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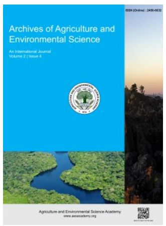

REVIEW ARTICLE

Bridging the gluten-free gap: A critical review of grain amaranth as a functional ingredient in global and east African food systems

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ABSTRACT

This critical review explores the possibilities of incorporating grain amaranth (*Amaranthus* spp.) as a functional ingredient to bridge gaps in the nutritional status of global gluten-free diets, thus enhancing food and nutritional security in East Africa. A comprehensive literature search was conducted across Web of Science, Scopus, PubMed, ScienceDirect and Google Scholar on peer reviewed papers, government policies and reports covering years 2015-2025, including some seminal earlier publications. The grains have ~16.6% protein content in the dry matter, contain high amounts of lysine (5.3-6.3 g/100g protein), ~7.2% lipids that consist of significant amounts of squalene (2-8% of total oil) and a high concentration of dietary fibre (7.1 -16.4%), as well as extremely high amounts of iron (7.6 mg/100g), magnesium (248 mg/100g) and manganese (3.4 mg/100g). Processing methods like germination, extrusion, fermentation and Instant Controlled Pressure Drop decrease phytate levels by ~30%, oxalate levels up to 83% and tannin levels by ~32%, and increase protein digestibility in vitro to greater than 83% compared to 76%. Global market analysis shows that the industry is worth USD 9.3-12.58 billion (2024) and expected to grow to USD 19.26-30.07 billion by 2030-2032 (CAGR 9.4-18.1%). Unique nutritional benefits, climate resistance, processibility and other properties make the grain ideal for use, but its widespread adoption remains hindered by poor value chains in East Africa and competitive positioning of quinoa in Europe. Strategic investments in breeding, decentralized processing, informed communications, and formal inclusion in food policies are necessary for promoting amaranth as a functional ingredient.

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INTRODUCTION

The global market for gluten-free foods has grown not only among patients with celiac disease (~1%) but also among millions of people who strive for functional foods, clean labels and minimally processed diets (Cai *et al*., 2005; Singh *et al*., 2018; Caio *et al*., 2019). The annual growth rate of the gluten-free market is currently above 9%, with the European gluten-free market alone reaching USD 2.59 billion in 2024 and expected to reach USD 5.37 billion by 2033 (Market Data Forecast, 2024; Precedence Research, 2025). The ancient grains and pseudo-cereals segment will grow at an even greater pace (~34.78%/year; Market Data Forecast, 2024). However, first generation gluten-free products continue to be based predominantly on refined starches from rice, maize, potato and tapioca, which provide adequate textural performance but low nutritional value (low protein and dietary fibre content, low iron, calcium, zinc and B vitamin content, and elevated glycaemic index compared to their wheat counterparts (Saturni *et al*., 2010; Pellegrini & Agostoni, 2015; Vici *et al*., 2016; Melini & Melini, 2019). This gap in meeting current demands for functional, clean label and minimally processed foods represents a clear "gluten-free gap", a need for ingredients that provide both technological functionality and superior nutritional quality.

Amaranth grain (*Amaranthus* spp.), a pseudocereal cultivated since antiquity, primarily includes three species: *A. cruentus*, *A. hypochondriacus* and *A. caudatus* (Rastogi & Shukla, 2013; Das, 2016). It contains high-quality protein with complete amino acid profile and exceptionally high lysine content, unsaturated lipids with high amounts of squalene, dietary fibre and high-density matrices of minerals, vitamins and phytochemicals (Caselato-Sousa & Amaya-Farfán, 2012; Venskutonis & Kraujalis, 2013; Tang & Tsao, 2017). Amaranth has strategic relevance in the era of climate change and resource-limited smallholder farming due to its C4 metabolism, drought tolerance, heat resistance and adaptation to poor soils (Mlakar *et al.*, 2010; Mabhaudhi *et al.*, 2017). However, the full exploitation of amaranth grain as a food resource remains far behind its biological potential, and there are stark regional differences in consumer attitudes towards the crop. While in Sub-Saharan Africa (the secondary center of amaranth diversity), the grain is still considered a "famine food" or only known as a leafy vegetable (e.g., mchicha), its processing infrastructure, breeding programs and policies remain underdeveloped (Macharia-Mutie *et al.*, 2011; Aderibigbe *et al.*, 2022). In Europe and North America, amaranth is positioned as a premium "ancient grain", although it has to compete with quinoa, which enjoys advantages of a more established supply chain and higher consumer awareness (Navruz-Varli & Sanlier, 2016; CBI, 2022). Several recent reviews have been devoted separately either to the nutritional properties of amaranth or to its agronomy, but no integrated and critical review of amaranth as a functional ingredient in the gluten-free diet market has yet been conducted. This paper fills this gap by critically reviewing the evidence (2015-2025) on four interconnected topics: (i) the nutritional composition and health benefits of amaranth, (ii) traditional and modern processing methods and their impact on nutritional and functional properties, (iii) consumer preferences and market dynamics in East Africa and Europe, and (iv) the regulatory and sustainability context. By comparing the perspectives of East African food security and European functional foods, we identify methodological limitations, inconsistent results and unexplored areas, and propose research, processing, policy and development priorities for scaling up amaranth grain as a mainstream gluten-free functional ingredient.

