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Review

Grain amaranth: A versatile untapped climate-smart crop for enhancing food and nutritional security

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Received: 24 March 2024 / Accepted: 15 July 2024
Published online: 06 August 2024

Abstract
Globally, food and nutritional state are marked by an acute prevalence of undernourishment, leading to malnutrition, starvation, and poverty. This state has remained vital for the past years, making attaining zero hunger for the anticipated period (2030) in Africa less possible. To alleviate this challenge, more sustainable food production systems, policy frameworks, mindset changes, and diversification of the food production systems must include some highly nutritious underutilized orphan crops. Acknowledging the potential of untapped, versatile, and climate resilience, *Amaranthus* significantly promotes sustainable and nutrient-rich food systems. Amaranth grain is a pseudocereal with 4 g of protein and 19 g of carbohydrates per 100 g of cooked amaranth. It is a nutrient powerhouse constituting valuable nutraceuticals, protein, and carbohydrates. Grain amaranth yield ranges from 1500 to 7200 kg/ha. Yield variableness of grain amaranth, lays openings for scientists and researchers to study crop improvement and access a rich pool of genetic materials. These attributes make *Amaranthus* (amaranth) the most suitable crop candidate in these climate change scenarios. The *Amaranthus* spp. are popularly known as weedy species and largely undomesticated crops with good adaptability to various geographical locations. Despite its good adaptability, it is less known, under-exploited, and less popular as human food, and its production is very scanty, especially in southern Africa. Efforts are needed to promote its adoption and commercialization. The authors searched pieces of literature in books, journals, and conference papers to establish the potential usage of *Amaranthus*, its nutritional composition, and its production practices.

Keywords Food security · Grain amaranth · Nutritional security · Malnutrition · Underutilized crops

1 Introduction

Nutriments and low food availability prevail as a significant challenge worldwide [1], evidenced by common famines and malnutrition among much of humankind despite increased production. Estimates of basic needs, particularly food, were 27.7% for Africa, 7% for Asia, 1.2% for North America and Europe, and 6.4% for South America [2]. To address sustainability, the United Nations (UN) developed a class of targets/objectives known as 'Sustainable Development Goals' (SDGs) [3]. Its SDG 2 aims to institute a world free of hunger by 2030. A global outline reviewing the situation of nutriments indicated that approximately 828 million people on the whole earth are short of food and appropriate nutrition with

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varying levels, from chronic to acute [4]. About two billion communities are now vulnerable to low access to primary and minor nutrients. One of the dietary inadequacies that continue to abide in most rural homes is invisible starvation, with minimum discernible indicators [5, 6], and the consequence of this scenario is associated with poor health outcomes [7, 8]. One of the most common challenges of these unnoticed food shortages is malnourishment, a disorder resulting from a lack of appropriate nutrition. The most exposed groups of people are minors (usually under the age of 5 years), expecting females, and infants growing and residing in developing countries where poverty is the order of the day. Most of the upcoming nations' economies reckon gloomily on agriculture; with this scenario, the agriculture sector is under pressure to generate 70% of the food needed to cater to the increasing inhabitants by 2050 or prior [9]. The world needs to adopt a more organized and revised agriculture system. Stakeholders can reduce food insecurity through crop production diversification and the inclusion of underutilized, forgotten, and climate-smart crops such as amaranth, teff (*Eragrostis tef*), quinoa (*Chenopodium quinoa*), and spider plant (*Cleome gynandra*) among others.

Most underutilized food plants are drought-tolerant, highly nutritious, disease- and pest-tolerant, and can produce better yields with minimal inputs. To date, just thirty (30) of the one hundred fifty (150) flora kingdoms that humans have domesticated are utilized to supply the world's nutriments needs [10, 11], with staple grains [maize (*Zea mays*), wheat (*Triticum aestivum* L.), rice (*Oryza*)] making up the bulky; despite being prone to recurring environmental changes [12] and other abiotic stresses [13]. Underutilized crops refer to a collection of natural and cultivated flora species with meager worldwide outlets (markets) [14, 15]. They can sometimes described as under-used, minor, promising, or orphan crops [16]. Typically, these crops are nourishing [15] and offer noteworthy well-being good [17]. They also pose a distinctive portrait of well-off in nutrients with affordable protein substitutes to support peasant farmers' lives [18], preserve the earth, and slow down carbon emissions [19].

One of the underused and usually undermined crop species is amaranth (*Amaranthus*), commonly recognized as pigweed, has over 70 breeds categorized as amaranth vegetables (leafy), grainy, weedy, as well as ornamental [20, 21]. Most amaranths are native to America, and domestication started in the 6000–8000 period. However, today, it is a universally propagated type [22, 23], with only 15 species originating in Asia, Africa, Australia, and Europe [24]. *Amaranthus* has been reclaimed in the middle of hardly any eatable crops with versatile, invaluable benefits, deserving quality attention, and no doubt it will be on the tables of many in this modern world due to its reasonable nourishment and low input production [20]. Research shows that amaranth production suits low-fertile areas and holds notable prospects for additional orientation and occurrence due to its standard divergence in genetic and physical traits [25–27]. It is plausible to thrive under the utmost warmth, rainlessness, and lousy soil conditions, including pests and other disorders. Farmers can successfully attain grain amaranth cultivation as leafy and seedy in some domains and periods where other floras hardly grow [28–30]. It has an innate strapping merchandise and production capacity yet to be prettily mined [31, 32]. It is a promising and resilient plant credit promotion. The current weather outlook has significantly given rise to undernutrition, starvation, and low productivity in the agriculture sector in southern Africa and beyond, and the scenario now calls for a newer approach, paying much attention to forgotten nutritious, health-beneficial, and drought-tolerant crops. Navigating *Amaranthus* collections may reveal their unrecognized potential and elevate the crop's adoption into the central cropping system and usage. Aderibigbe et al. [57] analyzed the value chain of amaranth for food and nutrition, Peiretti [33] outlined its usage in animals, Ruth et al. [35] explored the underutilization of *Amaranthus* versus nutritional and nutraceutical potential, and Alegbejo [122] offered an overview of the plant's nutritional value and consumption. Therefore, the recent review quests to sift the wholesome benefits, production practices, and remunerative prospects of versatile, underused, and orphan crop grain amaranth for global food and nutrient security, particularly for vulnerable regions.

