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Grain amaranth, a potential and resilient food crop amenable to processing for diverse food and other products

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Grain amaranth remains a neglected and underutilized indigenous food crop (IFC) despite its diverse accessions in sub-Saharan Africa. This is in comparison with a few cereal crops providing carbohydrates and other nutrients, especially in southern Africa. Grain amaranth, a pseudocereal crop, is resilient to climate variability or change that has plagued southern Africa with frequent droughts, food and nutrition insecurity. The region experiences semi-arid to arid conditions and poor soil fertility which severely affect cereal crop production. These challenges demand an increase in cereal crops that are adaptable to local environments and amenable to processing methods to preserve food for the lean periods. One such IFC is grain amaranth which is adapted to many conditions and has a potential to be utilized in food, cosmetic, computer and pharmaceutical industries. The objective of this review was to describe the status of grain amaranth in terms of research and development with respect to production, nutritional benefits, processing and/or preservation, utilization and seed systems. Southern Africa was the focus of this review due to the prevalence of acute human hunger in this region and limitations in cereal crop production. The results show that grain amaranth on-farm or commercial production and seed systems are scarce in southern Africa. Field trials have shown wide grain yield variations between accessions although this provides an opportunity to select high yielding accessions. There are a few studies on drought tolerance to select accessions exhibiting this trait. Available processing methods show potential to add value to amaranth grain products and enable preservation, but this has not been fully exploited to benefit end users. A good seed system is needed to foster quality assurance and seed accessibility to potential growers. Increasing investments in research and development with farmers' participation in the entire value chain would promote wider grain amaranth cultivation, processing and subsequent utilization. There is a need to test and develop grain amaranth accessions that are resilient to arid and frequent drought conditions and amenable to processing and preservation to improve cereal crop base, food and nutrition security in southern Africa.

KEYWORDS

Amaranthaceae, fermentation, drought tolerance, indigenous food crop, pseudocereal crop

1 Introduction

Many households in southern Africa have been facing acute hunger due to crop failure, especially cereal crops such as maize as the region relies on a few cereal crops for carbohydrates (energy) and other nutrients. Major cereal (grain) crops produced and consumed in southern Africa are maize, millet, rice and sorghum. Maize is a staple food crop in southern Africa, but

production has decreased in many countries of southern Africa due to extreme droughts (Nhamo et al., 2019). This is because maize production is susceptible to drought hence negatively affecting food security in the region (Nhamo et al., 2019). Other potential pseudocereal crops which are indigenous food crops (IFCs) are available in the region. These IFCs have a potential to contribute to addressing the acute human hunger, food security, including micronutrient and vitamin deficiencies (Chivenge et al., 2015; Mng'omba, 2000). While many nations in the region are striving to achieve zero hunger (SDG No. 2), IFCs have been left out despite their potential to contribute to good health and wellbeing (SDG No. 3) of many people, especially children. Southern Africa comprises Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Zambia, Zimbabwe, South Africa, and Eswatini. Many people in this region face acute hunger due to climate variability, droughts, and high temperatures (Nhamo et al., 2019).

The variability in weather and climate change, and poor soil fertility threaten productivity of farming systems. For instance, maize production has negatively been affected by poor soils, droughts, seed quality and high costs of farm inputs, especially inorganic fertilizer among many other factors (Mango et al., 2015; Mng'omba et al., 2024). This calls for cereal crop diversification and inclusion of grain amaranth which could play a critical role toward achieving food and nutrition security in southern Africa. Furthermore, the region has a narrow base of cereal crops to supply the needed energy as many IFCs continue to have a low profile despite being regarded as important future crops (Chivenge et al., 2015; Nkwonta et al., 2023). The region needs these IFCs, but it remains unclear when they will be brought into wider cultivation.

2 Grain amaranths

Grain amaranths (*Amaranthus species*) belong to Amaranthaceae family and are herbaceous annual crop plants. They grow rapidly in a wide range of agroecological environments ranging from tropics to semi-arid and arid areas (Alemayehu et al., 2015). They tolerate alkaline soils (pH as high as 8.5) and acid soils and withstand drought and heat stress conditions (Akin-Idowu et al., 2017; Aderibigbe et al., 2022; Netshimbupfe et al., 2023). *Amaranthus species* originated from Central and South America (Ogwu, 2020) except *A. blitum* which is thought to originate from the Mediterranean region (Grubben and Denton, 2004). Amaranth was introduced to Africa in the 20th century (Ochienga et al., 2019).