METHODOLOGY

A narrative review with a specific structure was performed to select peer-reviewed articles and gray literature related to nutrition, processing, consumer acceptance, marketing and policies of grain amaranth. The databases searched include Web of Science, Scopus, PubMed, Science Direct and Google Scholar. Other relevant resources included FAO, WHO, UNICEF, AGRA, East African Community, 2022, European Union and market intelligence platforms, namely 360iResearch, Market Data Forecast, Global Market Insights, Statista, Precedence Research and CBI. The Boolean search strings used the keywords "Amaranthus" OR "grain amaranth" OR "pseudo-cereal" together with at least one of the following: "gluten-free", "quality of protein", "squalene", "phytochemicals", "antinutrients", "processing methods", "extrusion", "germination", "consumer preference", "sensory analysis", "marketing", "food security", "East Africa", "Kenya", "Uganda", "Tanzania", "Ethiopia", and "policy". The initial selection period was from 2015 to 2025, which met the journal's criteria for recency. Any key literature that predated this period and was seminal enough to be referenced, such as Becker *et al.*, 1981, and Bressani & Garcia-Vela, 1990, remained in the selection process when not rendered obsolete by more contemporary research. For each citation, data regarding species, cultivar, methodology, number of replicates, preparation method, analytical method, and results were entered into a spreadsheet. Quantitative data for nutrient content and impact from processing were analyzed across studies for commonalities and discrepancies, allowing an understanding of general trends. If more than one set of values were available for a particular parameter, the most commonly cited figure or that which had been determined using a clearer methodology was retained, while a range was stated. Gaps in methodology, such as confusion regarding dry- versus wet weight content, undefined cultivars, and sensory evaluation in only one region, as well as knowledge gaps, such as value chain economics of amaranth in East Africa and regulatory issues for African grains in the EU, were noted and discussed accordingly. This systematic review is not a meta-analysis due to the diversity of species, methods of extraction, and analytical techniques used. However, clear documentation of the terms used for the search, selection criteria, and sources of data is provided.

NUTRITIONAL COMPOSITION AND HEALTH BENEFITS

The current revival of grain amaranth within the food system can be attributed to the exceptional nutrient composition that makes it distinct from other cereals and earns it a place among functional foods. Research into the nutrition of amaranth indicates that it is an excellent source of high-quality macronutrients, essential vitamins and minerals, and unique bioactive substances. This chapter reviews the evidence regarding the proximate composition, protein quality and amino acid composition, mineral and vitamin content, phytochemicals, antinutrient components and countermeasures, evidence-supported health benefits, and comparison with other non-gluten grains.

Proximate composition

The basic nutritional value of grain amaranth (Table 1) consistently surpasses that of common cereals and supports its promotion as a nutrient-dense crop with potential to address malnutrition and improve diet quality (Alegbejo, 2013; Akin-Idowu *et al.*, 2017). Mean protein content is approximately 16.6% on a dry-weight basis, exceeding wheat (12–14%), rice (7–8%) and maize (9–10%) (Mlakar *et al.*, 2010; Alegbejo, 2013). The protein content of *A. hypochondriacus* typically ranges from 11.4% to 18.8%,

Table 1. Proximate composition of grain amaranth (dry-weight basis).

Component	Mean Value	Range	Key References
Protein (g/100g)	16.6	12.0–22.0	Alegbejo (2013); Becker *et al.* (1981); Mota *et al.* (2016)
Total Carbohydrates (g/100g)	59.2	48.0–69.0	Alegbejo (2013); Venskutonis & Kraujalis (2013)
Starch (g/100g)	57.3	48.0–69.0	Venskutonis & Kraujalis (2013)
Lipids (g/100g)	7.2	5.0–10.9	Alegbejo (2013); He & Corke (2003)
Total Dietary Fibre (g/100g)	10.5	7.1–16.4	Alegbejo (2013); Schoenlechner *et al.* (2008)
Crude Fibre (g/100g)	3.4	2.2–5.8	Alegbejo (2013)
Ash (g/100g)	3.3	2.6–4.4	Alegbejo (2013); Becker *et al.* (1981)
Moisture (g/100g)	9.2	6.5–12.0	Mlakar *et al.* (2010); Alegbejo (2013)
Energy (kcal/100g)	371	350–391	USDA (2019); Das (2016)

Note: Values represent compiled data from multiple Amaranthus species (*A. cruentus*, *A. hypochondriacus*, *A. caudatus*). Variation reflects differences in species, cultivar, growing conditions and analytical methods.

Table 2. Mineral content of uncooked and cooked grain amaranth (per 100 g).

Mineral	Uncooked (mg/100g)	% Daily Value*	Cooked (mg/100g)	% Daily Value*
Calcium (Ca)	159	12	47	4
Iron (Fe)	7.6	42	2.1	12
Magnesium (Mg)	248	59	65	15
Phosphorus (P)	557	45	148	12
Potassium (K)	508	11	135	3
Zinc (Zn)	2.9	26	0.9	8
Manganese (Mn)	3.4	148	0.9	37
Copper (Cu)	0.5	58	0.2	17
Selenium (Se)	18.7 µg	34	5.5 µg	10
Sodium (Na)	4	<1	6	<1

*Daily Values (DV) based on a 2,000 kcal adult diet (FDA reference). Cooked values based on boiled amaranth grain. Source: USDA Food Data Central (USDA, 2018; 2019).