2 Amaranth botanical description

Amaranthus belongs to the family Amaranthaceous, previously the Chenopodium [34], order Caryophyllales, which has about 70 kinds of angiosperms as members and includes over 400 varieties. It is suitable for production in the tropical and world zones of average annual rainfall of the universe [24]. *Amaranthus* exists as dioecious (the two types of reproductive organs are found on segregate plants) and homothallic (the two types of reproductive organs are located on the same plant) [35]. The dioecious are aboriginal of North America, while the monoecious are extensively spread across different continents [36]. Diecious amaranth plants have a restricted distribution and are bushy in appearance. Amaranth expresses itself as a fixation of C4 carbon, which is usually observable in grasses rather than dicotyledons [37]. Plants are between 0.4 and 1.5 m tall [38] and 0.3 to 3.0 m in height [27]. Leaves possess egg shape and are spherical with color variations of pale to deep green, depending on the genetic constitution of the species, with some species presenting red all over. Figure 1 depicts some color variations of amaranth leaves.

Blossoms are wine-colored, orange, plum, maroon, and lemony, with the principal cane ending in a well-distinguished flower [39], with the blossoms developed on branched clusters or glomerules. Projected are the well-defined flowers, colorful, glowing, and concluding. Figure 2 shows amaranth growing in experimental fields at North-west University, South Africa.

The microspore of the homothallic of the amaranth has a golf ball-like opening in the center of its convex structure. The broadness of seeds is about 1 mm in diameter, although they can range between 0.9 and 1.7 mm in magnitude, and heaviness varies between 0.6 and 1.3 mg each. The small diameter makes amaranth seeds 30–70 times microscale in size compared to conventional wheat grain [40]. The grain seed color varies with species, with creamy, white, brown, gold, and pink. Figure 3 shows different colors of amaranth seeds harvested in the 2021–2022 growing season.

Different extension patterns, including sprawling, upright, forked, and branchless, are seen in amaranths. Native identifications for amaranth (English) includes 'pigweed, misbredie, morogo, tepe, thepe, serepelele, theepe, umfino, imbuia or utyutu' [28]. As for nutrient level and environmental tolerance, the species vary as well.

3 Geographic distribution of amaranth

The Aztecs and the previous American cultures depended heavily on amaranth as a staple food source [41]. Amaranth, as a crop, nearly perished in the Americas after the Spanish Conquistadors' occupation of Mexico at the start of the 1500s, only to be revived through U.S. research in the 1970s [42]. Due to the scaled U.S. research, there was a notable amaranth seed production in the United States through the late 1970s, even though the production was limited to a few acres annually. The production of seed amaranth later travelled over the globe and was well adopted in nations like India, Africa, and Nepal for food in either leaves or seeds. More and more farmers from China, Russia, Italy, Greece, Australia, and South America initiated its cultivation [43]. It has built a comeback as a crop in Mexico over 20 years ago.

Commonly cultivated species in East Africa, China, and India are *A. hybridus*, *A. blitum*, and *A. dubius*. South America uses *A. caudatus* as a grain, and in the Southwestern United States. *A. dubius* is mainly cultivated for its leaf in China and the Caribbean. *A. hybridus* is a dual crop in Mexico, Nepal, Indonesia, Malaysia, Thailand, and the Philippines [44, 45]. Southeast Asia and China are ranked highly for famous classic greens, and interestingly, amaranth comes first in rank, seconded by Chinese spinach [44]. Amaranth species are at one's disposal during the drier, warmer summer rainfall periods in southern Africa. Literature suggests that amaranth can adapt acceptably to the climates of Sub-Saharan localities,

Fig. 1 Amaranths growing in experimental fields in the 2021/2022 season with different leaf colors

Fig. 2 Amaranth variation in inflorescence colors: 2021/2022 season in the experimental field

Fig. 3 Amaranth seed colors

and people can observe its growth along the roadsides and many fallow landscapes [46]. The cultivation of amaranth is rare in South Africa and the rest of southern Africa; however, people find it in unmanaged lands and pick it up following the earliest precipitation [47]. Leafy amaranth (vegetable) usually grows as a wild vegetable. It is substantially consumed as a leafy vegetable by poor people living in the rural areas of Limpopo, Eastern Cape, Mpumalanga, Kwazulu-Natal, and Northwest [48] (parts of southern Africa). The cultivation of grain amaranth is mainly at the scientific level by the local universities in South Africa [49] and Zimbabwe, Botswana, and Cameroon [50]. In East Africa, the cultivation of amaranth leafy vegetables has gained momentum. The adoption and commercialization of grain amaranth in Africa, excluding Kenya, is hardly prevailing, and this can also be an indicator of why the production of grain amaranth is not lined up with other grains or cereals in the FAO statistics on production [51].

