling to maximize fiber and consumer acceptability in gluten-free yeast rolls (Drub et al., 2021), is essential to maximize the commercial utilization and public health utility of sorghum flour-based foods.

7. Gaps, contradictions and future directions in sorghum research

7.1. Future projections and climate resilience

Climate change will alter global crop suitability and compromise cereal crop yields by 2050, with production disruptions projected to drive global wheat prices up by 28–75% between 2010 and 2030 (FAO, 2022). To successfully advance sorghum flour as a primary functional wheat flour analog and mitigate global dependency on wheat imports, future initiatives must establish a transnational tropical framework to coordinate expansive industrial-scale cultivation across tropical regions. Crucially, this framework must align with the mandates of global food organizations, such as the FAO, to directly advance the SDGs for food policy by developing strategic policies for sustainable agrifood transformation that extend beyond the 2030 Agenda benchmarks to address the long-term projections of 2050 and 2100 (FAO, 2022). This collaborative structure will facilitate the systematic mapping of climate-resilient genotypes, randomized controlled clinical trials for nutritional validation and the integration of sorghum into national dietary guidelines, while ensuring it meets international commercial standards. By integrating unified open-access databases with energy-efficient processing, stakeholders can achieve functional equivalence of sorghum flour with wheat, providing the evidence-based policy implementation required to stabilize global food systems.

Table 8

Implications of sorghum flour processing for food applications, industry and policy in tropical climates (2020–2025).

Product Type & Tropical Sorghum Cultivation Area	Sorghum Flour Type & Milling/Grain Processing	Sorghum Flour (%, db)	Product Ingredients and Additives	Property Studied	Effect on Product Quality	Key Success Factors (Industry and Policy)	References
Cereal/Porridge (Cooked)							
Energy-dense thick porridge for toddlers (Mali)	• Unspecified colour/tannin (Darrel Ken variety) Refined flour: 1. Decortication (Abrasive dehuller) 2. Milling (Hammer mill)	16–20	Water, refined sorghum flour, beet sugar, waxy corn starch and lemon juice	1. Clinical Digestion/ Metabolism 2. Starch Digestion Kinetics 3. α-Amylase Activity 4. Rheological (Viscosity vs. Shear rate)	Thick sorghum porridge achieved equivalent starch digestibility to enzymatic thin porridge in stunted children, confirming that the high viscosity (2.9 Pa.s) did not impair nutrient uptake.	**Industry:** Favour thick sorghum porridges to achieve high energy density and lower production costs by eliminating the complexity and expense of enzymatic thinning. **Policy:** Integrate scientifically proven energy-dense thick sorghum porridges into national feeding guidelines to combat stunting, validating that thickness does not impair digestibility.	Cisse et al. (2025)
Couscous (*Boule*) (Cameroon)	• White with unspecified tannin Whole grain flour: 1. Washing 2. Sun drying (1 h) 3. Milling (Hammer mill) 4. Sieving (200 µm mesh) Refined flour: 1. Soaking in water (4 L water / 800 g grains) 2. Decortication 3. Sun drying (1 h) 4. Crushing (Wooden mortar) 5. Milling (Hammer mill) 6. Sieving (200 µm mesh)	100	Sorghum flour and water	1. Physical (pH) 2. Nutritional (Proximate, Soluble sugars and Soluble amino acid) 3. Functional (Bulk density, Swelling power, WAC, OAC and Kinetics swelling)	The optimized processing (soaking, crushing and sieving) showed a significant positive effect on quality, notably leading to increased protein and amino acids and a decrease in soluble sugars in the sorghum couscous samples.	**Industry:** Implement combination wet/ mechanical processing (soaking, crushing, sieving) to increase protein/amino acids and decrease soluble sugar in sorghum flour and optimize its flow/texture (WAC/ OAC) for improved couscous palatability and consistency. **Policy:** Promote simple, validated traditional processing (soaking, crushing, sieving) techniques within local mills to maximize nutritional (protein/amino acids) and techno-functional quality of the sorghum staple.	Laya et al. (2022)
Analog Rice							
Fermented extruded analog rice (Indonesia)	• Red with tannin; White with tannin Fermented flour: 1. Soaking in 0.3% NaOH (10 h) 2. Washing with distilled water 3. Drying in oven (55 °C, 2 h) 4. Grinding 5. Sieving (100 mesh) 6. Sterilization (Autoclave, 121 °C for 15 min) 7. pH adjustment using vinegar (~ 5.5) 8. Fermentation (7.5% *R. oligosporus*, 30 °C for 48 h) 9. Drying in oven (55 °C, 2 h)	50–100	Fermented sorghum flour (red/white), soybean flour, glycerol monostearate, olive oil and salt	1. Physical (Colour) 2. Nutritional (Proximate, Calorie and Minerals) 3. Microstructure 4. Functional (WAC and Solubility) 5. Sensory Profile	The optimal blend (50% fermented sorghum / 50% soybean) enhanced nutritional quality by increasing protein (16.67–17.07%) and fiber while reducing tannins to safe levels; however, consumers preferred the 100% fermented sorghum formulation, as soybean substitution imparted a strong beany aroma, nutty flavour and hard texture to the analog rice.	**Industry:** Utilize fermentation to market the analog rice, while prioritizing innovations to mitigate undesirable soybean flavours (beany aroma) and optimize texture (hardness) to ensure market viability. **Policy:** Promote local fermented sorghum analog rice as a nutrient-dense (high-protein, high-fiber) alternative to polished rice to support food diversification, while positioning it as a sustainable staple to achieve mass-market adoption.	Bahlawan et al. (2023)

(*continued on next page*)

Table 8 (*continued*)

Product Type & Tropical Sorghum Cultivation Area	Sorghum Flour Type & Milling/Grain Processing	Sorghum Flour (%, db)	Product Ingredients and Additives	Property Studied	Effect on Product Quality	Key Success Factors (Industry and Policy)	References
Extruded artificial rice (Indonesia)	• Unspecified colour with tannin Refined flour: 1. Dehulling 2. Washing 3. Drying 4. Milling 5. Sieving Malted flour: 1. Soaking (72 h, room temperature) 2. Germination (36 h, damp gunny) 3. Washing 4. Drying 5. Milling 6. Sieving	50	Sorghum flour (refined/ malted), corn flour, cassava starch, glucose monostearate and water	1. Physical (Colour and Shape) 2. Bioactive (Tannin)	Artificial rice produced from malted sorghum flour was brighter and more appealing than the darker analog made from refined sorghum flour; however, both formulations resulted in heterogeneous shapes with poor resemblance to natural rice, primarily due to the inconsistent pressure and speed of the manually operated mini extruder.	**Industry:** Prioritize germination to reduce tannins and improve the visual brightness and consumer appeal of sorghum artificial rice. **Policy:** Fund R&D to automate mini-extrusion technology for consistent product uniformity, while simultaneously promoting artificial rice production utilizing local drought-resistant sorghum to reduce import reliance and shift the prevailing reliance on rice as the sole staple.	Ridwansyah et al. (2020)
Flat Bread							
Injera (Traditional Ethiopian flatbread) (Ethiopia)	• White with low/no tannin (Melkam variety) Refined flour: 1. Dehulling 2. Sun drying 3. Milling (Cottage disk mill) 4. Sieving (710 μm)	43–100	Refined sorghum flour, composite flour (brown rice, white *teff* & flaxseed flour), water and starter culture (*Ersho*)	1. Nutritional (Proximate, Energy and Minerals) 2. Bioactive (Phytate, CT, Total phenolic and Flavonoids) 3. Microbial Load (Yeast–mold and Total bacteria)	Optimal blend (50% sorghum refined flour) and longer fermentation (72 h) significantly enhanced nutritional quality, yielding increased protein (9.30%), fiber (3.02%) and minerals (Fe/Ca/Zn) with high overall sensory acceptance.	**Industry:** Standardized fermentation time (72 h) and optimize composite blends (50% sorghum/*teff*/rice/flaxseed flour) to ensure consistent, high-quality *injera* with enhanced nutritional value and high acceptability. **Policy:** Promote the use of affordable composite flours to improve food security and directly address protein and mineral deficiencies in widely consumed traditional staple foods.	Amtataw et al. (2025)
Biofortified *Kisra* (Traditional Sudanese fermented flatbread) (Sudan)	• Unspecified colour with tannin iofortified variety (Dahab); Non-biofortified varieties (Wad Ahmed, Dabar-Tabat, Korokolo and Arfag-damek-8) Whole grain flour: 1. Milling (stone mill)	50	Whole grain sorghum flour, water and traditional starter (*Ajin*)	1. Sensory profile	Optimized biofortified cultivars (e.g., Dahab) enhanced *kisra* sensory quality through improved sweetness, smoothness and porousness, effectively mitigating the bitterness and coarseness of traditional sorghum varieties.	**Industry:** Market biofortified 'Dahab' sorghum *kisra* as a sensory-validated, mineral-rich staple to combat micronutrient deficiencies in high-stunting regions. **Policy:** Integrate biofortified sorghum (e.g., Dahab) into global food security frameworks and mandate sensory validation in crop releases to ensure cultural adoption and mitigate 'hidden hunger.	Hamid et al. (2025)