and that of *A. cruentus* from 13.2% to 18.2% (Velarde-Salcedo *et al.*, 2012; Akin-Idowu *et al.*, 2017). Storage proteins are predominantly albumins and globulins rather than the prolamins (gliadins and glutenins) responsible for the gluten complex in wheat (Martínez-López *et al.*, 2021), making amaranth proteins more soluble and digestible and especially suitable for infant foods and clinical diets. Carbohydrates account for the largest fraction of dry matter (~59.2%; Alegbejo, 2013), of which starch represents 62–65% of the grain. Amaranth starch granules are exceptionally small (~1–3 µm), influencing gelatinisation, swelling and digestibility (Repo-Carrasco-Valencia *et al.*, 2010; Zhu, 2017). Lipid content (~7.2% wb) is markedly higher than in wheat (~2%) or rice (<1%), with linoleic acid (~62%) and oleic acid (~20%) dominating the fatty-acid profile, and a notably high squalene content (2–8% of total oil) compared with olive oil (0.2–0.7%) (He & Corke, 2003; Baraniak & Kania-Dobrowolska, 2022). Total dietary fibre is 7.1–16.4% (Schoenlechner *et al.*, 2008), and ash content (~3.3%) reflects the rich mineral matrix.

Protein quality and amino-acid profile

Moreover, apart from quantity, the protein quality in amaranth affects its nutritional value. The term "complete" is used to refer to amaranth protein as it possesses all nine essential amino acids required by the human body in quantities comparable to the recommended amounts (Písaříková *et al.*, 2005; Venskutonis & Kraujalis, 2013). The limiting amino acid lysine occurs at 5.3–6.3 g per 100 g protein, twice or thrice the levels in wheat and maize (Martínez-López *et al.*, 2020). Sulfur-containing amino acids, which are limiting amino acids in legumes, are also found in relatively higher amounts. The share of essential amino acids in total protein ranges between 43% and 49%, exceeding WHO/FAO reference pattern (Mota *et al.*, 2016). The Biological Value (BV) of amaranth protein amounts to 75%, better than wheat (54%) and maize (49%) and similar to milk protein (~85%) (Písaříková *et al.*, 2005). PDCAAS scores 0.72 in the amaranth protein concentrate and between 0.23 and 0.36 in whole, unprocessed grains (Schaafsma, 2000; Mota *et al.*, 2016; Sidorova *et al.*, 2023), with true digestibility in the concentrate of ~97.6%, compared to casein (~99.3%). These numbers, while lower than animal proteins, perform comparably or even better against unprocessed cereal proteins.

Mineral content

Grain amaranth is a particularly rich source of essential minerals (Table 2), making it a valuable food to combat the micronutrient deficiencies that remain a major public-health issue in much of East Africa (Das, 2016; USDA, 2019). Per 100 g of raw grain, amaranth supplies manganese 3.4 mg (148% DV), magnesium 248 mg (59% DV), phosphorus 557 mg (45% DV) and iron 7.6 mg (42% DV), among the best plant-based sources of these minerals (USDA, 2019). It also contributes useful amounts of calcium (159 mg; 12% DV), zinc (2.9 mg; 26% DV), potassium (508 mg; 11% DV), copper (0.53 mg; 58% DV) and selenium (19 µg; 34% DV). Cooking reduces mineral content (e.g., calcium from 159 to 47 mg/100 g; iron from 7.6 to 2.1 mg/100 g; USDA, 2018), but cooked amaranth still makes a meaningful contribution. Genetic accessions of A. hypochondriacus exhibit substantial variation in calcium (90.5–249.7 mg/100 g) and iron (6.8–35.7 mg/100 g) (Jamalluddin *et al.*, 2022), supporting the case for biofortification breeding.

Vitamin profile

Amaranth grain is rich in B vitamins and vitamin E (Das, 2016; Tang & Tsao, 2017). A 100 g serving of uncooked grain provides vitamin B6 0.6 mg (45% DV), pantothenic acid 1.5 mg (29% DV), riboflavin 0.2 mg (15% DV), thiamine 0.1 mg (10% DV) and folate 54.1 µg (14% DV) (USDA, 2019). Vitamin E content (~1.2 mg/100 g; ~8% DV) includes a balanced mixture of α-, β- and δ-tocopherols, and amaranth oil contains 7.28–27.9 µg/g of total tocopherol, supporting both health benefits and natural oxidative stability (Repo-Carrasco-Valencia *et al.*, 2010; Baraniak & Kania-Dobrowolska, 2022).

Bioactive compounds and phytochemicals

Amaranth contains a diverse suite of bioactive compounds that justify its functional-food status (Caselato-Sousa & Amaya-Farfán, 2012; Tang & Tsao, 2017): squalene, phytosterols (β-sitosterol, stigmasterol, campesterol, clerosterol), phenolic acids (gallic, p-coumaric, caffeic, ferulic, vanillic), flavonoids (rutin, quercetin, isoquercitrin, kaempferol, nicotiflorin), betalains and saponins. Squalene (2–8% of grain oil) lowers blood cholesterol, exerts strong antioxidant activity and may have anti-carcinogenic effects (He & Corke, 2003; Baraniak & Kania-Dobrowolska, 2022). Phytosterols compete with dietary cholesterol for intestinal absorption (Caselato-Sousa & Amaya-Farfán, 2012). Coloured cultivars (red/purple *A. cruentus* and *A. tricolor*) are rich in betalains (amaranthine and isoamaranthine), which display antioxidant, anti-inflammatory and anticancer activity in experimental models (Repo-Carrasco-Valencia *et al.*, 2010). Saponins contribute slight bitterness but also anti-inflammatory and cholesterol-lowering effects (Baraniak & Kania-Dobrowolska, 2022).