4 *Amaranthus* species

Amaranthus mainly contains 400 species [27], with a handful currently under cultivation. The total number of species established to date still needs to be determined [52]. The genus comprises leafy vegetable amaranth, grain amaranth, ornamental, and weedy amaranth. Alemayehu et al. [53] outlined three major seed amaranth types: *A. caudatus* L., *A. hypochondriacus* L., and *A. cruentus*, with *A. tricolor* grouped as an ornamental. *A. blitum* (slender amaranth), *A. lividus*, *A. dubius* (spleen amaranth), *A. spinosus*, *A. thunbergia*, and *A. graecizans* are produced for their leaves (leafy amaranth) [54]. Typical types common in Sub-Sahara are *A. graezianus* & *thumbergii* [53]. The three principal species cultivated for their seed use include:

4.1 *A. cruentus*

This is one of the species mainly significantly produced for its use as grain seed, even though some people harvest the tender leaves for use as relish, thereby rendering it a dual-purpose amaranth. However, it is known as a grain species in America at the outset. *A. cruentus* is popularly considered for its leaves in Africa and Asia to a small extent [55]. In all tropical nations, *A. cruentus* is an example of traditional green. In Benin, Togo, and Sierra Leone, it is the primary leafy vegetable and is also a major leafy vegetable in India, Bangladesh, Sri Lanka, and the Caribbean [55]. It is thought to be the most versatile species of amaranth, blooming in a broader range of day length than others [56]. In Nigeria, *A. cruentus* is also grown for a specific purpose as an ornamental [57]. It can reach a height of 2 m and generates one dominating middle root (taproot) with a ribbed and red-dyed stem. Simple, stipule-free, spirally organized leaves range from oval to rhombic-ovate in shape. The seeds vary in color, from yellow and white to pale brown. This species is usually considered for cultivation conditions, primarily in mountain areas in India, because of its hardiness to adverse climatic conditions [58]. Figure 4 shows *A. cruentus* growing in the experimental field during the 2021/2022 growing season.

4.2 *A. hypochondriacus*

It is a species commonly grown for its grain in South America and Asia. It is the main domesticated species, and its production is mainly concentrated in the warm areas of Morelos, Puebla, and Guerrero states with a notable harvest in Mexico [59]. It is an ornamental in Africa, except at trial sites in Zimbabwe and South Africa [54]. It is a vigorous, upright plant that typically grows up to 40–200 cm in height [55]. It is ordinally red-tinted throughout the plant, distinguished by forked stems that are plump, angled, balloon-like, or well spread to relatively thickly fit out, coupled with multicellular hairs. The cotyledons (leaves) are lobed or unlobed and not broken into leaflets. Leaf style is alternate (one per node along the stem) with entire edges. The flowers of *A. hypochondriacus* mostly have a notable edge, are upright, often with minor or little projections observed at the end part of the axils, and have distinct deep red, purple, or beetroot red blooms; however, yellowish, and green blossoms are hardly present in these grain species. The *hypochondriacus* seeds are characterized by variations in seed color, including white, ivory, pinkish white, or black to dark reddish brown [60]. Seed sizes of 1–1.4 mm and smooth shiny surfaces are standard [24]. It matures early 75–90 days [61], is a mid-length season of 60–120 days [62], and is day-neutral.

Fig. 4 Amaranth grain species: *A. cruentus*

4.3 *A. caudatus* (*A. edulis*)

It is commonly called lovelies, bleeding amaranth, or tassel flower and gets its name from its tiny blood-red, petal-less flowers. *Caudatus* has the shortest season, with 45 to 75 days to maturity [62]. In Africa, it matures in 60 to 70 days, depending on altitude, with the fastest maturity at lower altitudes. Oval-shaped, light green leaves characterize it. Cultivars with yellow–green flowers are available. This plant is everlasting, and its flowers keep good color when dried for arrangement. In South America, it is popularly utilized as a cereal [46] and cultivated to use the seeds in parts of Argentina, Peru, and Bolivia [57]. This type produces flour. The leaves vary in color, but purple or green are most common. The stems are purple and green, with purple roots. The inflorescences are purple with no spikes [63]. Seeds are black, cream, or pink. Figure 5 shows *A. caudatus* growing in the experimental field at North-West University, South Africa, during the 2021–2022 season.

5 *Amaranthus* seed production

Amaranth is a very tiny-seeded cereal, but this does not limit the use of conventional seed machinery in its cultivation. Farmers should be cautious to maintain a planting depth of 3–5 mm. Any planting depth exceeding 5 mm will affect crop emergence. It is an extensively adaptable species that can thrive in various environments and conditions between 0 and 2400 m above sea level. Although adapts to many poor conditions, significant yields are realized when production is done on good soils. Farmers can successfully cultivate amaranth in mixed or single-production systems. If one considers mixed cultivation, maize is the best match [64].

5.1 Land preparation

The seeds of grain amaranth are very tiny in size and, therefore, require a fine tilth for enhanced germination. The plowing of the land at a depth of 250–300 mm, followed by discing and harrowing on virgin land. Land preparation through discing previously cultivated land is practicable, although this method of land preparation gives rise to weed challenges as compared to conventional plowing. Tilling can be done using tractors, ox-drawn ploughs, or hand hoes, depending on the production scale. Inorganic or organic fertilizers can be used as basal dressing. Organic fertilizers are applied during the dry period (August–September). Heaps of organic manure are made in the field, spread, and followed by plowing. Application of organic manures is usually as per soil analysis results, with an application rate of 4046.856 square meters (acre) [27].

Fig. 5 *A. caundatus*

5.2 Planting

Farmers can distribute amaranth seeds in well-prepared land with a fine tilth. We usually do not recommend no-till as amaranth is a poor competitor to weeds during the early weeks after emergence. You should rinse the soil well. Seeds are planted directly in the field by scattering or hill placement. By broadcasting, you can scatter seeds in rows or over the plot using a hand or a planter. This approach is not cost-effective. Direct planting is possible when seedbanks are abundant. It is also known as sowing in situ, meaning no seedlings movement will take place. This method gives amaranth seedlings the advantage of early take-off and a good crop stand if the seedling emergence is good. Seed trays provide an alternative option for sowing seeds individually. This method can be tiring as the amaranth seeds are tiny and might be difficult or impossible to hold individually. A 1.5–3 kg/ha seed rate is recommended [65]. Mixing seeds with sand ensures even distribution. Row spacing of grain amaranth varies from 45 to 75 cm, and plant spacing is 30–45 cm. Wider rows give high yields and permit using row cultivators for weed control.