(*continued on next page*)

Table 8 (*continued*)

Product Type & Tropical Sorghum Cultivation Area	Sorghum Flour Type & Milling/Grain Processing	Sorghum Flour (%, db)	Product Ingredients and Additives	Property Studied	Effect on Product Quality	Key Success Factors (Industry and Policy)	References
Bread							
Gluten-free bread (Thailand)	• White with low tannin (KU 804 variety) Whole grain flour: 1. Washing 2. Drying (Tray dryer, 80 °C 4 h) 3. Grinding (Blender) 4. Sieving (80 mesh)	10–100	Sorghum flour, composite flour (rice, tapioca flour & corn starch), sugar, salt, yeast, baking powder, xanthan gum, calcium propionate, unsalted butter, egg and warmwater	**Flour:** 1. Physiochemical (Colour and Moisture) 2. Rheological (Pasting Properties) **Bread:** 1. Physiochemical (Specific volume, Crumb color, Water activity and Moisture) 2. Texture Profile 3. Sensory Profile	Whole grain sorghum flour could be used at a maximum of 25% to achieve good volume and a uniform crumb structure, with increasing sorghum above this level causing an undesirable decrease in flour PV/BV, increased SV, reduced bread elasticity/cohesiveness and increased graininess, although it successfully introduced desirable nutty/brown flavours.	**Industry:** Formulate gluten-free bread by using an optimal whole grain sorghum flour ratio (≤ 25%) to maximize volume/elasticity, leveraging nutty/brown flavours and avoiding sensory degradation (high graininess) from excessive whole grain flour. **Policy:** Promote the utilization of white sorghum (e.g., KU 804) for gluten-free products due to its neutral flavour/colour and low-tannin content, supporting domestic substitution to meet Asia Pacific market demand.	Adzqia et al. (2023)
Gluten-free bread (Extruded functional) Brazil (Tropical area EMBRAPA Sete Lagoas)	• Red with low tannin Extruded Flour: 1. First Milling (Hammer mill) 2. Extrusion 3. Drying (Forced air oven, 55 °C for 10 h) 4. Second Milling (Hammer mill)	95–100	Extruded sorghum flour, water, palm fat, yeast, sugar and salt	**Flour:** 1. Physiochemical (Particle size, Proximate, Calorie and Minerals) 2. Rheological (Pasting and Dynamic mechanical (G′, G″). **Bread:** 1. Physical (Specific volume and Structural) 2. Texture Profile	Extrusion pre-treatment dramatically improved sorghum bread quality, achieving the highest increase in specific volume (82%) and better internal air cell distribution, effectively mimicking gluten when compared to the two other breads made from extruded parboiled brown rice flour and extruded corn flour.	**Industry:** Implement low-temperature extrusion (< 110 °C) as a scalable pre-treatment to create gluten−like viscoelasticity in whole grain sorghum flour, achieving high loaf volume and softness without costly added hydrocolloids. **Policy:** Fund R&D into novel thermomechanical processing (extrusion) of sorghum to create high value ingredients that improve gluten-free product quality while lowering industrial costs (time and energy).	Comettant-Rabanal et al. (2021)
Gluten-free bread (Low-GI) Brazil (Tropical area EMBRAPA Sete Lagoas)	• White (BRS 501); Brown (BR 305); Bronze (BRS 332) with unspecified tannin Whole grain flour: 1. Milling (Thermomix)	22.36	Whole grain sorghum flour, potato starch, whole egg, soy oil, cassava flour, brown sugar, egg whites, dry yeast, salt, xanthan gum and water	1. Nutritional (Proximate and RS) 2. Bioactive (Antioxidant, ORAC) 3. *In Vivo* (Clinical trial: GI, Insulin index and AUC Glucose/Insulin).	Brown sorghum bread (BR 305) was the most effective, classified as Low-GI (44) in human trials due to significantly higher fiber (5.79 g/100 g) and the highest antioxidant activity (45.49 μmol TE/g ORAC) compared to other sorghum genotypes (white and bronze) and the rice bread control.	**Industry:** Select and utilize brown sorghum genotypes (e.g., BR 305) to produce low-GI and fiber−rich gluten-free bread, maximizing clinical health benefits and marketability for diabetic and health-conscious consumers. **Policy:** Encourage the cultivation and consumption of brown sorghum genotypes to provide clinically validated low-GI staple foods and rich fiber sources, directly addressing public health issues like diabetes management.	dos Reis Gallo et al. (2021)

(*continued on next page*)

Table 8 (*continued*)

Product Type & Tropical Sorghum Cultivation Area	Sorghum Flour Type & Milling/Grain Processing	Sorghum Flour (%, db)	Product Ingredients and Additives	Property Studied	Effect on Product Quality	Key Success Factors (Industry and Policy)	References
Gluten-free yeast rolls Brazil (Tropical area EMBRAPA Sete Lagoas)	• White with unspecified tannin (BRS 501 variety) Whole grain flour: 1. Milling at Level 0 (Fine)	100	Whole grain sorghum flour, water, whole egg, margarine, powdered milk, white cane sugar, salt, dry baker's yeast and xanthan gum	1. Physical (Specific volume, Crumb moisture) 2. Nutritional (Proximate) 3. Sensory Profile	100% sorghum yeast rolls showed a significant increase in fiber (5 ×), classified as high in fiber and protein (2 ×), achieving satisfactory sensory acceptance (6.83) and presenting a desirable lighter colour compared to yeast rolls made from 100% whole grain flour (millet/buckwheat/quinoa/ amaranth)	**Industry:** Use finely milled 100% whole-grain sorghum (BRS 501) to produce "high in fiber" gluten-free yeast rolls, maximizing nutritional value (5 × fiber) and functional appeal while meeting consumer acceptability standards. **Policy:** Encourage the use of locally developed sorghum cultivars (e.g., BRS501) in gluten-free product lines to enhance nutritional density and variety, benefiting celiac and health-conscious consumers	Drub et al. (2021)
Noodle							
Kwetiau (Wet rice noodles) (Indonesia)	• Unspecified colour with tannin Whole grain flour: 1. Grinding (Blender) 2. Sieving (80 mesh)	25–75	Whole grain sorghum flour, rice flour, tapioca starch, oil and water	1. Physiochemical (Elongation, Cooking loss, Proximate) 2. Bioactive (Tannin) 3. Functional (WAC) 4. Sensory Profile	The optimal 75% sorghum blend significantly improved nutritional quality by increasing protein and water absorption while decreasing cooking loss however, this high substitution level resulted in undesirable characteristics, including decreased elongation, increased tannin content, yellowish brown color, and being easily broken.	**Industry:** Utilize sorghum substitution with rice flour to create a highly accepted, high-fiber gluten-free *kwetiau* noodle that reduces import reliance and increase product value. **Policy:** Support the development of gluten-free staple alternatives (*kwetiau*) based on local sorghum and rice, directly targeting import reduction and diversifying national food options.	Bartolomiussihosa and Amrinola (2023)
Cookies							
Functional cookies (Nigeria)	• Unspecified colour/tannin Whole grain flour: 1. Washing 2. Drying (10 − 12% moisture content) 3. Milling (Hammer mill) 4. Sieving (0.2 μm mesh)	30–60	Whole grain sorghum flour, orange fleshed sweet potato, mushroom protein isolate. margarine, whole egg, sugar and baking powder	1. Nutritional (Proximate, and Amino acid profile) 2. Bioactive (Antioxidant and Anti-inflammatory) 3. *In Vivo* (Glycemic load in rats) 4. Sensory Profile	The optimized 30% sorghum blend achieved the highest protein content (35.20%) and antioxidant activity (91.33%), while exhibiting strong anti-inflammatory activities and successfully meeting metabolic targets (low glycemic load < 20)	**Industry:** Formulate multi-component blends (sorghum, mushroom protein isolate, orange fleshed sweet potato) to achieve exceptionally high protein (> 35%) and antioxidant capacity, creating a highly acceptable functional cookies that addresses inflammatory and metabolic diseases. **Policy:** Promote sorghum blended with orange fleshed sweet potato as potent, local functional food ingredients backed by *in vitro/in vivo* evidence to mitigate chronic diseases (diabetes, inflammation) in African countries	Akinbode et al. (2023)