Grain amaranth is a promising pseudo cereal crop to feed the human population (Mekonnen et al., 2018) and a good forage for livestock (Mustafa et al., 2011; Ahrar et al., 2020). Several studies indicate that grain amaranth can rise to prominence for food use (Mng'omba, 2000; Akin-Idowu et al., 2017; Aderibigbe et al., 2022).

Grain amaranth has a dual purpose as its grain can be processed (milled) into flour, while its leaves and tender stems are used as leafy vegetable (Mng'omba, 2000; Emmanuel and Babalola, 2021). In southern Africa, the leafy amaranth spp. are mostly grown around homesteads and utilized more as food (vegetable) than the grain amaranth. Three common grain amaranth species include *A. hypochondriacus*, *A. cruentus*, and *A. caudatus* (Aderibigbe et al., 2022; Trucco and Tranel, 2011).

In this review, the objective is to describe the status of grain amaranth in terms of research and development with respect to production, nutritional benefits, processing and/or preservation, utilization and seed systems. Furthermore, the review provides new thinking into future research areas on grain amaranth to attract wider cultivation, utilization, processing, preservation and marketing. Currently, many countries are yet to recognise the huge transformational potential of cultivation and utilizing grain amaranth to improve agrifood systems.

3 Methods

The method used in this review included a literature search of relevant amaranth studies, especially articles published in journals, book chapters, theses and dissertations, and other peer reviewed outlets. The literature was accessed through searching databases such as Google Scholar, Scopus, [Sciencedirect.com](https://www.sciencedirect.com) and Researchgate websites. This methodology followed the Higgins et al. (2024) guidelines.

Where grain yield data were available a stress tolerance index (STI) was calculated to identify accessions with drought tolerance. This review covers only grain amaranth as a potential pseudocereal crop and IFC which is a neglected and underutilized crop. The focus of this study for grain amaranth production and utilization is southern Africa because of persistent food and nutrition challenges due to frequent droughts, erratic rainfall and semi-arid or arid conditions despite abundant IFCs. Keywords used in this review were 'grain amaranth' OR 'amaranth' OR 'drought tolerance' OR 'stress tolerance'. Both research and review articles were selected excluding non-peer reviewed articles and news items.

4 Synthesis and discussion

4.1 Amaranthus species

There are several amaranth species or accessions in southern Africa. South Africa alone has about 16 localized amaranth species (Emmanuel and Babalola, 2021) despite scanty records of actual species/accessions available in each country of southern Africa.

According to Stetter et al. (2025) there are three subgenera of *Amaranthus*, one of them being *Amaranthus* which has cultivated grain amaranth species. These are *A. caudatus*, *A. cruentus*, and *A. hypochondriacus*, and other wild species. For cultivated leafy amaranth species, they include *A. tricolor*, *A. viridis* and *A. blitum*, *A. cruentus*, *A. dubius*, *A. albus*, and *A. hybridus* (Stetter et al., 2025). A brief description of a few common grain amaranth species is as follows:

4.1.1 *Amaranthus hypochondriacus*

This is native to Mexico and Guatemala. It produces big inflorescence but no branches. It is one of the high yielding cultivars of all the grain amaranth types (Dinssa et al., 2018; Emmanuel and Babalola, 2021) though this may depend on the environment. It is a short-day variety and goes to seed early when exposed to long-day conditions. It grows between 40 and 200 cm tall and matures within 75–90 days after sowing (Mukuwapasi et al., 2024).

4.1.2 *Amaranthus tricolor*

This is native to India, China and the islands of the Pacific (Ajayi et al., 2016). It is considered the best of the leafy vegetable amaranth species. It is extensively grown in arid regions. It is a multi-colored species hence used as an ornamental plant (Alemayehu et al., 2015; Mukuwapasi et al., 2024). It grows in the wild in South Africa and can grow up to 125 cm tall and produces smooth black or brown seeds (Emmanuel and Babalola, 2021).