5.3 Nursery management

Apply water frequently, and it would be best not to overwater the seedlings as over-application can lead to damping off disease. Transplant after 4–5 weeks and hardening off should start a week before transplanting. The most appropriate time for transplanting is in the morning or late afternoon for best results. Apply adequate moisture to the new transplants.

5.4 Climatic and soil requirements

Amaranth can grow in temperate, tropical, and subtropical climates [27, 66]. It grows well between the temperature range of 18–35 °C [27], and at planting, the temperature should be at least 18 °C [58]. Warm and sunny conditions enhance an outstanding germination rate. Despite receiving only 500 mm of rainfall per year, amaranth still manages to produce a satisfactory yield. Amaranth produces a satisfactory yield despite receiving only 500 mm of yearly rain. Irrigation supplements are desirable during the dry season. Amaranth does well in medium–heavy, loose, and friable soils. Soil pH ranges from 5.0 to 8.0 [27]. Selecting soils that are low in clay will help reduce crusting problems, resulting in poor seedling emergence. It is sensitive to compacted soils [67]. Amaranth is a hardy species that withstand unfavorable conditions like full sun, inadequate moisture, and raised temperatures [26].

5.5 Crop management

5.5.1 Pest and disease management

Amaranth seed production experiences minimal disorders and pests that result in notable crop depletion. Amaranth seed production experiences minimal disorders and pests that result in notable crops. The usually notable prevailing diseases are damping off and seedling wilts due to pythium [68]. Diseases are managed through cultural practices, as no fungicides are labelled for the amaranth use [69]. Grain amaranth can tolerate considerable insect leaf feeding without affecting yields. On the other hand, leafy amaranth may have contrasting characteristics in this context, in which researchers have observed an increased incidence of insects and pathogens [70]. Grain amaranth farmers in Brazil recorded a few challenges of Lepidoptera larvae causing falling over of plants preceding the seed-filling stage in sprinkled fields [71]; besides this, the seed amaranth is ordinarily resilient to pests' destruction, including nematodes.

Production of amaranth can be a challenge due to the lack of approved weed killers. Farmers can employ cultural practices such as cover crops and crop rotations to manage the difficulty of weeds, providing crops with the advantage of early take-off [43]. Mechanical weeding, 2–3 rounds in a growing season, can be carried out until plants form large canopies to shadow weeds. There are numerous benefits of keeping the area under production and the surroundings weed-free through hoeing, hand pulling, and using row crop cultivators. Once amaranth gets to 15–25 cm in height, the growth rate will be fast and will be able to resist the impacts of weeds by out-competing the later weeds [72]

5.5.2 Harvesting

Farmers should commence crop disposal early when the panicles (heads) color changes from green to gold, and the seeds shade with a light touch as grain amaranth readily breaks. The administration of the produce is the most pivotal phase of the production of grain amaranth; beyond attentive harvesting tactics, very high seed loss is possible. Delays in crop disposal may result in a percentage loss of up to 50% or higher [61]. The crop can be reaped manually using hand-cutting tools or a combined harvester.

6 Uses of amaranth

Amaranth is the only pseudo-cereal with the whole plant used for food and other uses. There are numerous techniques to treat the grain for ingestion, with expanded grain being the most famous. The seeds of amaranth are popped or boiled and eaten as rice [73]. The grains' flaking, extruded, and ground-to-flour shapes have given them certain functional advantages, hence they earned the name 'pseudocereal' [74]. Flour is the most critical by-product of amaranth seeds. The flour is used in the baking industry [20]. It is the main component of a gluten diet with other pseudocereals such as quinoa and teff. Amaranth does not contain gluten; this trait makes its flour excellent for manufacturing foods for people with gluten allergies and celiac diseases [75].

Flour from amaranth seeds is traditionally used to produce snack bars or snake cakes in Mexico and other nations by putting together honey and popping amaranth [27]. In India, laddoos are typically made from grain amaranth and added to rice meals [76–78]. Farmers who used livestock feed obtained from seed amaranth noted increased digestibility [79]. The seeds are used for making chaqa (a local beverage) in Ethiopia [53]. An alcoholic drink known as 'borde', 'kita' (a yeast-free bread), and 'atmit' (a thin porridge) for breastfeeding women and their young ones is also made from grain amaranth. It is predominantly given to these mothers after giving birth [26]. It is crushed and combined with fish, flour obtained from maize, sorghum, or millet to process porridge for children [80]. Due to its ability to prevent and treat chronic degenerative disorders, the beverage sector utilizes amaranth grain as a raw ingredient [57]. In South Africa, grain amaranth has a lengthy history of use in folklore, local medicine, and as a source of dye [81]. Oil-containing squalene from grain amaranth species, *hypochondriacus* has since impacted the food, cosmetic, and pharmaceutical industries [82, 83]. According to reports, the squalene content of the amaranths is the highest of any plant species [84, 85]. It is applied to enhance protein, including critical nutrients of the terminating diets [86, 87]. People in Peru sprout and malt the seed amaranth to obtain a traditional *chicha* beer, while in Asia, it is an alternative for soy in producing a soy soup called 'shoyu' [30]. Uji, a type of porridge usually taken for breakfast in Kenya, is produced from flour made from amaranth seeds. Amaranth extracts addressed a variety of illnesses, including diabetes, diarrhea, and skeleton fractures, a long time ago [21, 88]. Research has evaluated amaranth's therapeutic benefits in treating numerous chronic conditions [89–91]. The inflorescences are used as decorations, and the entire top portion of the plant can used as animal feed.