Anti-nutritional factors and mitigation strategies

Similar to other plant sources, amaranth contains anti-nutritional factors (ANFs), which include phytates, oxalates, and tannins (Schoenlechner *et al.*, 2008; Jimoh *et al.*, 2018). These ANFs have been linked with decreased mineral availability and digestion due to their ability to form insoluble bonds with various ions such as Fe^{2+}, Zn^{2+}, Ca^{2+}, and Mg^{2+} (Gupta *et al.*, 2015). Oxalates form bonds with calcium that may be related to stone formation in the kidneys. On the other hand, tannins reduce iron and protein bioavailability. Nonetheless, ANF contents in amaranth are moderate relative to other legumes, and traditional processing greatly minimizes ANFs. Boiling dissolves and partially denatures the soluble ANFs like phytates, oxalates, and tannins, while popping or roasting at temperatures between 120 and 150°C in 5–30 seconds also reduces ANFs significantly (Gamel *et al.*, 2006). Germination activates phytase and reportedly leads to a 29.6% and 32.3% reduction in phytates and tannins, respectively. Fermentation with lactic acid reduces phytates while enhancing the palatability of the grain. Instant Controlled Pressure Drop (DIC) technology can eliminate oxalate content by up to 83%.

Evidence-based health benefits

Amaranth grain is known to have a unique nutritional composition that has led to various scientifically supported health benefits. Since it is a rich source of antioxidants, such as phenolic acids, flavonoids, vitamin E, squalene, and betalains, it helps reduce oxidative stress (Alvarez-Jubete *et al.*, 2010; Tang & Tsao, 2017). Research conducted on animals and in vitro indicates anti-inflammatory effects due to reduced levels of IL-1 and CRP. Regarding cardiovascular health, amaranth grain is linked to lower levels of total cholesterol and LDL cholesterol, an increase in HDL cholesterol, and slight reduction in blood pressure, which results from the synergistic effect of dietary fibre, phytosterols, and squalene (Caselato-Sousa & Amaya-Farfán, 2012). The low glycaemic index of amaranth grain, along with its high fibre and protein content, helps regulate blood sugar levels. Being a gluten-free grain, amaranth has additional benefits since it provides the nutrients that individuals who are gluten-sensitive lack, including protein, fibre, iron, calcium, zinc, and B vitamins (Vici *et al.*, 2016; Melini & Melini, 2019).

Comparative nutritional analysis of gluten-free grains

In comparison to quinoa, buckwheat, millet, sorghum and teff (Table 3), grain amaranth possesses the highest percentage of fat, mainly comprising unsaturated fatty acids and squalene, as well as surpassing other foods in magnesium, phosphorus and selenium content. The amount of iron in grain amaranth equals that of teff, which has the highest level of iron among the mentioned grains, an important fact due to the prevalence of iron-deficiency anaemia in East Africa. Calcium and total dietary fibre are abundant in teff, whereas the highest folate content is observed in quinoa.

PROCESSING TECHNOLOGIES AND PRODUCT DEVELOPMENT

The suitability of grain amaranth for food depends upon the post-harvest processing of the raw material, because raw grain amaranth is processed by traditional and modern techniques to create safe, palatable, and functional food ingredients. Processing of raw grain amaranth modifies its physical and chemical properties, and increases its nutrient bioavailability, while also developing the necessary flavors, textures, and functional properties for manufacturing different food products.

Traditional processing methods

The consumption of amaranth grain is associated with agricultural practices and traditions of Latin America, Africa and Asia (Rastogi & Shukla, 2013; Das, 2016). The popping, or puffing, process, one of the principal methods of grain treatment, involves expansion of heavy seeds into porous products with nutty taste. For effective processing, temperature and time must be between 120–150 °C for 5–30 seconds with a popped volume of 0.41 to 0.54 cm^3 per 100 seeds and a popping ratio of 5.2 to 6.7 (Bressani & Garcia-Vela, 1990; Muyonga *et al.*, 2013). The conventional pan-popping technique is subject to non-uniform heating and scorching effects; thus, the introduction of fluidized-bed poppers became necessary for improved efficiency (Muyonga *et al.*, 2013). In traditional milling processes, stone or

Table 3. Comparative nutritional profile of cooked gluten-free grains (per 1-cup serving).

Nutrient	Amarant (246 g)	Quinoa (185 g)	Buckwheat (168 g)	Millet (174 g)	Sorghum (192 g)	Teff (252 g)
Energy (kcal)	251	222	155	207	217	255
Protein (g)	9.4	8.1	5.7	6.1	8.4	9.8
Total Fat (g)	3.9	3.6	1.0	1.7	1.9	1.8
Carbohydrates (g)	46.0	39.4	33.5	41.2	47.2	50.0
Dietary Fibre (g)	5.2	5.2	4.5	2.3	6.5	7.1
Calcium (mg)	116	31	12	3	13	87
Iron (mg)	5.2	2.8	1.3	1.1	3.4	5.2
Magnesium (mg)	160	118	86	77	87	126
Phosphorus (mg)	364	281	118	174	222	302
Potassium (mg)	332	318	148	108	250	269
Zinc (mg)	2.1	2.0	1.0	1.6	1.7	2.4
Manganese (mg)	2.1	1.2	0.7	0.3	—	5.2
Lysine (mg)*	747	766	320	122	148	243
PDCAAS**	0.45–0.69	0.68	0.50	0.38	0.35	0.42

*Lysine values from amino-acid composition databases and published literature. **Protein Digestibility-Corrected Amino Acid Score; values vary by processing method. Sources: USDA Food Data Central; Navruz-Varli & Sanlier (2016); Mota *et al.* (2016); Gebremariam *et al.* (2014).

hammer mills can be used. A traditional method of milling in mountain regions of India involves using the gharat – a water-operated stone mill grinding at speeds of 60–80 rpm, which prevents thermal destruction of polyunsaturated fatty acids and vitamins (Rastogi & Shukla, 2013). Fermentation, such as chicha de amaranto, improves phytate content, facilitates mineral absorption and synthesizes bioactive peptides (Repo-Carrasco-Valencia *et al.*, 2010).