4.1.3 *Amaranthus cruentus*

It is native to Mexico and Guatemala and used both as a grain and leafy vegetable but primarily grown for its grain. It is also used to extract red dye for coloring foods. Its seed color varies from yellow and white to pale brown (Mukuwapasi et al., 2024). Its protein has high levels of amino acids such as methionine and cysteine (Escudero et al., 2004). Its seeds can be germinated and eaten as a sprout, while its leaves are used as a leafy vegetable at tender stage (Emmanuel and Babalola, 2021). It can provide a good quality silage for livestock (Aderibigbe et al., 2022).

4.1.4 *Amaranthus caudatus*

This species originated from the Andean highlands of Argentina, Peru and Bolivia. It is sold in Europe as an ornamental plant. Its grain can be toasted, popped or ground into flour. This species is mainly grown for its grain which is dried and milled for human consumption as a whole-meal amaranth flour, crackers, brown bread without gluten, biscuits and cookies (Mekonnen et al., 2018). It matures between 60 and 70 days depending on altitude. *Amaranthus caudatus* is rich in protein, minerals and fat compared to other cereals (Mekonnen et al., 2018).

4.1.5 *Amaranthus hybridus*

This species originated from tropical America and is now spread throughout the tropical regions and one of the commonly cultivated species in East Africa (Mukuwapasi et al., 2024; Netshimbupfe et al., 2023). It is mainly used both as a leafy vegetable or grain (Orona-Tamayo and Paredes-Lopez, 2017). It is an early maturing species which grows up to 1.5 m tall (dwarf). Its tender leaves are used for soup and stew. The green stemmed accessions are used as vegetable (Emmanuel and Babalola, 2021; Aderibigbe et al., 2022).

4.1.6 *Amaranthus blitum* (lividus)

Amaranthus blitum probably originated from the Mediterranean region. Its use has been reported in many African countries and probably occurs throughout tropical Africa, from Senegal to Ethiopia and South Africa (Grubben and Denton, 2004). According to Aderibigbe et al. (2022), *A. blitum* is one of the three amaranth species widely grown in West Africa.

4.2 Grain amaranth utilization

4.2.1 Nutritional value and food uses of grain amaranth

There are several food products made from grain amaranth flour and these include porridge, dough, bread, biscuits, cakes, noodles, puffed grains, sprouts, beverages, cookies, breakfast cereal and several beverages (Emire and Arega, 2012; Aderibigbe et al., 2022). This shows that grain amaranth has a great potential in food industry.

Grain amaranth is superior in nutrient contents (Table 1) to other cereal crops such as maize, millet, sorghum and rice (Mustafa et al., 2011). It has a high protein content rich in lysine and tryptophan which are limiting amino acids in many cereals like rice and maize (Amare et al., 2015; Netshimbupfe et al., 2023). Amaranth is gluten-free hence its flour is important for dietetic food (gluten-free products) suitable for people allergic to gluten (Stetter et al., 2025). This makes a good blend with cereals for complementary food and snack formulations recommended for celiac patients (Malik et al., 2023). Furthermore, Malik et al. (2023) reported that amaranth has high levels of sulphur-containing amino acids which are limited in pulses or legumes. Therefore, amaranth makes a good blend with legumes for a balanced amino acid profile (Malik et al., 2023) hence a nutritious diet.

In southern Africa, stunting and wasting, especially among children due to nutrient deficiencies are of great concern and need urgent attention. Grain amaranth flour can be used to fortify maize flour to achieve enhanced nutritional quality of the refined maize flour (Kamotho et al., 2017). The use of grain amaranth flour in food-to-food fortification could improve nutritive value of diets in the region.

Grain amaranth has a balanced content of essential amino acids and unsaturated fatty acids, and vital sources of vitamins

TABLE 1 Nutrient composition of grain amaranth compared to other cereal crops.