7 Amaranth as a versatile crop

During the 1970s, there was recovered attention on amaranth, which inspired farmer in Mexico to rediscover amaranth from wild cultivars because of the crop's critical role in their way of life. What promoted this resurgence was the identified crop's ability to resist bad weather and its taste. This was when the US considered resilient and undeveloped plant species that could increase the globe's nourishment output. After being brought to the fore as a product with 'superiority and agriculture potential' by the US National Academy in 1975, the crop experienced an outpouring of adoration [92]. Unlike today's one-purpose staples, Amaranth is extensively adaptable, and all portions of the plant are ingested. The adjustment capacity of amaranth to numerous climatic situations is one of the significant drivers behind its resurgence in present-day farming. Delving studies have reaffirmed this old cognition, conceding the crop's distinctive capacity to live in hilly terrain and open plains, including its good stand for drought, raised salt media, and ice [93]. Like other crops that demand complicated techniques to survive, it is a crop that is typically flexible for eliminating the effects of increasing seasonal uncertainty. A universal rotational crop, amaranth is also adaptable to a range of geographic elevations, giving farmers from locales alternatives. Amaranth is a suitable match for the nitrogen-lack soils of southern Africa since it also uses C4 photosynthesis, a system that permits plants to have a higher photosynthetic rate. A remarkable nutritional status and climate adaptability are two outstanding benefits of amaranth. The Aztecs may have believed it granted them 'supernatural power' since it is a nutritional powerhouse. The grain has most industrial, medical, and domestic uses. Snake bites and foot and mouth disease in cattle are all treated with it [73]. The grains cure measles in adolescents by decreasing the body temperature when they sleep over grain spread on the bed [73]. Meat and apples are placed inside the grain chaff/thrash in boxes and noted to extend the longevity of the products by one and a half months for beef and apples 6 months [73]. Amaranth is suitable for many families in southern Africa due to these characteristics, where power outages are frequent.

8 Grain amaranth a climate-smart crop

The new re-establishment of amaranth in modern agriculture can be chiefly accredited to its remarkable resilience across manifold climate conditions. Upcoming research has corroborated prehistoric cognition about the crop's unique hardness, highlighting its capacity to flourish in both hilly terrains and open plains. Amaranth demonstrates a high tolerance for challenging factors such as drought, saline soils, and frost [93]. A key factor underpinning amaranths's resilience is its utilization of the C4 photosynthetic pathway. The Hatch and Slack pathway allows the plant to achieve greater photosynthetic efficiency and to flourish even in nitrogen-poor soils reducing its reliance on irrigation except in exceedingly waterless regions. Amaranth is a member of the NAD-ME subtype of C4 plants, it utilizes NAD^+ as a cofactor in its decarboxylation process [94]. The NAD-ME subtype manifests lower water use efficiency under drought conditions compared to the NADP-ME subtype. This is due to differences in leaf structure and leaf curling rates in the NAD-ME subtype. In contrast, the NADP-ME subtype displays improved nitrogen efficiency under similar moisture deficit conditions [94]. Amaranth plants display higher transpiration rates compared to typical C3 photosynthetic plants. This allows amaranths to continue transpiring and assimilating CO_2 even when experiencing early-stage drought stress conditions. Maize and sorghum may start to restrict transpiration and CO_2 uptake more quickly in response to limited soil moisture [95]. However, Amaranth can maintain its gas exchange and carbon assimilation processes until the drought becomes critically limiting.

In summary, the physiological adaptations give amaranths an advantage in coping with intermittent or moderate drought episodes, as they can keep growing and accumulating biomass for a longer period before shutting down their photosynthetic machinery. These attributes position amaranth as a valuable solution for combating the challenges advanced by progressively seasonal unreliability and enhancing overall agricultural productivity.

9 Nutritional value of amaranth

The dual-purpose plant, nutrient-rich grains, and leaves give a very delicious relish and soup, utilized across the universe as nourishment to both people and fauna and are gaining momentum to be a superior nutrient powerhouse because of their attributes. Carbohydrates, dietary fiber, lipids, significant amino acids, as well as a variety of other crucial constituents like squalene, tocopherols, phenolic compounds, flavonoids, phytates, vitamins, and minerals, are available in this wonder crop [96, 97]. The seeds come with simple protein 13.1–21.0% and albumins, which digest quickly, including globulins, the greater part of their composition [38]. Protein content differs between amaranth species and varieties [98, 99]. The field-managed species were discovered to carry less protein and amino acids throughout other nutrients compared to the wild species [100, 101]. Baraniak and Kania-Dobrowolska [102] noted that climate, soil conditions, and the method of fertilization also influence protein content. The leaves are also a source of affordable, well-to-do protein and other crucial compounds such as carotenoids, vitamin C, dietary fiber, calcium, zinc, and magnesium [103, 104]. Compared with the main staples, specifically rice, amaranth poses a high value in nutrient composition, with three times more in calcium quantity than the main grains [105]. Amaranth's wealthy composition warrants it to be most convenient for humankind dwelling in the communal areas of the less developed societies for bodybuilding and prevention of nutrients malfunctioning [106, 107]. To ascertain this fact [108], outlined the high sulfur present in amaranth compared with a legume. Although amaranth's nutritional profile is valuable, on the other side, it lacks a variety of amino acids such as leucine, isoleucine, and valine, which are not much of a challenge to living organisms' diets, as they are available in large amounts in amaranth compliments (millet, maize, cassava, etc.) [109].

Amaranth has a cholesterol-lowering effect [110, 111]. In addition, it carries vitamins required for daily uptake, which helps minimize vitamin shortfalls [112]. Besides, it also comes with riboflavin (vitamin B_2) and vitamin C, much higher compared to cereals, coupled with vitamin E essential for delaying aging [113]. It also carries reasonable ash content in the leaves and less in the seeds, which helps to estimate the mineral composition [114]. Table 1 below shows the average nutritional composition of *Amaranthus*, other potential crops, and major food crops.