(*continued on next page*)

Table 8 (*continued*)

Product Type & Tropical Sorghum Cultivation Area	Sorghum Flour Type & Milling/Grain Processing	Sorghum Flour (%, db)	Product Ingredients and Additives	Property Studied	Effect on Product Quality	Key Success Factors (Industry and Policy)	References
Cakes							
Muffin (Indonesia)	• Unspecified colour with tannin (Soper61 variety) Fermented flour: 1. Milling 2. Soaking in water (6 h) 3. Draining 4. Sieving (80–90 mesh) Fermented–Pregelatinized flour: 1. Milling 2. Soaking in water 3. Draining 4. Sieving (80–90 mesh) 5. Cooking in water (250 g/750 ml) 6. Cooling in refrigerator (12 h) 7. Drying at oven (60 °C, > 12 h) 8. Sieving (80–90 mesh)	• Fermented flour: 100 • Fermented–Pregelatinized flour: 40–100	Sorghum flour, wheat flour, eggs, liquid milk, sugar, margarine, baking powder and vanilla	1. Nutritional (Proximate) 2. Bioactive (Antioxidant) 3. Sensory Profile	The optimal muffin variant used a 60% substitution of fermented-pregelatinized flour, which improved the texture to be spongy and was the most preferred, all while retaining 5.04% of its antioxidant activity.	**Industry:** The simple and cost-effective pre–gelatinization modification should be prioritized as it is a feasible technology for improving the texture (spongy) and consumer acceptance of high-substitution sorghum–wheat muffin products. **Policy:** Support the dissemination of simple modification techniques (pre – gelatinization) at the community level to reduce dependence on wheat imports and diversify local food products	Suarni and Sulistyaningrum (2023)
Ready To Eat (RTE) Snacks & Convenience Foods							
Extruded flakes Brazil (Tropical area EMBRAPA Sete Lagoas)	• Brown with tannin (BRS 305 variety) Whole grain flour: 1. Milling 2. Extrusion	40 g flakes / 100 mL probiotic milk	Whole grain sorghum flour	1. *In Vivo* (Clinical Trial (Gut microbiota and Gastrointestinal symptoms)	Daily consumption of symbiotic meals significantly reduced uremic toxins and BMI successfully increased short-chain fatty acid and improved intestinal health (evacuation frequency and microbial richness).	**Industry:** Develop extruded tannin sorghum (BRS 305) symbiotic flakes that enhance SCFA synthesis to mitigate chronic systemic health issues. **Policy:** Provide clinical evidence for extruded sorghum meals as a validated, low- cost dietary therapeutic option for managing chronic kidney diseases, encouraging integration into clinical nutritional care guidelines.	Lúcio et al. (2024)
Dairy/Cheese Products							
Cream cheese (Brazil; Tropical area EMBRAPA Sete Lagoas)	• Brown with tannin (BRS 305 variety) Whole Grain Flour: 1. Milling 2. Gamma irradiation treatment Extruded Flour: 1. Extrusion 2. Drying (Forced air, 60 °C 4 h) 3. First Milling (Disc mill) 4. Second Milling (Hammer mill)	1–2	Minas Frescal cheese, pasteurized milk, milk cream, sorghum flour (whole grain / extruded flour), salt and xanthan gum	1. Physiochemical (Proximate, Colour, pH and Titratable acidity) 2. Bioactive (Total phenolics, CT and Antioxidant capacity (ABTS)) 3. Texture 4. Microbial Stability 5. Sensory Profile	Sorghum flour significantly reduced fat and increased protein and antioxidant capacity (highest at 2% inclusion), imparting a rosy tint and greater firmness to the cream cheese, while the whole grain flour formulation achieved the best overall sensory acceptance and purchase intention compared to the extruded or control samples	**Industry:** Prioritize whole grain sorghum flour (e.g., BRS 305 with tannin) to achieve optimal sensory acceptance and lower operational costs (avoiding extrusion), while leveraging its bioactive compounds for functional and premium product positioning. **Policy:** Promote the integration and standardization of local tannin-sorghum flour into food standards to create healthier, high-antioxidant and low-fat alternatives	Tadeu da Veiga Correia et al. (2022)

Data Source: The findings were qualitatively synthesized from a purposively selected subset of 15 primary studies (out of the 69 total included). These studies were specifically chosen to highlight distinct sorghum flour-based product categories and applications.

Abbreviations: BMI: body mass index; BV: breakdown viscosity; Ca: calcium; Fe: iron; GI: glycemic index; OAC: oil absorption capacity; ORAC: oxygen radical absorbance capacity; PV: peak viscosity; R&D: research and development; SCFA: short-chain fatty acid; SV: setback viscosity; WAC: water absorption capacity; Zn: zinc.

Ultimately, these synthesized processing guidelines establish key success factors required to drive large-scale commercialization of sorghum flour, thereby ensuring both sustainable tropical and global food security.

7.2. Nutritional integrity, bioavailability and policy

A critical policy gap exists regarding sorghum mineral bioavailability and product stability in tropical climates. While sorghum flour demonstrates potential for extended shelf life in derived products (Yulviatun et al., 2024), data on storage stability under high-humidity, high-temperature conditions remains scarce. Additionally, despite sorghum's inherent mineral richness, its bioavailability compared to fortified wheat is under-researched. Validating *in vivo* efficacy is critical to substantiate sorghum's potential as a sustainable public health solution, offering policy bodies a cost-effective alternative to synthetic fortification programs. Furthermore, despite extensive antidiabetic research on whole sorghum grains, there is a significant translational gap; studies insufficiently assess the antidiabetic potential of sorghum flour itself at the *in vitro* and *in vivo* levels. Addressing this is crucial for developing a validated low-GI sorghum flour, a key requirement for commercialization in the growing market for diabetes management.

7.3. Data standardization and nutritional transparency

Current nutritional reference data for sorghum flour is fundamentally limited and lacks transparency. The widely referenced USDA database reflects US-centric, non-representative sorghum, where approximately 99% of cultivation is tannin-free (Palacios et al., 2021). Consequently, this standard fails to adequately represent the full varietal diversity (both high-tannin and tannin-free types) prevalent in major sorghum-consuming regions. Furthermore, Codex Alimentarius standards offer only basic proximate composition, preventing accurate nutrient intake assessment. Future research must prioritize the establishment of standardized, climate-specific nutritional tables that explicitly stratify tannin levels to rectify this global data discrepancy.

7.4. Processing technologies and industrial translation

A significant translational gap persists between laboratory findings and industrial feasibility of sorghum flour production. There is a lack of optimized guidelines linking particle size fractionation to rheological requirements for specific end-products, particularly within tropical climates. Furthermore, current literature (2020–2025) reveals a near complete absence of research on advanced processing methods such as nixtamalization, ultrasound, SC–CO2, high pressure processing and cold plasma technology specifically applied to sorghum within tropical contexts. Future investigations must bridge this gap to establish how diverse agroecological environments, including tropical, subtropical, temperate and semi-arid regions, influence sorghum processing outcomes.

8. Conclusion

This comprehensive review (2020–2025) affirms that climate-resilient sorghum is a critical, gluten-free wheat alternative for tropical food production, exhibiting significant nutritional advantages, including substantial mineral concentrations and a rich polyphenol profile. However, the transition of sorghum from a subsistence crop to a functional industrial ingredient relies fundamentally on optimized grain processing; specifically, the advancement of milling technologies requires an in-depth understanding of how genotype-environment interactions affect flour rheology. Advancing this sector offers a strategic pathway to address the SDGs. By enhancing food security, nutrition and health (SDGs 2, 3), and driving industrial innovation and economic growth in developing tropical regions (SDGs 1, 8, 9, 10), sorghum commercialization directly mitigates poverty and inequality. Furthermore, its inherent drought tolerance supports sustainable consumption and climate action (SDGs 12, 13, 15). Ultimately, sustained commercial success requires a coordinated multi-stakeholder partnership (SDG 17) involving continued research, industrial investment and favourable national food policies to fully exploit sorghum as a high-quality, sustainable global staple.

Acknowledgment

This work was supported/funded by the Universiti Putra Malaysia under *Cabaran Perdana Putra* Grant (GCPP) (GCPP/2025/9819100).

Ethical statement

This study did not involve human participants or animals. Therefore, ethical approval and informed consent were not required.