Nutrients	Amaranth	Millet	Sorghum	Rice	Maize
Protein (%)	13.56	11.02	10.62	6.67	9.42
Lipid (%)	7.2	4.2	3.46	2.22	4.74
Carbohydrate (%)	65.23	72.85	72.09	75.56	74.26
Energy (Kcal/100 g)	371	375	329	356	365
Fiber (%)	6.7	8.5	6.7	2.2	ND
Minerals (mg/100 g)					
Iron	7.61	3.01	3.30	1.11	2.17
Potassium	508	198	363	202	287
Zinc	287	1.68	1.67	ND	2.21
Calcium	159	8	13	4	7

Source: Gebhardt et al. (2008), ND means not determined.

such as vitamin C, B6, folate and carotene (Musa et al., 2011). It is gluten free unlike wheat hence a suitable substitute raw material for formulating gluten-free products (Aderibigbe et al., 2022). According to Malik et al. (2023) grain amaranth has a higher protein (15.4%–16%) with balanced amino acids than wheat (13.5%–14.5%) and maize (10.6%–13.8%). Its flour has good baking and organoleptic qualities. It also blends well with wheat flour to make bread and various confections. Grain amaranth flour is used for unleavened bread and can be used as sole or predominant flour ingredient (Emire and Arega, 2012).

Grain amaranth has antioxidants which are natural defence against diseases such as cardiovascular, cancer, cataracts, retinopathy, malaria, arthritis, emphysema and others (Sarker and Oba, 2021; Netshimbupfe et al., 2023). It has been shown that regular consumption of amaranths can reduce cholesterol level, hypertension and cardiovascular diseases (Karamac et al., 2019).

4.2.2 Industrial use

Grain amaranth has strong market and industrial potentials (Mustafa et al., 2011; Akin-Idowu et al., 2017) despite not being fully exploited. Grain amaranth starch granule is used as lubricant in the computer (lubrication of computer disks) and cosmetic industry (Grubben and Denton, 2004; Schippers, 2002). The grain oil contains squalene used in food, cosmetic and pharmaceutical industries (He et al., 2002; He and Corke, 2003). Squalene is an antioxidant which can reduce cholesterol level in the blood (Smith, 2000) and fight against cancer (Ronco and Stefan, 2013). The squalene found in grain of *A. hypochondriacus* is an alternative to the one in marine shark (He et al., 2002). According to Baraniak and Kania-Dobrowolska (2022) amaranth seed oil is used in skin creams and lotions including shampoos and shower gels. Furthermore, the amaranth oil is used in beauty clinics for body massages, baths, relaxation treatments and innovative sunscreen formulations (Baraniak and Kania-Dobrowolska, 2022).

4.3 Grain amaranth production

There have been a few records of grain amaranth research studies in southern Africa (Table 2) and almost no records for commercial production despite reports of seed exports from South Africa to Europe (Netshimbupfe et al., 2023). Gelaye (2023) reported limited amaranth cultivation and/or production in Africa although South Africa has been conducting several research projects on amaranths. According to Aderibigbe et al. (2022), there have been no global records on production of amaranth. The leafy amaranth dominates production around homesteads in southern Africa (Emmanuel and Babalola, 2021; Mukuwapasi et al., 2024). The low prices for vegetable amaranth offer no incentives to potential growers (Emmanuel and Babalola, 2021). The World Vegetable Centre has been involved in research and development of many IFCs including grain amaranth. The Centre has about 1,453 amaranth accessions in the gene bank,¹ but wide production is yet to be realised in southern Africa.

¹ <https://genebank.worldveg.org>

TABLE 2 Some research studies conducted on grain amaranths in Africa.

Type of study	Site and country	Parameters measured	References
Laboratory test (blending grain flour)	Nairobi, Kenya	Biofortification of maize flour with grain amaranth flour	Kamotho et al. (2017)
Field trials and survey	Kamuli and Wakiso, Uganda	Soil amendment trials and a survey	Graham (2010)
Field trials (30 accessions)	Ibadan, Nigeria	Drought tolerance of 30 accessions	Ajayi et al. (2016)
Field trials (10 accessions)	Bunda and Bvumbwe, Malawi	Genotype field evaluations and drought tolerance	Mng'omba (2000)
Field trial (2 species)	Maputo, Mozambique	Water regimes and day length	Ribeiro et al. (2018)
Field trial (17 accessions)	Arusha, Tanzania	Leaf harvest and grain yield	Dinssa et al. (2018)
Field trial on four local collections	Lilongwe, Malawi	Agromorphological characterisation of amaranth accessions	Nyasulu et al. (2021)