10 Health benefits of grain amaranth

Grain amaranth is a nourishing ancient pseudocereal attained remarkable consciousness in recent years due to its important health good. This multiple-purpose grain, grown and consumed for ages by many cultures is constituted of critical nutrients, antioxidants, and bioactive compounds that help the gross welfare of animals and humankind [117]. The various nutrients in amaranth play crucial roles in many bodily functions, such as energy production, red blood cell formation, and maintaining healthy bones and teeth. Consuming amaranth seeds contributes to heart health in some ways. Seeds of amaranth are naturally low in saturated fat and cholesterol, making them heart-friendly by lowering cholesterol levels and regulating blood pressure [118]. Squalene, found in grain amaranth is attributed to cholesterol level reduction and prevents the building up of arterial plaque [117]. Regular inclusion of amaranth seeds prevents constipation due to their fiber content. The existence of resistant starch helps to nourish important bacteria in the gut and promote their growth. The presence of bacteria in the gut supports improved digestion, nutrient absorption, and overall gut health. The antioxidants in amaranth, vitamin E, phenolic compounds, and flavonoids help neutralize detrimental free radicals in the body thereby lowering the danger of cancer, diabetes, and stroke [118]. Eating amaranth grains helps to reduce inflammation by slowing the body's production of Immunoglobulin E. Grain amaranth meal serves as a substitute for wheat, barley, and rye in diverse recipes, facilitating those with gluten limitations alternative meals [119]. In some regions of Africa, seeds of amaranth have been traditionally employed for curing HIV/AIDS in human population [120]. Grain amaranth meal is mixed with moringa (*Moringa oleifera*) leaf powder in a ratio of one (1) cup of grain amaranth to 1 tablespoon of moringa leaf powder [121]. The moringa–amaranth mixture is believed to minimize the side effects of the ARV [120]. Although amaranth seeds contribute to many health interests, users need to understand that they should be taken at moderate levels as excess amaranth eating can cause health complications.

11 Antinutrients in amaranth

Antinutrients (ANF) are compounds produced in naturally existing food products through a variety of procedures, such as the dismissal of certain nutrients, reduction in the digestive process, or a metabolic utilization of feed, that have an unfavourable outcome upon required condition [122]. The term 'anti-nutritional factors' relates to organically operative chemical substances that repress the accessibility of nutrients to the body of a living organism and obstruct normal metabolic operations [123, 124]. The subsidiary biogenic substances found in amaranth include saponins, tannins, trypsin inhibitors, nitrates, oxalates, phytates, alkaloids, and cyanogenic chemicals [125]. Phytates and oxalates are particularly problematic [126]. Phytic and phytate work as anti-nutrients through reactions with minerals and trace elements like zinc,

Table 1 Average nutritional composition of principal and potential crops (per 100 g edible portion). Source: Raw [115], Angeli et al. [116]

Nutrient	Wheat	Rice	Maize	Barley	Soyabean	Lentil	Buckwheat	Amaranth	Quinoa
Carbohydrates	80.6	86.3	82.9	69.6	20.9	59.0	72.9	65.25	74
Protein (g)	14.8	8.8	10.5	11.5	43.2	25.1	12.0	13.56	16.3
Fat (g)	2.8	3.2	5.3	1.3	19.5	0.7	7.4	7.02	7.0
Fibre (g)	10.7	3.5	7.3	3.9	3.7	0.7	17.8	6.7	7.0
Mineral (g)	1.8	1.7	1.3	1.2	4.6	2.1	2.9	2.88	2.7
Energy (kcal/100/g)	406.8	409.2	421.3	336	432	343	355	371	424.2
Mineral content (mg per 100 g dry matter basis)									
Calcium	50.3	6.9	17.1	26	240	69	110	159	148.7
Iron	3.8	0.7	2.1	1.67	10.4	7.58	4.0	7.61	13.2
Magnesium	169.4	73.5	137.1	–	–	–	390	248	249.6
Phosphorus	467.7	137.8	292.6	215	690	293	330	557	383.7
Potassium	578.3	118.3	377.1	–	–	–	450	508	926.7
Zinc	4.7	0.6	2.9	–	–	–	0.8	2.87	4.4

iron, calcium, and magnesium. They interrupt the assimilation of these minerals in the stomach, thereby minimizing their potency [125, 127]. Young children are more vulnerable to this risk of this chelation as their digestive systems are more sensitive compared to adults; therefore, they need more of these nutrients for growth [128]. Saponins can potentially damage the cell lining of the intestines, and if they are in access, they can cause holes in the intestines, allowing toxins and bacteria to enter the bloodstream [129]. Furthermore, they disturb the utility of the digestive enzymes leading to dyspepsia-linked health issues and lessening the absorption of numerous nutrients [130, 131]. One of the setbacks with these underutilized promising crops like amaranth is the existence of antinutritional elements, which typically demand operations prior to incorporation in the dietary formulation. It is possible to minimize anti-nutritional elements in the leaves and seeds by employing a variety of techniques. Some of these techniques are used at the household level, while others are used extensively in the manufacturing sector, and they include alkali treatment (chemical treatment), cooking, popping, roasting, and extrusion (heat treatment).

12 Grain amaranth production in southern Africa

Southern Africa, a southern region of the African continent, comprises Zimbabwe, South Africa, Zambia, Malawi, Botswana, Lesotho, Mozambique, Swaziland, Namibia, and Angola. Seasonal climates in Africa range from semiarid to arid and from temperate to tropical [132]. Seasonality plays a significant role in regulating plant growth and food availability. In a larger portion of the region, droughts are frequent. Poverty is also rampant as the region is one of the upcoming nations, resulting in a lot of deficits specifically starvation and nutritional insecurity. Over the past two decades, the number of individuals living in poverty has increased [133], and the area has some of the greatest levels of income variations in the world. Over the past 10 years, the average annual growth rate for agriculture in the region has been only 2.6% [134]. To ensure food security, a variety of natural resources that are abundant in the area must be used as only 48,653,300 ha are under cultivation, with just around 25% of the land being arable, and about 80% of the inhabitants engaging in subsistence farming [135]. Agriculture plays a pivotal role in eradicating food insecurity. The region needs to widen its crop base to include potential crops such as amaranth.