CRediT authorship contribution statement

Nurul Farhanah Mohd Aluwi: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Radhiah Shukri:** Writing – review & editing, Validation, Supervision, Conceptualization. **Wan Zunairah Wan Ibadullah:** Supervision. **Rabiha Sulaiman:** Supervision. **Nor Afizah Mustapha:** Supervision. **Roseliza Kadir Basha:** Supervision. **Barakatun Nisak Mohd Yusof:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Abdelhalim, T.S., Abdelhalim, N.S., Kamal, N.M., Mohamed, E.E., Hassan, A.B., 2021. Exploiting the potential of Sudanese sorghum landraces in biofortification: physicochemical quality of the grain of sorghum (*Sorghum bicolor* L. Moench) landraces. Food Chem. 337, 127604. https://doi.org/10.1016/j.foodchem.2020.127604.

Achalu, B.I., Tessema, H.A., Ayele, A.T., 2025. Development and characterization of gluten-free bread enriched with whey protein from sorghum-rice composite flours. Appl. Food Res. 5 (2), 101133. https://doi.org/10.1016/j.afres.2025.101133.

Adepehin, J.O., 2020. Microbial diversity and pasting properties of finger millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) sourdoughs. Food Biosci. 37, 100684. https://doi.org/10.1016/j.fbio.2020.100684.

Adeyanju, A.A., Emmanuel, P.O., Adetunji, A.I., Adebo, O.A., 2025. Nutritional, pasting, rheological, and thermal properties of sorghum–okara composite flours and porridges. Int. J. Food Sci. Technol. 60 (1). https://doi.org/10.1093/ijfood/vvae021.

Adu, M., Anim, S.O., Odoom, W., Adomako, C., Osei-Asibey, R.K., 2024. Sprouting days: its influence on quality characteristics of millet and sorghum flour. Appl. Food Res. 4 (2), 100518. https://doi.org/10.1016/j.afres.2024.100518.

Adzqia, F., Suwonsichon, S., Thongngam, M., 2023. Effects of white sorghum flour levels on physicochemical and sensory characteristics of gluten-free bread. Foods. 12 (22). https://doi.org/10.3390/foods12224113.

Aisha, L.N., Kurniasih, N., 2024. Nutritional and antioxidant analysis of cookies made from sorghum flour. ISTEK 13 (1), 32–35. https://doi.org/10.15575/istek.v13i1.931.

Akinbode, B.A., Malomo, S.A., Asasile, I.I., 2023. *In vitro* antioxidant, anti-inflammatory and *in vivo* anti-hyperglycemia potentials of cookies made from sorghum, orange-flesh-sweet-potato and mushroom protein isolate flour blends fed to Wistar rats. Food Chem. Adv. 2, 100263. https://doi.org/10.1016/j.focha.2023.100263.

Almaiman, S.A., Albadr, N.A., Alsulaim, S., Alhuthayli, H.F., Osman, M.A., Hassan, A.B., 2021. Effects of microwave heat treatment on fungal growth, functional properties, total phenolic content, and antioxidant activity of sorghum (*Sorghum bicolor* L.) grain. Food Chem. 348, 128979. https://doi.org/10.1016/j.foodchem.2020.128979.

Amtataw, M., Kassahun, E., Tibebu, S., Andargie, T., Ayanaw, T., Agazie, A., Wogayehu, M., Teshome, A., Jemal, S., Teferi, D., 2025. Nutritional and anti-nutritional evaluation of injera made from sorghum, rice, teff, and flaxseed flours using D-optimal mixture design. Sci. Rep. 15 (1), 3959. https://doi.org/10.1038/s41598-025-88407-4.

Antarlina, S.S., Estiasih, T., Zubaidah, E., Harijono, 2021. The physicochemical properties of white sorghum (*Sorghum bicolor* L.) flour in various particle sizes by soaking the seeds before and after dehulling. Food Res. 5 (3). https://doi.org/10.26656/fr.2017.5(3).541.

Ariningsih, E., Saliem, H.P., Nurhasanah, A., Gunawan, E., Agustian, A., Saptana, 2023. Challenges and alternative solutions in developing sorghum to support food diversification in Indonesia. IOP Conf. Ser. 1153 (1), 012032. https://doi.org/10.1088/1755-1315/1153/1/012032.

Atuna, R.A., Ametei, P.N., Bawa, A.-A., Amagloh, F.K., 2022. Traditional processing methods reduced phytate in cereal flour, improved nutritional, functional and rheological properties. Sci. Afr. 15, e01063. https://doi.org/10.1016/j.sciaf.2021.e01063.

A'yunin, N.A.Q., Atmadja, T.F.A.-G., Aini, N., Haryanti, P., 2022. Characterisation of polishing frequency for three varieties of sorghum grain in Java, Indonesia. Int. J. Food Sci. 2022, 1–10. https://doi.org/10.1155/2022/2949665.

Bah, L., Kourouma, K., Sakho, A.M., Diallo, A., Sow, M.M., 2024. Study and formulation of composite flours based on gluten flour and local cereal flours: fonio, millet and sorghum. J. Agric. Chem. Environ. 13 (01), 169–181. https://doi.org/10.4236/jacen.2024.131011.

Bahlawan, Z.A.S., Damayanti, A., Megawati, M., Cahyari, K., Margiyanti, Y., Mufidati, M., 2022. Effect of fortification and fermentation on the nutritional value of sorghum (*Sorghum bicolor* (L.) Moench) flour. Trends Sci. 19 (15), 5534. https://doi.org/10.48048/tis.2022.5534.

Bahlawan, Z.A.S., Kumoro, A.C., Megawati, M., 2023. Physico-chemical characteristics of novel analog rice from fermented sorghum flour by *Rhizopus oligosporus* and soybean flour. Curr. Res. Nutr. Food Sci. J. 11 (3), 1022–1038. https://doi.org/10.12944/CRNFSJ.11.3.09.

Bahlawan, Z.A.S., Kumoro, A.C., Wahono, S.K., Megawati, M., Tan, C.P., 2024. Thermal and concentration impacts on tannin and physical properties changes during alkaline soaking of sorghum grain. J. Adv. Res. Fluid Mech. Therm. Sci. 120 (2), 115–124. https://doi.org/10.37934/arfmts.120.2.115124.

Bahlawan, Z.A.S., Kumoro, A.C., Wahono, S.K., Megawati Ping, T.C., Rizal, W.A, 2025. Investigating the kinetics of tannin removal in sorghum [*Sorghum Bicolor* (L.) Moench] grains through a soaking process. ASEAN J. Chem. Eng. 25 (1). https://doi.org/10.22146/ajche.18116.

Bartolomiussihosa, J.A., Amrinola, W., 2023. The effect of sorghum flour substituted in *kwetiau* (rice noodles) on the characteristics of physicochemical, functional, and sensory. IOP Conf. Ser. 1169 (1), 012102. https://doi.org/10.1088/1755-1315/1169/1/012102.

Batariuc, A., Ungureanu-Iuga, M., Mironeasa, S., 2021. Effects of dry heat treatment and milling on sorghum chemical composition, functional and molecular characteristics. Appl. Sci. 11 (24), 11881. https://doi.org/10.3390/app112411881.

Bazié, D., Dibala, C.I., Kondombo, C.P., Diao, M., Konaté, K., Sama, H., Kayodé, A.P.P., Dicko, M.H., 2023. Physicochemical and nutritional potential of fifteen sorghum cultivars from Burkina faso. Agriculture 13 (3), 675. https://doi.org/10.3390/agriculture13030675.

Bhukya, R., Chamarthy, R.V, Ediga, S., Reddy, A.C., Marriboina, S.B., Tonapi, V.A., 2020. Variability of polyphenols, antioxidant activity and UFLC phenolic acid profiles of different sorghum genotypes. Schol. Int. J. Biochem. 03 (05), 104–113. https://doi.org/10.36348/sijb.2020.v03i05.001.

Bianco-Gomes, A.C., Nogueira, L.D.S., Bono-Lopes, N.V.M., Gouvêa-Souza, C.P., Boldrini-França, J., Gomes, V.M., Cherene, M.B., Alves, N.E.G., Vasconcelos, C.M., 2022. Dry heat and pressure favor bioactive compounds preservation and peptides formation in sorghum [*Sorghum bicolor* (L.) Moench]. Curr. Res. Food Sci. 5, 117–124. https://doi.org/10.1016/j.crfs.2021.12.013.

Cabrera-Ramírez, A.H., Luzardo-Ocampo, I., Ramírez-Jiménez, A.K., Morales-Sánchez, E., Campos-Vega, R., Gaytán-Martínez, M., 2020. Effect of the nixtamalization process on the protein bioaccessibility of white and red sorghum flours during *in vitro* gastrointestinal digestion. Food Res. Int. 134, 109234. https://doi.org/10.1016/j.foodres.2020.109234.