4.4 Field trials and grain yields

From a few available field studies undertaken there has been wide variations in grain yield among grain amaranth species or accessions under different treatments (Table 3). The wide grain yield variations offer a great prospect for selection of drought or stress tolerant accessions in southern Africa. The highest grain yields range was reported from Zimbabwe (Table 3).

4.5 Seed system

The Southern Africa Development Community (SADC) region possesses 110 grain amaranth accessions available in gene banks in different countries (Mativavarira et al., 2024). This is an opportunity for grain amaranth seed trade and wide field production in the SADC region. There is a need for national agriculture institutions to test and develop grain amaranth accessions that are resilient to arid and frequent drought conditions prevailing in southern Africa. A vibrant seed system (with certified seed with quality assurance) can promote grain amaranth production, processing and preservation, utilization and trade.

Currently, there has been an informal seed system where there are no laws and policies regulating the seed system for many IFCs (Mng'omba et al., 2024). Farmers sow their own saved seeds which might be admixtures. Due to a wide genetic diversity among amaranth species (Gerrano et al., 2017), seed quality assurance becomes vital. Although grain amaranths are self-pollinated, there is a high cross-pollination tendency leading to hybrid seed production (Aderibigbe et al., 2022) hence off-type seeds and seed purity are major challenges. Proliferation of poor seed quality, due to seed admixtures, lead to poor field plant establishment and high seed-borne diseases hence a good seed system must be the focus for productivity gains.

TABLE 3 Grain yields of amaranths evaluated in East and southern Africa.

Number of varieties / accessions	Grain yield (t/ha)	References
Four accessions (Malawi)	1.4–5.7	Nyasulu et al. (2021)
Ten accessions for rainy season (Malawi)	0.9–2.4	Mng'omba (2000)
Ten accessions for dry season (Malawi)	0.5–1.0	Mng'omba (2000)
14 accessions for rainy season (Tanzania)	1.1–2.9	Mbwambo et al. (2015)
Zimbabwe	1.5–7.2	Mukuwapasi et al. (2024)
South Africa	0.7–1	Netshimbupfe et al. (2023)
17 accessions (2013), Tanzania	0.91–5.52	Dinssa et al. (2018)
17 accessions (2014), Tanzania	0.21–2.47	Dinssa et al. (2018)

4.6 Harvesting grain amaranth

The common practice to harvest grain amaranth is to collect seed heads before they are dry and become brittle to avoid grain losses due to shattering of the pods. The seed heads are placed on a cloth (cloth bags) or inside paper to completely dry and then seeds are removed from seed heads by rubbing with hands or by beating seed heads in a bag or outside the bag (Graham, 2010). This harvesting method addresses the challenge of grain shattering.

4.7 Drought tolerance

Grain amaranth, a C4 plant, is known to tolerate arid and semi-arid conditions due to its low water requirement and high photosynthetic efficiency (Ajayi et al., 2016; Malik et al., 2023). According to Johnson and Henderson (2002) drought tolerance in grain amaranth is attributed to its long taproot and extensive lateral root growth. They further reported that it increases its root depth to extract soil water from deeper soil layers under water stress conditions. Critical growth stages for many grain crops are flowering and grain filling (Fisher and Maurer, 1979; Mng'omba et al., 2003). A few published studies were found identifying drought tolerant grain amaranth accessions. This is despite reports that grain amaranth is adapted to several agroecological areas with arid conditions, but not all accessions can be stress tolerant. Some accessions possess early maturing traits to escape drought, but such short growing condition might reduce grain yield. There must be a balance between drought escape (early maturity) and drought tolerance to maintain adequate level of productivity (Mng'omba, 2000).