Amaranth produced for its seed use is very rare in the region. Production of the superfood grain is mainly at the research level, with some try-outs in Zimbabwe and South Africa. *A. hypochondriacus* L. is reported to have been introduced to the two wards of Binga district in Zimbabwe (Manjolo and Sikalenge), as a method of increasing the diversity of crops that are adapted to climate change [136]. The production was at a very minimal scale as it was comprised of only 47 women growers. The grain amaranth grown in South Africa is observed in institutions for scientific purposes, with patch productions of amaranth leafy by smallholder farmers, and a great portion of the amaranth leafy grew in the wild. He tested the crop on 8000 m^2. Amaranth seed has not been produced commercially, hence there are no records of its output [137].

13 Prospects of grain amaranth in southern Africa

Recently, much attention has been directed to orphan crops, resulting in hundreds of crop types identified, and undoubtedly, amaranth is top in preference [127] and has been acknowledged as one of the most promising future plant species to feed the worldwide inhabitants [138]. The adoption of grain amaranth production seems promising since amaranth is drought tolerant and can produce an acceptable yield under stress environments. Amaranth is a niche crop with lucrative markets in Europe [139]. The smallholder farmers in Southern regions can produce and export amaranth, thereby eradicating poverty through earning foreign currency. Farmers in southern Africa can exploit this advantage and adopt amaranth production to eradicate hunger and malnutrition. Mono cropping is high in southern Africa, and amaranth can be used in many rotations. In addition, amaranth processing is more straightforward than other small grains (finger millet and sorghum).

In Europe, pseudo cereals are a specialized market with rising yearly requests. North America, Latin America, the Middle East, Europe, Africa, and the Asia Pacific region are the seed amaranth's primary trade routes. The global amaranth market is anticipated to grow with a compound annual growth rate (CAGR) of 10.4% through the era [140]. Europe makes up about 65% of the world's market dominance [141]. The Confederation of British Industry revealed, that importing from developing nations 6000 tonnes of specialty cereals, the bulky of which were amaranth seeds, and the report also outlined that Germany is the primary consumer market of amaranth seeds [142]. Other industrialized nations like the UK, the Netherlands, Sweden, Belgium, and France are getting more and more familiar with this product, although amaranth is mostly used as a health food, and it can be purchased in tiny packages (raw, popped or milled) holding up to 500 g of the commodity, or it can be used as the primary product in breakfast cereals, baked goods, or healthy snacks. This gives southern Africa a great opportunity to take advantage of the prospects presented by the amaranth market at a global scale since the economies of many of the countries in this region are built on agriculture. The markets for amaranth products in Africa are small and undeveloped because of the scarcity of some goods, short of standard demand, and poor policies. Smallholder farmers who grow grain amaranth have low sales potential without significant connections to consumers.

African kingpins and other significant business sector players can create solid market ties with European nations and offer readily valuable data on markets with substantial insistence on amaranth seeds. This will increase income creation and lessen poverty in the southern African region. Mexico, Russia, China, India, Peru, and Kenya are some of the significant nations that cultivate amaranth for seed and hold market dominance [143]. Kenya has outperformed most African nations outside southern Africa. Amaranth is more prevalent in its food systems and is farmed on a commercial basis, marketed in metropolitan markets, and even traded outside of the country [144]; making it the only African country to export seed amaranth.

14 Constraints to production

Besides the positive attributes of the food crop, grain amaranth, the crop's adoption into the main cropping system and acceptance is faced with uncertainties along its value chain. The principal constraints are related to some physical characteristics of the amaranth grain, propagation, refinement, and distribution of the grain and its derivatives [145]. Amaranth's texture, color, and size can limit its acceptance and production [44]. The dimensions, and appearance of quinoa make it a simple substitute for rice. Cultivation of grain amaranth is challenged by the absence of endorsed seeds (formal) and the unavailability of transmissible and biological quality seeds [52].

15 Conclusion

In this review paper, some details of amaranth including their botany, species, production practices, nutrition, health, and anti-nutrient values were explored. Grain amaranth has been called a nutrient powerhouse and is gaining global attention as an important plant species due to its high nutritional value, health-boosting, resilience to diverse negative production conditions, ease of cultivation, short maturation period, and easy grain processing compared to other small grains. The nutritional profile of amaranth seeds, with their valued protein composition, appraised amino acids constitutions, and rich mineral and vitamin content, positions it as a valuable source of critical nutrients. Amaranth poses unique bioactive compounds such as squalene and flavonoids which contribute to its superior health benefits that include cardiovascular protection, anti-inflammatory properties, and immune system support. Many scholarly works have shown that amaranth is a highly adjustable crop species in the face of climatic change. Its ability to survive in insignificant lands with minimum water and fertilizer requirements further ascertains its suitability for sustainable farming practices. Furthermore, many amaranth species show a wide range of genetic diversity, promoting opportunities for improvement and adaptation to specific environments.