Célia, J.A., Resende, O., Silva, L.C., de, M., Ferreira, S.V., Correia, J.S., de Almeida, A.B., Mabasso, G.A., 2024. Characterization and evaluation of grain sorghum flour (*Sorghum bicolor* (L.) Moench subjected to storage in different packaging. J. Stored. Prod. Res. 105, 102256. https://doi.org/10.1016/j.jspr.2024.102256.

Cesbron-Lavau, G., Goux, A., Atkinson, F., Meynier, A., Vinoy, S., 2021. Deep dive into the effects of food processing on limiting starch digestibility and lowering the glycemic response. Nutrients 13 (2), 381. https://doi.org/10.3390/nu13020381.

Chiodetti, M., Tuccio, M.G., Carini, E., 2024. Effect of water content on gelatinization functionality of flour from sprouted sorghum. Curr. Res. Food Sci. 8, 100780. https://doi.org/10.1016/j.crfs.2024.100780.

Chiremba, C., Taylor, J.R.N., Duodu, K.G., 2009. Phenolic content, antioxidant activity, and consumer acceptability of sorghum cookies. Cereal. Chem. 86 (5), 590–594. https://doi.org/10.1094/CCHEM-86-5-0590.

Cisse, F., Swackhamer, C., Diall, H.G., Rahmanifar, A., Sylla, M., Opekun, A.R., Grusak, M.A., Lin, A.H.-M., Pletsch, E.A., Hayes, A.M.R., Quezada-Calvillo, R., Nichols, B.L., Hamaker, B.R., 2025. Stunted African toddlers digest and obtain energy from energy-dense thick sorghum porridge. Eur. J. Clin. Nutr. 79 (10), 1018–1028. https://doi.org/10.1038/s41430-025-01632-y.

Codex Alimentarius Commission, 2023a. Standard for Sorghum Flour (CXS 173-1989). https://www.codexalimentarius.org.

Codex Alimentarius Commission, 2023b. Standard for Sorghum Grains (CXS 172-1989). https://www.codexalimentarius.org.

Comettant-Rabanal, R., Carvalho, C.W.P., Ascheri, J.L.R., Chávez, D.W.H., Germani, R., 2021. Extruded whole grain flours and sprout millet as functional ingredients for gluten-free bread. LWT 150, 112042. https://doi.org/10.1016/j.lwt.2021.112042.

Curti, M.I., Belorio, M., Palavecino, P.M., Camiña, J.M., Ribotta, P.D., Gómez, M., 2021. Effect of sorghum flour properties on gluten-free sponge cake. J. Food Sci. Technol. 59 (4), 1407–1418. https://doi.org/10.1007/s13197-021-05150-0.

Curti, M.I., Palavecino, P.M., Camiña, J.M., Savio, M., Ribotta, P.D., 2022. Effect of tempering conditions and mill type on physicochemical and functional properties of sorghum (*Sorghum bicolor* [L.] Moench) flour. J. Food Process. Preserv. 46 (10). https://doi.org/10.1111/jfpp.16851.

Curti, M.I., Palavecino, P.M., Savio, M., Baroni, M.V., Ribotta, P.D., 2023. Sorghum (Sorghum bicolor L. Moench) gluten-free bread: the effect of milling conditions on the technological properties and *in vitro* bioaccessibility of polyphenols and minerals. Foods 12 (16), 3030. https://doi.org/10.3390/foods12163030.

D'Almeida, C.T.dos S., Mameri, H., Menezes, N.dos S., de Carvalho, C.W.P., Queiroz, V.A.V., Cameron, L.C., Morel, M.-H., Takeiti, C.Y., Ferreira, M.S.L, 2021. Effect of extrusion and turmeric addition on phenolic compounds and kafirin properties in tannin and tannin-free sorghum. Food Res. Int. 149, 110663. https://doi.org/10.1016/j.foodres.2021.110663.

de Oliveira, L.de L., de Oliveira, G.T., de Alencar, E.R., Queiroz, V.A.V., de Alencar Figueiredo, L.F., 2022. Physical, chemical, and antioxidant analysis of sorghum grain and flour from five hybrids to determine the drivers of liking of gluten-free sorghum breads. LWT 153, 112407. https://doi.org/10.1016/j.lwt.2021.112407.

Dhanya, R., Sunil, C.K., Vidyalakshmi, R., Natarajan, V., 2024. Effect of size reduction methods on raw and microwave-parboiled white sorghum and their physico-chemical, functional, rheological, and structural characteristics. J. Cereal. Sci. 117, 103917. https://doi.org/10.1016/j.jcs.2024.103917.

Djou, L.D.G., Lanamana, W., Murdaningsih, Lulan, T.Y.K, 2024. Improvement of cultivation techniques to increase sorghum productivity in Ende Regency, Indonesia. In: E3S Web Conference, 513. https://doi.org/10.1051/e3sconf/202451304008.

dos Reis Gallo, L.R., Reis, C.E.G., Mendonça, M.A., da Silva, V.S.N., Pacheco, M.T.B., Botelho, R.B.A, 2021. Impact of gluten-free sorghum bread genotypes on glycemic and antioxidant responses in healthy adults. Foods 10 (10), 2256. https://doi.org/10.3390/foods10102256.

Drub, T.F., Garcia dos Santos, F., Ladeia Solera Centeno, A.C., Capriles, V.D., 2021. Sorghum, millet and pseudocereals as ingredients for gluten-free whole-grain yeast rolls. Int. J. Gastron. Food Sci. 23, 100293. https://doi.org/10.1016/j.ijgfs.2020.100293.

Dwipajati, D., Widajati, E., Ainaya, A.F., Novanda, R.D., 2022. Potential of Indonesian community food sources which are rich in fiber as an alternative staple food for Type 2 diabetics: a scoping review. Open. Access. Maced. J. Med. Sci. 10 (T8), 47–53. https://doi.org/10.3889/oamjms.2022.9470.

Endalamaw, C., Tsegaye, D., Nida, H., van Biljon, A., Herselman, L., Labuschagne, M., 2025. Environmental impact on grain quality in Ethiopian sorghum landraces. J. Agric. Food Res. 21, 101916. https://doi.org/10.1016/j.jafr.2025.101916.

Ervina, E., Tenadi, A., Renata, G., Aurelia, S., 2023. Does consumer knowledge of sorghum impact their liking? Investigating consumers preferences on sorghum biscuits using JAR (Just-About-Right) scale. IOP Conf. Ser. 1169 (1), 012088. https://doi.org/10.1088/1755-1315/1169/1/012088.

FAO, 2022. The future of food and agriculture – drivers and triggers for transformation. The Future of Food and Agriculture – Drivers and Triggers for Transformation. FAO. https://doi.org/10.4060/cc0959en.

FAOSTAT, 2023. Sorghum Production. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/QC.

Farha, M.N., Brown, F., Cernusak, L.A., Sitch, S., Cheesman, A.W., 2025. Examining ozone effects on the tropical C4 crop *Sorghum bicolor*. PeerJ. 13, e18844. https://doi.org/10.7717/peerj.18844.

Gebremedihin, L.B., Abera, W.G., 2024. Quality assessment of gluten-free sorghum bread prepared with sourdough and the addition of sweet lupin flour. CyTA 22 (1). https://doi.org/10.1080/19476337.2024.2397022.

George, T.T., Obilana, A.O., Oyenihi, A.B., Obilana, A.B., Akamo, D.O., Awika, J.M., 2022. Trends and progress in sorghum research over two decades, and implications for global food security. South Afr. J. Bot. 151, 960–969. https://doi.org/10.1016/j.sajb.2022.11.025.

Gunawan, S., Dwitasari, I., Rahmawati, N., Darmawan, R., Wirawasista Aparamarta, H., Widjaja, T., 2022. Effect of process production on antinutritional, nutrition, and physicochemical properties of modified sorghum flour. Arab. J. Chem. 15 (10), 104134. https://doi.org/10.1016/j.arabjc.2022.104134.

Hajjarpoor, A., Eltigani, A., Seiler, C., Matros, A., Kottmann, L., Balko, C., Windpassinger, S., Goldbach, J., Eder, J., Rahman, A.S., Quade, M., Jorzig, C., Perovic, D., Stahl, A., Feike, T., 2023. Germany-wide suitability analysis of sorghum cultivation for climate change mitigation. In: Halm, L. (Ed.), Tagung der Gesellschaft für Pflanzenbauwissenschaften e. V.: Digital Tools, Big Data, Modeling and Sensing Methods for Sustainable and Climate Smart Crop and Grassland Systems. Kurzfassungen der Vorträge und Poster, pp. 95–96. https://www.openagrar.de/receive/openagrar_mods_00090370.