A few studies have been undertaken to assess grain amaranth drought tolerance. Ajayi et al. (2016) evaluated 30 grain amaranth accessions for drought tolerance using several water stress tolerance indices. They reported that stress tolerance index (STI) was robust in measuring drought tolerance since there was a positive correlation between grain yield and yield components. Five (16.7%) grain amaranth accessions out of 30 were declared drought tolerant using STI and other indices. These were *A. spinosus*, *A. cruentus*, *A. hypochondriacus*, *A. tricolor*, and *A. hybridus* (Ajayi et al., 2016).

This is evidence that accessions must be assessed to select drought or stress tolerant accessions for cultivation in regions with frequent drought stress.

Mng'omba (2000) assessed 10 grain amaranth accessions in Malawi using STI. Three accessions (30%) out of 10 were drought tolerant when water stress was imposed at 50% flowering stage. These were *A. tricolor* (STI = 1.33), *A. cruentus* (STI = 1.17) and *A. caudatus* (10) (STI = 1.07). Only two accessions were drought tolerant when water stress was imposed at grain filling stage. These accessions were *A. caudatus* (10) (STI = 1.18) and *A. cruentus* (STI = 1.11). These two accessions were found drought tolerant at both growth stages (STI > 1). Ajayi et al. (2016) reported that an accession is declared stress tolerant when its stress tolerance index (STI) is greater than 1.

4.8 Processing and preservation

Processing is important for food or beverage preparation, value addition and preservation (shelf life extension). Processing has been used to improve nutrient availability and food digestibility and some processing methods reported for amaranth grains include blanching, boiling, fermentation, milling, popping, roasting, and steaming (Roa et al., 2015; Cornejo et al., 2019; Malik et al., 2023). Selection of any processing method depends on available processing equipment (Mazike et al., 2022).

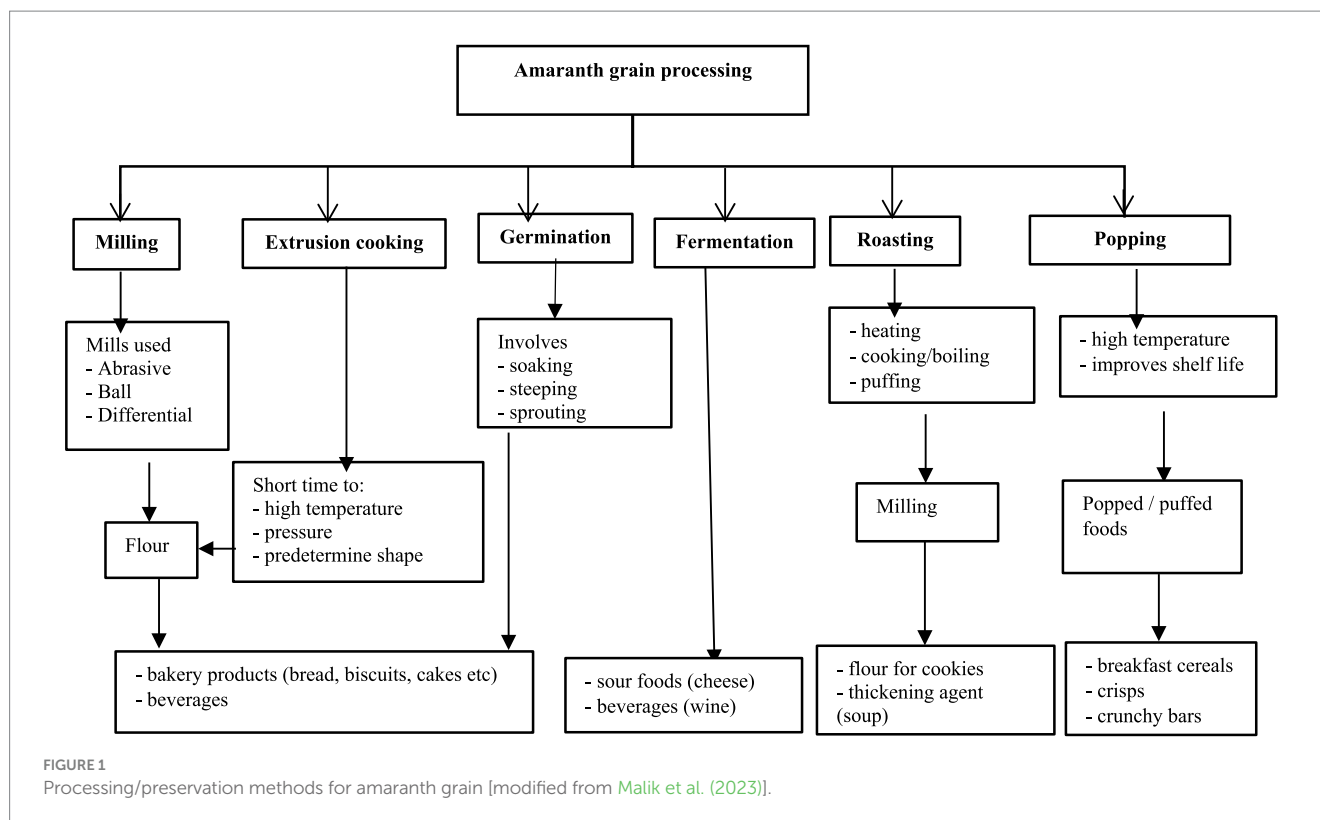
Grain amaranth contains some antinutrients despite its numerous nutritional benefits. Through proper grain processing antinutrient content can be minimised though other important nutrients might be lost. Figure 1 summarises processing methods used for amaranth grains [modified from Malik et al. (2023)].