Modern processing technologies

The extrusion cooking process, which involves HTST processing, can be extensively used for amaranth (Chávez-Jáuregui *et al.*, 2000). The extruder accomplishes cooking, mixing, kneading, and forming functions simultaneously on amaranth flour. Factors such as barrel temperature (90–192 °C), moisture content (12–40%), and screw speed (50–600 rpm) have a significant impact on the texture, expansion, colour, and aroma of the product. Extrusion of *A. caudatus* under conditions close to 150 °C and 15% moisture level results in products with excellent organoleptic properties. The starch present becomes completely gelatinized and denatured, making it easily digestible by the body, but, at the same time, ANFs lose activity because of the high temperatures. Too high temperature and prolonged contact between the material and the equipment make the Maillard reaction go too far, decreasing the availability of lysine and damaging heat labile vitamins (Zapotoczny *et al.*, 2006). A 48- to 72-h-long germination treatment with a temperature range of 26–28 °C turns out to be quite efficient since, as a result, the content of crude protein rises from 13.76 ± 0.054 to 14.86 ± 0.043 g/100 g, the amount of in vitro digestible protein from 76% ± 0.070 to 83.58% ± 0.055, while that of phytochemicals – phytic acid, oxalate, and tannin decreases by approximately 30%, 38%, and 32%, respectively (Gamel *et al.*, 2006). Germinated amaranth starch exhibits reduced viscosity and greater swelling power, useful properties for beverages and bulk-reduced infant foods. In recent years, non-thermal methods became popular in amaranth processing industry, and one of them is ultrasound-assisted extraction (UAE) in the frequency range of 20–100 kHz (Chemat *et al.*, 2017). By using NADES in combination with UAE, researchers managed to boost betalain yield without causing molecular degradation, thus obtaining an approximate increase of 12-fold.

Product development applications

Amaranth flour has been used in gluten-free bread, cookies, cakes, muffins and pasta (Schoenlechner *et al.*, 2010; Woomer & Adedeji, 2021). Gluten-free breads with 60–70% popped amaranth flour and 30–40% raw flour exhibit uniform crumb structure and a specific volume of ~3.5 mL/g (De la Barca *et al.*, 2010). Composite breads incorporating up to 15% amaranth flour with wheat retain volume and texture while gaining protein and minerals (Sanz-Penella *et al.*, 2013). Gluten-free cookies with 20% popped amaranth flour and 13% whole popped grains show acceptable spread, texture and flavour. In Sub-Saharan Africa, amaranth-based complementary foods are particularly relevant for infants: a blend of 40% amaranth grain, 25% orange-fleshed sweet potato, 20% soybean and 15% pumpkin seed offers a nutrient-dense option (Akande *et al.*, 2020), and a 90:10 amaranth –sorghum blend delivers ~14.4% protein (Muyonga *et al.*, 2013). Germination and extrusion lower porridge bulk density and improve mineral bioavailability. Amaranth protein isolate (API) shows useful water- and oil-absorption capacity, emulsifying, foaming and gelling properties, and its high lysine content elevates the overall protein quality of meat analogues (Tovar-Pérez *et al.*, 2009; Martínez-López *et al.*, 2021).

Effects of processing on nutritional and functional properties

Heat-based processing, including cooking and extrusion, causes starch gelatinization and protein denaturation, which increases digestibility in general (Repo-Carrasco-Valencia *et al.*, 2010); germination increases protein digestibility in vitro from about 76% to more than 83%, while lysine bioavailability increases by up to 41% (Gamel *et al.*, 2006). High extrusion temperatures, on the other hand, cause excessive progression of the Maillard reaction, leading to a decrease in lysine bioavailability and heat-labile vitamin content. Functional properties are affected as well: pH treatment and ultrasonication cause unfolding of protein molecules, leading to better foaming and emulsifying capabilities (Tovar-Pérez *et al.*, 2009); germination enhances

Table 4. Overview of processing technologies applied to grain amaranth and their effects.