Hamid, M.G., Böhme, C., Mustafa, K.A., Idris, Y.M.A., Muneer, F., Elsafy, M., Rahmatov, M., Johansson, E., Abdelhalim, T.S., 2025. Sensory evaluation and consumer acceptance of *Kisra*, a sudanese fermented flatbread made with biofortified sorghum: insights from check-all-that-apply (CATA) method. Appl. Food Res. 5 (1), 100920. https://doi.org/10.1016/j.afres.2025.100920.

Handa, V., Sharma, D., Kaur, A., Arya, S.K., 2020. Biotechnological applications of microbial phytase and phytic acid in food and feed industries. Biocatal. Agric. Biotechnol. 25, 101600. https://doi.org/10.1016/j.bcab.2020.101600.

Hatmi, R.U., Wirabhuana, A., Wanita, Y.P., Tando, E., Musyadik, 2021. The effect of the polishing process and sorghum type (brown and white) on the content of crackers nutrition. IOP Conf. Ser. 759 (1), 012037. https://doi.org/10.1088/1755-1315/759/1/012037.

Heikonen, S., Heino, M., Jalava, M., Siebert, S., Viviroli, D., Kummu, M., 2025. Climate change threatens crop diversity at low latitudes. Nat. Food 6 (4), 331–342. https://doi.org/10.1038/s43016-025-01135-w.

Indrianingsih, A.W., Khasanah, Y., Noviana, E., Rahayu, E., Hastuti, H.P., Ni'maturrohmah, D., Suryani, A.E., Darsih, C., Windarsih, A., Handayani, S., 2023. The effect of soaking of white and red varieties of *Sorghum bicolor* flour on its antioxidant, antidiabetic and physicochemical properties. Food Human. 1, 1531–1538. https://doi.org/10.1016/j.foohum.2023.10.020.

Irondi, E.A., Adewuyi, A.E., Aroyehun, T.M., 2022. Effect of endogenous lipids and proteins on the antioxidant, *in vitro* starch digestibility, and pasting properties of sorghum flour. Front. Nutr. 8. https://doi.org/10.3389/fnut.2021.809330.

Jagtap, S., Trollman, H., Trollman, F., Garcia-Garcia, G., Parra-López, C., Duong, L., Martindale, W., Munekata, P.E.S., Lorenzo, J.M., Hdaifeh, A., Hassoun, A., Salonitis, K., Afy-Shararah, M., 2022. The Russia-Ukraine conflict: its implications for the global food supply chains. Foods 11 (14). https://doi.org/10.3390/foods11142098.

Jia, H., Ren, F., Liu, H., 2025. Development of low glycemic index food products with wheat resistant starch: a review. Carbohydr. Polym. 361. https://doi.org/10.1016/j.carbpol.2025.123637.

Joseph, M., Alavi, S., Adedeji, A.A., Zhu, L., Gwirtz, J., Thiele, S., 2024. Adaptation of conventional wheat flour mill to refine sorghum, corn, and cowpea. AgriEngineering 6 (3), 1959–1971. https://doi.org/10.3390/agriengineering6030114.

Joseph, M., Guo, Q., Lindshield, B., Adedeji, A.A., Alavi, S., 2025. Characterization of extruded sorghum-soy blends to develop pre-cooked and nutritionally dense fortified blended foods. Foods 14, 779. https://doi.org/10.3390/foods14050779.

Keyata, E.O., Tola, Y.B., Bultosa, G., Forsido, S.F., 2021. Optimization of nutritional and sensory qualities of complementary foods prepared from sorghum, soybean, karkade and premix in Benishangul - Gumuz region, Ethiopia. Heliyon 7 (9), e07955. https://doi.org/10.1016/j.heliyon.2021.e07955.

Keyata, E.O., Tola, Y.B., Bultosa, G., Forsido, S.F., 2023. Bioactive compounds, antioxidant capacity, functional and sensory properties of optimized complementary weaning flour processed from sorghum, soybean, and karkade (*Hibiscus sabdariffa* L.) seeds. Sci. Afr. 19, e01457. https://doi.org/10.1016/j.sciaf.2022.e01457.

Kristanti, D., Setiaboma, W., Iwansyah, A.C., Pangestu, A., Permadi, S.N., Ningrum, A., Puspitaningtyas, E.L., 2023. Study on red and white sorghum (*Sorghum bicolor*) germination flour: physicochemical properties and it's correlation. BIO Web Conf. 69, 03007. https://doi.org/10.1051/bioconf/20236903007.

Kumari, P.K., Umakanth, A.V., Narsaiah, T.B., Uma, A., 2021. Exploring anthocyanins, antioxidant capacity and α-glucosidase inhibition in bran and flour extracts of selected sorghum genotypes. Food Biosci. 41, 100979. https://doi.org/10.1016/j.fbio.2021.100979.

Kurniadi, M., Nurcholis, M., Roeslan, M., Widodo, R.A., Widodo, T., Rosyida, V.T., Nurhayati, R., Kusumaningrum, A., Human, S., 2021. The effect of urea fertilizer doses on the chemical characteristics of the Samurai1, Samurai-2, and Pahat mutant sorghum (*Sorghum bicolor* L.) grain varieties. Food Res. 5 (2), 254–261. https://doi.org/10.26656/fr.2017.5(2).475.

Lal, M.K., Singh, B., Sharma, S., Singh, M.P., Kumar, A., 2021. Glycemic index of starchy crops and factors affecting its digestibility: a review. Trends. Food Sci. Technol. 111, 741–755. https://doi.org/10.1016/j.tifs.2021.02.067.

Lavanya, J.P., Gowthamraj, G., Sangeetha, N., 2021. Effect of heat moisture treatment on the physicochemical, functional, and antioxidant characteristics of white sorghum (*Sorghum bicolor* (L.) grains and flour. J. Food Process. Preserv. 45 (12). https://doi.org/10.1111/jfpp.16017.

Laya, A., Siewe, F.B., Wangso, H., Falama, D., Djibrilla, H., Koubala, B.B., 2022. Effect of different processing methods on maize, sorghum and millet flours on nutritional couscous quality consumed in the Far North region of Cameroon. J. Agric. Food Res. 9, 100328. https://doi.org/10.1016/j.jafr.2022.100328.

Li, T., Huang, J., Yu, J., Tian, X., Zhang, C., Pu, H., 2024. Effects of soaking glutinous sorghum grains on physicochemical properties of starch. Int. J. Biol. Macromol. 267, 131522. https://doi.org/10.1016/j.ijbiomac.2024.131522.

Lohani, U.C., Muthukumarappan, K., 2020. Influence of fermentation followed by ultrasonication on functional properties of sorghum extrudates. J. Food Process. Eng. (6), 43. https://doi.org/10.1111/jfpe.13390.

Lúcio, H.G., Lopes, R., de, C.S.O., Gomes, M.J.C., da Silva, A., Grancieri, M., Della Lucia, C.M., Queiroz, V.A.V., da Silva, B.P., Martino, H.S.D., 2024. A symbiotic meal containing extruded sorghum and probiotic (Bifidobacterium longum) Ameliorated intestinal health markers in individuals with chronic kidney disease: a secondary analysis of a subsample from a previous randomized and controlled clinical trial. Nutrients 16 (12), 1852. https://doi.org/10.3390/nu16121852.

Luzardo-Ocampo, I., Ramírez-Jiménez, A.K., Cabrera-Ramírez, Á.H., Rodríguez-Castillo, N., Campos-Vega, R., Loarca-Piña, G., Gaytán-Martínez, M., 2020. Impact of cooking and nixtamalization on the bioaccessibility and antioxidant capacity of phenolic compounds from two sorghum varieties. Food Chem. 309, 125684. https://doi.org/10.1016/j.foodchem.2019.125684.

Majzoub, R.Al, Hamdan, S.A., Khaled, S., Khatib, S.El, Krayem, M., 2023. A comparison between wheat and sorghum flour in biscuits application: a review. Food Sci. Eng. 89–102. https://doi.org/10.37256/fse.4120232140.

Medina Martinez, O.D., Lopes Toledo, R.C., Vieira Queiroz, V.A., Pirozi, M.R., Duarte Martino, H.S., Ribeiro de Barros, F.A., 2020. Mixed sorghum and quinoa flour improves protein quality and increases antioxidant capacity *in vivo*. LWT 129, 109597. https://doi.org/10.1016/j.lwt.2020.109597.

Medina Martinez, O.D., Vieira Theodoro, J.M., Grancieri, M., Lopes Toledo, R.C., Vieira Queiroz, V.A., Ribeiro de Barros, F.A., Duarte Martino, H.S., 2021. Dry heated whole sorghum flour (BRS 305) with high tannin and resistant starch improves glucose metabolism, modulates adiposity, and reduces liver steatosis and lipogenesis in Wistar rats fed with a high-fat high-fructose diet. J. Cereal. Sci. 99, 103201. https://doi.org/10.1016/j.jcs.2021.103201.