4.8.1 Milling

Amaranth grains are milled or ground into flour to produce a wholegrain meal or white flour, but one disadvantage of milling grains including amaranth grains is a short storage period (shelf life). This means a longer period of storage (preservation) is achieved when amaranth grains are left intact. An abrasive mill used for sorghum or rice milling can be used for amaranth grains (Malik et al., 2023). Also, a ball mill can process amaranth flour into liquid foods. This mill produces small particle sizes and increases solubility (Roa et al., 2015). Differential milling is another method used to separate germ, endosperm and bran from amaranth grains and this milling method produces amaranth flour rich in protein, starch and fiber (Malik et al., 2023).

4.8.2 Germination

Amaranth grains can be soaked and allowed to germinate (sprout) and this process improves nutritional value (Hubner and Arendt, 2013). Hejazi and Orsat (2017) reported that germination of amaranth grain increased protein availability and starch digestibility. Generally, germination of grain, especially cereals is commonly used to prepare traditional food and beverages. Malik et al. (2023) cited that steeping amaranth grain followed by germination and kilning increased amino acids, while soaking and sprouting increased antioxidants and total phenols. Cornejo et al. (2019) recommended germinating *A. caudatus* for bakery products. Sprouted *A. hypochondriacus* grains have been reported to have high fiber and protein contents (Malik et al., 2023).



4.8.3 Fermentation

Fermentation is fundamentally a process whereby carbohydrates are converted into alcohol or organic acids with the help of microbes such as yeasts or bacteria. It is used for preservation of sour foods due to lactic acid production such as in yogurt, wine and cheese. [Castro-Alba et al. \(2019\)](#) reported that both amaranth grain or flour fermentation degraded its phytate content and amaranth flour fermentation was more effective than fermentation of its grains. Fermented amaranth grains retained free amino acids and improved protein digestibility ([Amare et al., 2015](#)). Fermented amaranth flour had increased mineral accessibility by 1.7–2.5-fold and reduced phytate by 1.8-fold ([Castro-Alba et al., 2019](#)).

4.8.4 Roasting and hydrothermal treatments

Roasting is a dry heating process and is known to improve digestibility, palatability, and organoleptic properties of foods ([Sruthi et al., 2021](#)). Roasting *A. hypochondriacus* and *A. cruentus* grains in an oven then milling after cooling increased antioxidant activity and viscosity ([Malik et al., 2023](#)). This processing method is preferred to popping for amaranth flour when making a thickening agent ([Malik et al., 2023](#)). Also, roasting *A. cruentus* grains increased digestible starch content, glycemic index, and hydrolysis index ([Malik et al., 2023](#)).