Processing Method	Key Parameters	Effects on Nutritional & Functional Properties	Primary Applications	References
Popping/Puffing (Traditional)	120–150 °C; 5–30 s; dry heat	↑ Starch digestibility; ↑ Aroma; ↓ ANFs (tannins, saponins); Partial protein denaturation; Volume expansion 5–8×	Ready-to-eat snacks; breakfast cereals; traditional foods (alegría, laddoo)	Zapotoczny *et al.* (2006); Muyonga *et al.* (2013)
Milling (Traditional)	Stone/hammer mill; 60–80 rpm (gharat water mill)	Whole grain → flour; Retains fibre & minerals; Particle size affects functionality	Flour for baking; porridges; composite flours	Das (2016); Rastogi & Shukla (2013)
Extrusion Cooking	90–192 °C; 12–40% moisture; 100–500 rpm; HTST process	↑ Starch gelatinisation; ↑ Protein digestibility (up to 80%); ↓ ANFs; Maillard reactions; Expansion & texturisation	Snack foods; breakfast cereals; infant foods; meat analogues	Chávez-Jáuregui *et al.* (2000); Repo-Carrasco-Valencia *et al.* (2010)
Germination/Malting	48–72 h; 26–28 °C; controlled humidity	↑ Protein digestibility; ↓ Phytate (40–55%); ↑ Free amino acids; ↑ Vitamin C, B-vitamins; Enzyme activation	Malted beverages; infant foods; improved flours; functional ingredients	Gamel *et al.* (2006)
Fermentation	Lactic acid bacteria; 24–72 h; ambient or controlled temperature	↓ Phytate (50–70%); ↑ Mineral bioavailability; ↑ Protein quality; Improved flavour & texture; Probiotic potential	Fermented porridges; acidified beverages; sourdough breads; complementary foods	Gamel *et al.* (2006); Sanz-Penella *et al.* (2013)
Ultrasound- Assisted Extraction (UAE)	20–100 kHz; cavitation-based cell disruption	↑ Extraction yield of bioactives; ↑ Protein recovery; Preserves heat-sensitive compounds; ↓ Solvent use	Protein isolate extraction; bioactive compound recovery; oil extraction	Chemat *et al.* (2017)
Supercritical CO_2 Extraction (SFE)	CO2 at >31 °C, >73.8 bar; tunable selectivity	Selective squalene extraction; Solvent-free oil; Preserves thermolabile compounds	High-purity squalene; specialty oils; pharmaceutical and cosmetic ingredients	Venskutonis & Kraujalis (2013)
Instant Controlled Pressure Drop (DIC)	High pressure followed by abrupt vacuum release	↑ Bioavailability; ↓ ANFs; Improved texture; Controlled expansion	Pre-treated flours; functional ingredients; novel textures	Rocha-Guzmán *et al.* (2023)

HTST = High Temperature Short Time; ANFs = Anti-Nutritional Factors; ↑ = increase; ↓ = decrease. Processing effects vary with specific conditions, amaranth species and grain characteristics.

amylase activity, resulting in reduced flour viscosity and increased caloric density in infant porridges. Sensory properties change accordingly; roasted amaranth acquires a nutty flavor, while extruded flour obtains crispy texture, and 15% amaranth incorporation into wheat flour increases the nutritional value of bread without affecting its bulkiness, grain structure, and sensory qualities (Sanz-Penella *et al.*, 2013). A comprehensive summary of amaranth processing techniques, conditions, and consequences is provided in Table 4.

CONSUMER ACCEPTANCE AND MARKET DYNAMICS

Successful integration of grain amaranth into global and regional food systems is ultimately determined by consumer acceptance and viability within complex market environments.

Consumer acceptance in East Africa

Introducing nutrient-dense, climate-resilient crops such as amaranth into Sub-Saharan diets is shaped by cultural tradition, taste and texture, price and shifting eating habits (Macharia-Mutie *et al.*, 2011; Aderibigbe *et al.*, 2022). Kenya is the most commercialised market, where unfermented maize porridge with 70% amaranth flour is highly rated and an 80:20 maize–amaranth ugali is the most acceptable composite. Taste, mouthfeel and aroma are the principal drivers of acceptance and willingness to pay. In Uganda, amaranth has been integrated into popular snacks such as "daddies" made from composite wheat–amaranth–maize flour. In Tanzania, improved varieties from the World Vegetable Center cover ~70% of cultivated amaranth area, although utilisation is still concentrated in the leafy vegetable form (Dinssa *et al.*, 2019). In Ethiopia, despite traditional uses in injera, tej and tella, the grain remains an orphan crop with limited systematic promotion (Gelaye, 2023; Alemayehu *et al.*, 2015). In Rwanda and Malawi, amaranth is consumed mainly as a leafy vegetable, and grain utilisation remains marginal.

Consumer acceptance in Europe

Interest in amaranth among Europeans stems from health, wellness, and sustainability concerns and from the fast-growing gluten-free category, wherein amaranth proves nutritionally better than most processed gluten-free foods for people suffering from celiac disease or non-celiac gluten sensitivity (Melini & Melini, 2019). Consumers who focus on health see ancient grains as “superfoods” and pay up to 10–15% higher prices (Janssen *et al*., 2016). Quinoa, however, outperforms amaranth in terms of marketing, taste and versatility; consumers find the latter too strong-tasting and stickier when prepared and use it for more specialized dishes (Navruz-Varli & Sanlier, 2016; CBI, 2022).

Methodologies for assessing sensory acceptability

A 9-point hedonic scale remains the most common approach, with values of 7 or higher indicating good market potential (Lawless & Heymann, 2010; Stone *et al*., 2020). Breads made from wheat with 10–15% amaranth flour experience little change in their texture or total liking (Sanz-Penella *et al*., 2013); breads made without gluten but with 50–70% amaranth replacement still have good acceptability levels (De la Barca *et al*., 2010); pastas made with amaranth content of 30% are more nutritious without negatively affecting cooking quality (Woomer & Adedeji, 2021). The current methodological problem is the frequent use of samples from a single region.