Mohamed, H.I., Fawzi, E.M., Basit, A., Kaleemullah Lone, R., Sofy, M.R, 2022. Sorghum: nutritional factors, bioactive compounds, pharmaceutical and application in food systems: a review. Phyton-Int. J. Exp. Botany 91 (7), 1303–1325. https://doi.org/10.32604/phyton.2022.020642.

Mukkun, L., Lalel, H.J.D., Klenden, Y.L., 2021. The physical and chemical characteristics of several accessions of sorghum cultivated on drylands in East Nusa Tenggara, Indonesia. Biodivers. J. Biol. Divers. 22 (5). https://doi.org/10.13057/biodiv/d220509.

Myers, J.S., Bean, S.R., Aramouni, F.M., Wu, X., Schmidt, K.A., 2023. Textural and functional analysis of sorghum flour cookies as ice cream inclusions. Grain Oil Sci. Technol. 6 (2), 100–111. https://doi.org/10.1016/j.gaost.2022.12.002.

Naveed, H., Sultan, W., Awan, K.A., Imtiaz, A., Yaqoob, S., Al-Asmari, F., Faraz, A., Qian, J.-Y., Sharma, A., Mugabi, R., Alotaibi, S.S., Nayik, G.A., 2024. Glycemic impact of cereal and legume-based bakery products: implications for chronic disease management. Food Chem. X. 24, 101959. https://doi.org/10.1016/j.fochx.2024.101959.

Ndlovu, E., Maphosa, M., van Staden, J., 2024. Pre-anthesis morpho-physiological response of tropical sorghum to combined drought and heat stress. South Afr. J. Botany 172, 448–461. https://doi.org/10.1016/j.sajb.2024.07.045.

Orr, A., Schipmann-Schwarze, C., Gierend, A., Nedumaran, S., Mwema, C., Muange, E., Manyasa, E., Ojulong, H., 2020. Why invest in Research & Development for sorghum and millets? The business case for East and Southern Africa. Glob. Food Sec. 26. https://doi.org/10.1016/j.gfs.2020.100458.

Paes, L.T., D'Almeida, C.T.dos S., do Carmo, M.A.V., da Silva Cruz, L., Bubula de Souza, A., Viana, L.M., Gonçalves Maltarollo, V., Martino, H.S.D., Domingues de Almeida Lima, G., Larraz Ferreira, M.S., Azevedo, L., Barros, F.A.R.de, 2024. Phenolic-rich extracts from toasted white and tannin sorghum flours have distinct profiles influencing their antioxidant, antiproliferative, anti-adhesive, anti-invasive, and antimalarial activities. Food Res. Int. 176, 113739. https://doi.org/10.1016/j.foodres.2023.113739.

Palacios, C.E., Nagai, A., Torres, P., Rodrigues, J.A., Salatino, A., 2021. Contents of tannins of cultivars of sorghum cultivated in Brazil, as determined by four quantification methods. Food Chem. 337, 127970. https://doi.org/10.1016/j.foodchem.2020.127970.

Patil, S., Sonawane, S.K., Mali, M., Mhaske, S.T., Arya, S.S., 2020. Pasting, viscoelastic and rheological characterization of gluten free (cereals, legume and underutilized) flours with reference to wheat flour. J. Food Sci. Technol. 57 (8), 2960–2966. https://doi.org/10.1007/s13197-020-04328-2.

Patty, M.D., Murtini, E.S., Putri, W.D.R., 2023. Physiochemical characteristics of starch noodles based on sorghum flour (*Sorghum bicolor* L. Moench) and sago flour (*Metroxylon* Sp). J. Pangan Dan Agr. 11 (3), 147–157. https://doi.org/10.21776/ub.jpa.2023.011.03.5.

Peterson, J., Santana, A.L., Cox, S., Perez-Fajardo, M., Covarrubias, J., Perumal, R., Bean, S., Wu, X., Wang, W., Smolensky, D., 2024. Impact of heat and high-moisture pH treatments on starch digestibility, phenolic composition, and cell bioactivity in sorghum (*Sorghum bicolor* L. Moench) flour. Front. Nutr. 11. https://doi.org/10.3389/fnut.2024.1428542.

Petri, P.Z., De Souza Silva, P., Ascheri, J.L.R., 2026. Rethinking structure; Challenges in the development of gluten-free pasta and baked goods: a review. Discov. Agric. Food Sci. 14 (01), 22–50. https://doi.org/10.14738/tnc.1401.19861.

Pinheiro, S.S., Anunciação, P.C., Cardoso, L.de M., Della Lucia, C.M., de Carvalho, C.W.P., Queiroz, V.A.V., Pinheiro Sant'Ana, H.M., 2021. Stability of B vitamins, vitamin E, xanthophylls and flavonoids during germination and maceration of sorghum (*Sorghum bicolor* L.). Food Chem. 345, 128775. https://doi.org/10.1016/j.foodchem.2020.128775.

Probosari, E., Dewi, S.N., Alfadila, T.I., Handayani, E.N., Rizkita, M.S., Candra, A., Ardiaria, M., Puruhita, N., Murbawani, E.A., 2025. Sorghum-soybean flour enteral formula reduces blood glucose, cholesterol, triglycerides, LDL, and increases HDL and albumin in hyperglycemic rats. Mol. Cell. Biomed. Sci. 9 (1), 13. https://doi.org/10.21705/mcbs.v9i1.507.

Pujiharti, Y., Paturohman, E., Ikhwani, 2022. Prospect of sorghum development as corn substitution in Indonesia. IOP Conf. Ser. 978 (1), 012019. https://doi.org/10.1088/1755-1315/978/1/012019.

Rebellato, A.P., Orlando, E.A., Thedoropoulos, V.C.T., Greiner, R., Pallone, J.A.L., 2020. Effect of phytase treatment of sorghum flour, an alternative for gluten free foods and bioaccessibility of essential minerals. J. Food Sci. Technol. 57 (9), 3474–3481. https://doi.org/10.1007/s13197-020-04382-w.

Ridwansyah, Sinaga, H., Adiba, I.F, 2020. Making artificial rice from sorghum flour, corn flour and cassava starch by using mini extruder. IOP Conf. Ser. 454 (1), 012116. https://doi.org/10.1088/1755-1315/454/1/012116.

Ronoh, A.K., Serrem, C.A., Tumwebaze, S.B., Were, G.M., 2024a. Descriptive and rapid sensory profiling of wheat and wheat-sorghum biscuits fortified with longhorn grasshopper (*Ruspolia differens*) powder. Appl. Food Res. 4 (2), 100504. https://doi.org/10.1016/j.afres.2024.100504.

Ronoh, A.K., Serrem, C.A., Tumwebaze, S.B., Were, G.M., 2024b. Rat bioassay for evaluation of protein nutritional quality of wheat and wheat-sorghum biscuits fortified with longhorn grasshopper (*Ruspolia differens*) powder. Food Sci. Anim. Products 2 (2), 9240062. https://doi.org/10.26599/FSAP.2024.9240062.

Rumler, R., Bender, D., Speranza, S., Frauenlob, J., Gamper, L., Hoek, J., Jäger, H., Schönlechner, R., 2021. Chemical and physical characterization of sorghum milling fractions and sorghum whole meal flours obtained via stone or roller milling. Foods 10 (4), 870. https://doi.org/10.3390/foods10040870.

Saeed Omer, S.H., Mohamed, H.A., Zheng, X., 2025. Effects of various sorghum flour particle sizes on the properties of sorghum–wheat composite dough sheets and noodles. Processes 13 (12). https://doi.org/10.3390/pr13123840.

Samtiya, M., Aluko, R.E., Dhewa, T., 2020. Plant food anti-nutritional factors and their reduction strategies: an overview. Food Production, Processing and Nutrition 2 (1). https://doi.org/10.1186/s43014-020-0020-5.

Sawadogo-Lingani, H., Owusu-Kwarteng, J., Glover, R., Diawara, B., Jakobsen, M., Jespersen, L., 2021. Sustainable production of African traditional beers with focus on Dolo, a West African sorghum-based alcoholic beverage. Front. Sustain. Food Syst. 5. https://doi.org/10.3389/fsufs.2021.672410.

Setyowati, D., Muna, A.N., Septiyani, A., Widyastuti, N., Margawati, A., Ardiaria, M., Tsani, A.F.A., 2023. Sorghum flour's effect on improving plasma lipid profile and atherogenic index in diabetic rats. AcTion 8 (2), 186. https://doi.org/10.30867/action.v8i2.735.