Apart from roasting, amaranth grains can be boiled or steamed to prepare various food products. There have been many nutrient dynamics with respect to different processing methods. For instance, boiling the whole grain increased protein digestibility by 15%, while boiling grain flour increased protein digestibility by 24% ([Aderibigbe et al., 2022](#)). Heat treatment such as autoclaving and blanching were more effective in reducing tannin and oxalate content in amaranth grains ([Aderibigbe et al., 2022](#)).

4.8.5 Popping

Popping is a processing method which involves exposing grains to high temperatures for a short period or toasted to gelatinize and expand grain starch. Popping amaranth grains has been reported to produce a pleasant taste and smell for human food ([Graham, 2010](#)). Popped amaranth grains have been used as breakfast cereals or crunchy bars due to its good nutrition, desired digestible protein, lysine content and palatability ([Malik et al., 2023](#)). Popped amaranth has been reported to be beneficial compared to raw grains due to high antioxidant activity, dietary fiber, flavonoids, fat, ash and ease to mill (due to more grain volume). [Amare et al. \(2015\)](#) reported decreases in *in vitro* protein digestibility, and in some amino acids such as lysine, methionine and cysteine in popped amaranth compared to raw and fermented amaranth flour.

4.8.6 Extrusion cooking

Extrusion cooking is a food processing method which involves a combination of thermal and mechanical treatment where protein or starch-rich ingredients are plasticized. The final product goes through a die (hole) to produce a variety of products ([Alam et al., 2016](#); [Riaz, 2019](#)). This processing method makes an instant composite flour. It has been found to improve vitamin A retention. Furthermore, it breaks down food proteins to enhance their availability to enzymes ([Montoya-Rodriguez et al., 2015](#)). Extrusion cooking involves the use of high barrel temperatures and feed moisture which contribute to reducing antinutritional factors such as polyphenols and phytic acid ([Montoya-Rodriguez et al., 2015](#)). Extruded amaranth flour has good quality protein, higher water absorption and retention ([Montoya-Rodriguez et al., 2015](#)).

4.8.7 Oil extraction

The other processing method for amaranth grains is oil extraction. The amount of oil extracted from amaranth grains depends on flow rate of the extraction solvent, pre-treatment, temperature and pressure during extraction (Malik et al., 2023). This extraction method does not affect nutritional content and characteristics of the extracted oil (Malik et al., 2023).

5 Conclusions and future prospects

Many potential end users are still not aware of the food and nutritive values of grain amaranth, especially through processing hence limited field production and utilization in southern Africa. More research studies are needed to identify cost effective processing methods into different products. Also, selection of drought tolerant accessions that offer improved grain yield and quality is vital.

In this review, several processing methods have been explained, but local processing methods among different communities remain unknown. There is a need to assemble such indigenous knowledge to complement the more advanced processing technologies described in this review as local processing methods might be cheap and easy to adopt by smallholder farmers. Developing grain amaranth enterprises around the local processing and preservation methods could promote grain amaranth cultivation, utilization and marketing.

Considering a wide diversity of grain amaranths locally available in the SADC region and those conserved in the gene banks of World Vegetable Centre, genotype characterisation is important to select the most adaptable accessions for cultivation to reduce grain yield and quality risks during unfavorable growing conditions.

Currently, there are no known on-farm agronomical practices developed hence the need for research to develop management practices for grain amaranths for high grain yield. This is also important considering that grain amaranths serve both as leafy vegetables and grain. Investments are needed for research to optimize production in southern Africa to ensure its productivity and contribute to food and nutrition security in southern Africa.

There are opportunities to expand grain amaranth cultivation in southern Africa as a pseudocereal food crop considering its nutritive values. Inclusion of grain amaranth into farming system could broaden food grain base to safeguard food and nutrition security. Despite some tolerance to the challenging environmental conditions, there is a need to test and develop grain amaranth accessions or cultivars that are resilient to arid conditions to improve the food grain crop base in southern Africa. Both advanced and local processing technologies need to be explored to add value to grain amaranth

production. This could possibly elevate grain amaranth to commercial production. Significant investments in research and development are required for grain amaranth production by smallholder farmers. Furthermore, developing better agronomic practices are needed to sustain better grain amaranth production in southern Africa.

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Conflict of interest

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