Market analysis: global and regional dynamics

The global amaranth market was valued at approximately USD 9.3–12.58 billion in 2024 (Figure 1) and is projected to reach USD 19.26–30.07 billion by 2030–2032 at a CAGR of 9.4–18.1% (360iResearch, 2025). Growth is driven by demand for plant-based and gluten-free foods, rising consumer awareness of amaranth’s nutritional profile and the broader move toward sustainable, organic ingredients. In East Africa the value chain is largely informal except in Kenya, where commercial production reports retail prices of US$0.94–1.42/kg, and in Uganda (US$0.69–1.38/kg). In Europe, the total gluten-free product market is projected to grow from USD 2.59 billion (2024) to USD 5.37 billion (2033) at a CAGR of 9.21%, while the ancient-grains segment expands fastest at CAGR ~34.78% (Market Data Forecast, 2024).

Adoption barriers and drivers

The key factors encouraging adoption of amaranth include high nutritive content, adaptability to different climatic conditions, increasing preference for vegetarian and gluten-free meals, and the successful spread of improved varieties in some African countries such as Kenya and Tanzania (Dinssa *et al*., 2019; Macharia-Mutie *et al*., 2011). The main challenges facing amaranth production and consumption in Africa continue to be lack of information about amaranth among producers and consumers, existing cultural practices, issues associated with taste and texture during processing and development of products, as well as major infrastructure gaps throughout the continent.

POLICY FRAMEWORK AND FOOD SECURITY INTEGRATION

Successful integration of grain amaranth into national and global food systems is closely intertwined with the policy landscape governing agriculture, food security, trade and sustainability.

Food and nutrition security challenges in Sub-Saharan Africa

Food and nutrition insecurity in Sub-Saharan Africa (SSA) remains acute. In 2022, 30% of African children under five were stunted, against a global average of 22.3% (FAO *et al*., 2023); stunting reaches 57.7% in some East African countries (UNICEF, 2023), and anaemia affects 40.4% of women of reproductive age. These outcomes are exacerbated by conflict, climate shocks and food/fuel price volatility, which expose maize-, rice- and wheat-centred production systems. Greater investment in under-utilised, neglected and indigenous crops (UUCs); including grain amaranth, millets, sorghum and indigenous legumes, offers a credible pathway forward (Mabhaudhi *et al*., 2017; Padulosi *et al*., 2013). Amaranth, which can yield 1,500–7,200 kg/ha with low external inputs (Alemayehu *et al*., 2015), is directly relevant to SDG 2 (Zero Hunger).

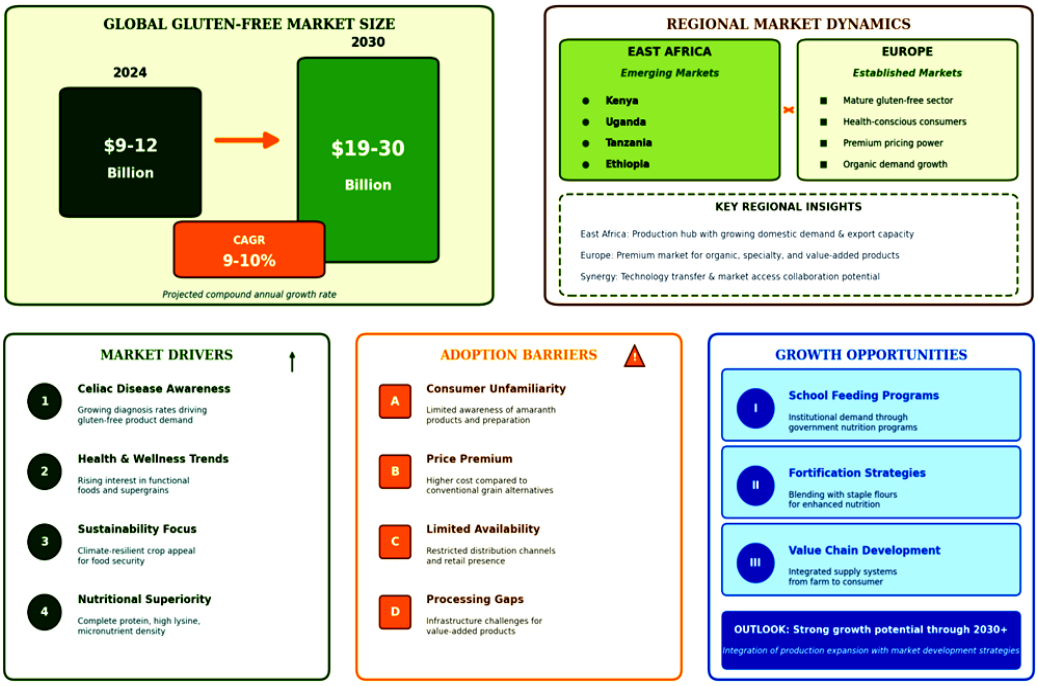

Figure 1. *Global amaranth market analysis and regional dynamics.*

Agricultural policies supporting amaranth in East Africa

In Kenya, amaranth has been prioritized in its National Food and Nutrition Security Policy and Agri-Nutrition Implementation Strategy for 2020–2025 (Farmers Review Africa, 2023). In Uganda, amaranth promotion has been spearheaded by NGOs like VEDCO, together with Makerere University scientists, through farmer–processor partnerships and value chain development (Aderibigbe *et al.*, 2022). Amaranth has been revisited but remains underrepresented in national policy in both Ethiopia and Tanzania (Dinssa *et al.*, 2019; Gelaye, 2023). At the regional level, the EAC Food and Nutrition Security Strategy and the 2022 EAC Bioeconomy Strategy, Africa's first regional bioeconomy framework, highlight sustainable agriculture and coordinated cross-border trade (EAC, 2022). At the continental level, the African Union's CAADP emphasizes food system resilience and diversification (African Union, 2017).