Sheng, X., Cui, Q., Yin, H., Xi, Z., Yi, J., Zhang, H., Xu, X., Ma, Y., 2025. Application of hydrocolloids in the quality improvement of flour-based products. Trends. Food Sci. Technol. 164, 105211. https://doi.org/10.1016/j.tifs.2025.105211.

Shinda, C.A., Nthakanio, P.N., Gitari, J.N., Runo, S., Mukono, S., Maina, S., 2022. Nutrient content of sorghum hybrid lines between Gadam and hard coat tannin sorghum cultivars. Food Sci. Nutr. 10 (7), 2202–2212. https://doi.org/10.1002/fsn3.2830.

Silva, T.L., Lacerda, U.V., da Matta, S.L.P., Queiroz, V.A.V., Stringheta, P.C., Martino, H.S.D., de Barros, F.A.R., 2020. Evaluation of the efficacy of toasted white and tannin sorghum flours to improve oxidative stress and lipid profile in vivo. J. Food Sci. 85 (7), 2236–2244. https://doi.org/10.1111/1750-3841.15301.

Sobowale, S.S., Bamidele, O.P., Adebo, J.A., 2024. Physicochemical, functional, and antinutritional properties of fermented Bambara groundnut and sorghum flours at different times. Food Chem. Adv. 4, 100729. https://doi.org/10.1016/j.focha.2024.100729.

Souza, P., Peterson, J., Andeta, A.F., Bascom, N., Karkle, E., 2025. Characterization and functionality of fermented sorghum and enset flours in a gluten-free deposited biscuit. J. Cereal. Sci. 122, 104106. https://doi.org/10.1016/j.jcs.2025.104106.

Sruthi, N.U., Rao, P.S., Rao, B.D., 2021. Decortication induced changes in the physico-chemical, anti-nutrient, and functional properties of sorghum. J. Food Composit. Anal. 102, 104031. https://doi.org/10.1016/j.jfca.2021.104031.

Suarni, Sulistyaningrum, A., 2023. Modified sorghum flour as a wheat substitute in functional food muffin products. BIO Web Conf. 69. https://doi.org/10.1051/bioconf/20236903010.

Suraj, M., Abewaa, M., Mengistu, A., Bultosa, G., Bussa, N., 2024. Influence of fermentation conditions, and the blends of sorghum and carrot pulp supplementation on the nutritional and sensory quality of tef *injera*. Sci. Rep. 14 (1), 12819. https://doi.org/10.1038/s41598-024-62420-5.

Sustriawan, B., Aini, N., Setyawati, R., Hania, R., Sandi, R.T., Irfan, R., 2021. The characteristics of cookies from sorghum flour and almond flour with variations in the type of fat. IOP Conf. Ser. 653 (1), 012128. https://doi.org/10.1088/1755-1315/653/1/012128.

Tadeu da Veiga Correia, V., D'Angelis, D.F., Neris dos Santos, A., Silva Roncheti, E.F., Vieira Queiroz, V.A., Fontes Figueiredo, J.E., Azevedo da Silva, W., Ferreira, A.A., Fante, C.A, 2022. Tannin-sorghum flours in cream cheese: physicochemical, antioxidant and sensory characterization. LWT 154, 112672. https://doi.org/10.1016/j.lwt.2021.112672.

Tanwar, R., Panghal, A., Chaudhary, G., Kumari, A., Chhikara, N., 2023. Nutritional, phytochemical and functional potential of sorghum: a review. Food Chem. Adv. 3. https://doi.org/10.1016/j.focha.2023.100501.

Tasie, M.M., Gebreyes, B.G., 2020. Characterization of nutritional, antinutritional, and mineral contents of thirty-five sorghum varieties grown in Ethiopia. Int. J. Food Sci. 2020, 1–11. https://doi.org/10.1155/2020/8243617.

Taylor, J.R.N., Duodu, K.G., 2022. Resistant-type starch in sorghum foods—factors involved and health implications. Starch 75, 9–10. https://doi.org/10.1002/star.202100296.

Thelwall, M., 2018. Dimensions: a competitor to Scopus and the Web of Science? J. Informetr. 12 (2), 430–435. https://doi.org/10.1016/j.joi.2018.03.006.

USDA, 2019. Sorghum Flour, Whole-Grain. Food Data Central. U.S. Department of Agriculture. https://fdc.nal.usda.gov/fdc-app.html#/food-details/168943/nutrients/.

Usman, S., Suhartono, M.T., Purwani, E.Y., Sitanggang, A.B., Trisnawati, W., 2024. Characteristics of sorghum flour modified with physical and enzymatic treatments. Emir. J. Food Agric. 36, 1–9. https://doi.org/10.3897/ejfa.2024.119095.

Ussembayeva, Z., Dautkanov, N., Yerbulekova, M., Dautkanova, D., 2024. Revealing the influence of sorghum flour on the rheological and baking properties of dough, the quality and nutritional value of bread. Eastern-Eur. J. Enterpr. Technol. 4 (130), 43–55. https://doi.org/10.15587/1729-4061.2024.310516, 11.

Vilanculos, S.L., Svanberg, U., 2021. Degradation of phytate in composite wheat/cassava/sorghum bread by activation of intrinsic cereal phytase. Afr. J. Food Sci. 15 (1), 1–9. https://doi.org/10.5897/AJFS2020.2008.

Wahjuningsih, S.B., A, M.N., K, R.W, 2022. Physicochemical, functional and sensory properties of wheat noodles substituted by sorghum and mung bean flours. Food Res. 6 (5), 84–90. https://doi.org/10.26656/fr.2017.6(5).604.

Wahyuni, S., Khaeruni, A., Asnani, Ramadhan, R., Dewi, N.D.P., Ramli, A.R, 2021. Modification of sorghum flour (*Sorghum bicolor* l. Moench) using lactic acid bacteria from *wikau maombo*. IOP Conf. Ser. 681 (1), 012031. https://doi.org/10.1088/1755-1315/681/1/012031.

Wang, Y., Trani, A., Knaapila, A., Hietala, S., Coda, R., Katina, K., Maina, N.H., 2020a. The effect of in situ produced dextran on flavour and texture perception of wholegrain sorghum bread. Food Hydrocoll. 106, 105913. https://doi.org/10.1016/j.foodhyd.2020.105913.

Wang, Y., Trani, A., Knaapila, A., Hietala, S., Coda, R., Katina, K., Maina, N.H., 2020b. The effect of in situ produced dextran on flavour and texture perception of wholegrain sorghum bread. Food Hydrocoll. 106, 105913. https://doi.org/10.1016/j.foodhyd.2020.105913.

Widowati, S., Luna, P., 2022. Nutritional and functional properties of sorghum (Sorghum bicolor (L.) Moench)-based products and potential valorisation of sorghum bran. IOP Conf. Ser. 1024 (1), 012031. https://doi.org/10.1088/1755-1315/1024/1/012031.

Winarti, C., Widaningrum, Widayanti, S.M., Setyawan, N., Qanytah, Juniawati, Suryana, E.A., Widowati, S., 2023. Nutrient composition of Indonesian specialty cereals: rice, corn, and sorghum as alternatives to combat malnutrition. Prev. Nutr. Food Sci. 28 (4), 471–482. https://doi.org/10.3746/pnf.2023.28.4.471.

Xiao, R., Lou, H., Hu, R., Li, S., Zheng, Y., Wang, D., Xu, Y., Xu, Y., Li, Y., 2024. Enzymatic production and physicochemical and functional properties of sorghum protein isolates. Int. J. Biol. Macromol. 283, 137421. https://doi.org/10.1016/j.ijbiomac.2024.137421.

Xu, F., Dube, N.M., Han Zhao, R., Wang, Y., Chen, J., 2021. The effect of Zimbabwean tannin-free sorghum flour substitution on fine dried noodles quality characteristics. J. Cereal. Sci. 102, 103320. https://doi.org/10.1016/j.jcs.2021.103320.

Yoganandan, M., Bean, S.R., Miller-Regan, R., Dogan, H., Pulivarthi, M.K., Siliveru, K., 2021. Effect of tempering conditions on white sorghum milling, flour, and bread properties. Foods 10 (8), 1947. https://doi.org/10.3390/foods10081947.

Yulviatun, A., Gea, D.C.T.T., Praseptiangga, D., Anam, C., Samanhudi, 2024. Study on the quality and consumer acceptance of sorghum (*Sorghum bicolor* L. Moench) flour-based dried noodle. IOP Conf. Ser. 1364 (1), 012082. https://doi.org/10.1088/1755-1315/1364/1/012082.