EU regulations and novel-food status

Regulation (EU) 2015/2283 governs novel foods those not consumed to a significant degree in the Union before 15 May 1997 (European Commission, 2018). Grain amaranth is generally not classified as a novel food, given its documented history of consumption in Europe, which simplifies market entry. The regulation also provides a streamlined procedure for "traditional foods from third countries", requiring evidence of at least 25 years of safe use; in December 2018 this pathway authorised decorticated fonio grain (Digitaria exilis) and sorghum syrup, demonstrating its applicability to traditional African grains.

Sustainability aspects

Several traits make amaranth attractive from a sustainability standpoint. As a C4 species, it is highly efficient at converting CO_2 to biomass under hot, dry conditions; experimental evidence shows it sustains gas exchange during early drought longer than other C4 crops such as maize, with water-use efficiency further enhanced under elevated CO_2. Its lower fertiliser requirement reduces carbon footprint, and its inclusion in rotations diversifies fields, breaks pest and disease cycles and increases farming-system resilience (Mabhaudhi *et al.*, 2017; Padulosi *et al.*, 2013).

Integration into national food systems

The Home-Grown School Feeding (HGSF) model is a practical approach that will help to facilitate scaling up the consumption of amaranth (GCNF, 2023). For example, in Zambia, the HGSF programme covers more than four million children, with amaranth sourced from women's cooperatives. In Rwanda, the WFP purchases amaranth for schools by working with farmer cooperatives (WFP, 2022). Apart from school feeding, there is tremendous potential in using amaranth for fortifying foods and developing new products. Researchers at Makerere University in Uganda and VEDCO have developed nutritious recipes for porridges, soups, and baked foods (Aderibigbe *et al.*, 2022). The key to scaling up such interventions lies in dependable value chain management and PPPs between small-scale farmers and market outlets (AGRA, 2017).

FUTURE PERSPECTIVES AND RESEARCH PRIORITIES

From a niche product to a global gluten-free commodity, it is essential to address various gaps ranging from research, technology advancement, policies development and enforcement, and marketing. There is a need for more systematic activities related to data collection, characterization, and preservation of amaranth landraces, whereas breeding programmes have to aim for higher yields, tolerance to heat and drought conditions, low ANFs, easy-to-process seeds, desirable taste, and high content of valuable nutrients (Alemayehu *et al.*, 2015; Mlakar *et al.*, 2010). Research concerning crop rotation, conservation agriculture, and pests control will assist smallholders with practical guidelines. There is still much to explore regarding the bioavailability of iron and zinc, squalene, polyphenols, and betalains during processing. In terms of food science and technology, it is important to develop affordable technologies for the community-level processing of amaranth seeds in East Africa. For instance, there is a need for efficient poppers, inexpensive mills, and simple extruders. The gluten-free market requires more investigations about protein gelling, emulsifying characteristics, and moisture retention properties in order to develop meat analogues, dairy substitutes, and stable baked products (Martínez-López *et al.*, 2021; Tovar-Pérez *et al.*, 2009; Woomer & Adedeji, 2021). As far as demand is concerned, there is a necessity to conduct educational campaigns on the nutritional value of amaranth through recipes appealing to consumers according to sensory research results. In Europe, there is a requirement for transparent and certified (organic, fair trade) supply chains targeted at health-oriented consumers' segments. Policy-related measures include budget allocation for research, extension services, seed systems, and scaling-up HGSF initiatives with procurement pledges (AGRA, 2017; Mabhaudhi *et al.*, 2017; Padulosi *et al.*, 2013). Specialized financing instruments like loans and micro-grants for farmers and SMEs, crop insurance, regional and international collaboration with African universities having laboratories, and connections between associations of smallholders and buyers are critical factors.

Conclusion

This critical review reveals that grain amaranth (Amaranthus spp.) represents a uniquely convergent solution to two strategic priorities – the creation of a nutritious "gluten-free gap" product for global markets and the enhancement of food and nutrition security in East Africa. This conclusion is supported by the following findings. Firstly, amaranth represents an exceptionally nutritious ingredient containing up to 16.6% protein with high content of lysine (5.3–6.3 g/100 g of protein), 7.2% lipids with significant amount of squalene (2–8% of oil content), 7.1-16.4% dietary fibre, and high amounts of iron (7.6 mg/100 g), magnesium (248 mg/100 g), and manganese (3.4 mg/100 g). Secondly, processing techniques such as popping, extrusion, germination, fermentation and DIC significantly improve nutrient bioavailability reducing the levels of antinutritional factors like phytates by ~30%, oxalates by 83%, tannins by ~32% and increasing in vitro digestibility of proteins by 1-2%. It makes possible to use amaranth in production of gluten-free breads, complementary porridges, snacks and plant-based meat substitutes. Thirdly, there is strong potential in market opportunities. According to Statista, the value of global amaranth market in 2024 is estimated to be USD 9.3–12.58 billion and may reach USD 19.26–30.07 billion by 2030-2032. However, currently East African farmers face problems with promotion of amaranth on global markets and lack of awareness among the local population due to dominance of quinoa in Europe. Finally, some regulatory framework is available in terms of policy. Kenya and the EAC specifically mention amaranth in their strategies for food security, while EU regulations do not consider it as a novel food making it eligible for export. Consequently, key practical priorities involve the adoption of grain amaranth in national food security plans, expansion of Home-Grown School Feeding programme with official procurement contracts, breeding programs, investments in inexpensive decentralised processing technologies, and partnerships between farmer cooperatives and private sectors.

DECLARATIONS

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