Production practices of grain amaranth have been examined, including planting techniques, pest, disease, weed management, and harvesting procedures. These practices, when deployed appropriately, can increase yield and quality, ensuring the standard output of nutritious grains. Although grain amaranth gives appraisable nutritional merits, it is essential to acknowledge the presence of anti-nutrients in its make-up. Appropriate processing techniques, such as cooking, fermentation, and soaking, can effectively reduce the antinutritional content and improve the bioavailability of nutrients, rendering optimal utilization by the human body. It also demonstrated its climate-smart attributes through its low carbon footprint and efficient use of resources. Grain amaranth's ability to stand up to bad climatic conditions, such as deficit moisture and heat stress, makes it an appealing option for zones prone to inconsistent rainfall patterns. In addition, its low water requirements and high seed productivity contribute to water and land conservation, supporting the principles of precision agriculture. Lastly, grain amaranth provides a significant opportunity to address the impacts of climate change. Tapping the potential of this versatile and climate-smart crop requires further research, technological advancements, production practices awareness, and stakeholder and policy support. Adoption of grain amaranth as a stable food and incorporating it into main cropping systems have the potential to change the state of food and nutrition as well as promote human and environmental sustainability.

Acknowledgements The writers thank all other authors and investigators whose work we have cited for their important and valuable contribution to this study.

Author contributions Betty Mukuwapasi: conceptualization, visualization, drafting, and writing the first manuscript draft. Sydney Mavengahama: supervision, review, and editing. Abe Shegro Gerrano: review and editing. All authors read and approved the final manuscript.

Funding Open access funding provided by North-West University.

Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests There were no uncovered capable conflicts of interest.

References

1. Ziervogel G, Ericksen PJ. Adapting to climate change to sustain food security. Wiley Interdiscip Rev Clim Change. 2010;1:525–40. https://doi.org/10.1002/wcc.56.
2. FAO, IFAD, UNICEF, WFP, WHO. The state of food security and nutrition in the world 2019. Safeguarding against economic slowdowns and downturns. 2019. http://www.fao.org/3/ca5162en/ca5162en.pdf.
3. UN. Transforming our world: the 2030 agenda for sustainable development 2015. https://sdgs.un.org/2030agenda.
4. FAO, UNICEF, IFAD, WFP, WHO. The state of food security and nutrition in the world 2022: repurposing food and agricultural policies to make healthy diets more affordable 2022. https://doi.org/10.4060/cc0639en.
5. Harding KL, Aguayo VM, Webb P. Hidden hunger in South Asia: a review of recent trends and persistent challenges. Public Health Nutr. 2018;21:785–95. https://doi.org/10.1017/S1368980017003202.
6. Saltzman A, Birol E, Wiesman D, Prasai N, Yohannes Y, Menon P, et al. 2014 global hunger index: the challenge of hidden hunger. Washington, DC: Intl Food Policy Res Inst; 2014.
7. Bailey RL, West KP Jr, Black RE. The epidemiology of global micronutrient deficiencies. Ann Nutr Metab. 2015;66:22–33. https://doi.org/10.1159/000371618.
8. Unicef, FAO, IFAD, WFP, WHO. The state of food security and nutrition in the world 2018: building climate resilience for food security and nutrition. 2018. http://www.fao.org/3/i9553en/I9553EN.pdf.
9. Aswal J, Bisht B, Dobhal R, Uniyal D. Historical journey with amaranth. Asian Agri-History. 2016;20:201–10.
10. Arora R. Diversity in underutilized plant species: an Asia-Pacific perspective. Rome: Bioversity International; 2014.
11. Shelef O, Weisberg PJ, Provenza FD. The value of native plants and local production in an era of global agriculture. Front Plant Sci. 2017;8:2069. https://doi.org/10.3389/fpls.2017.02069.
12. Popoola J, Ojuederie O, Omonhinmin C, Adegbite A. Neglected and underutilized legume crops: improvement and future prospects. London: IntechOpen; 2020.
13. Ertiro BT, Azmach G, Keno T, Chibsa T, Abebe B, Demissie G, et al. Fast-tracking the development and dissemination of a drought-tolerant maize variety in Ethiopia in response to the risks of climate change. The climate-smart agriculture papers: investigating the business of a productive, resilient and low emission future. 2019. p. 79–86. https://doi.org/10.1007/978-3-319-92798-5.
14. Harouna DV, Venkataramana PB, Ndakidemi PA, Matemu AO. Under-exploited wild *Vigna* species potentials in human and animal nutrition: a review. Global Food Secur. 2018;18:1–11. https://doi.org/10.1016/j.gfs.2018.06.002.
15. Tyagi R, Pandey A, Varaprasad K, Paroda R, Khetarpal R. Proceedings and recommendations of regional expert consultation on underutilized crops for food and nutritional security in Asia and the Pacific, Asia-Pacific Association of Agricultural Research Institutions (APAARI); 2018.
16. Kasolo W, Cheminingwa G, Temu A. Neglected and underutilized species (NUS) for improved food security and resilience to climate change: a contextualized learning manual for African colleges and universities. Nairobi: ANAFE; 2018.
17. Clydesdale F. Functional foods: opportunities & challenges. Food Technol. 2004;58:35–40.

18. Bailey RL, Akabas SR, Paxson EE, Thuppal SV, Saklani S, Tucker KL. Total usual intake of shortfall nutrients varies with poverty among US adults. J Nutr Educ Behav. 2017;49:639–46. https://doi.org/10.1016/j.jneb.2016.11.008.
19. Mall T. Diversity of potential orphan plants in health management and climate change mitigation from Bahraich (Uttar Pradesh). Int J Curr Res Biosci Plant Biol. 2017;4:106–45.
20. Park S-J, Sharma A, Lee H-J. A review of recent studies on the antioxidant activities of a third-millennium food: *Amaranthus* spp. Antioxidants. 2020;9:1236. https://doi.org/10.3390/antiox9121236.
21. Peter K, Gandhi P. Rediscovering the therapeutic potential of *Amaranthus* species: a review. Egypt J Basic Appl Sci. 2017;4:196–205. https://doi.org/10.1016/j.ejbas.2017.05.001.
22. Achigan-Dako EG, Sogbohossou OE, Maundu P. Current knowledge on *Amaranthus* spp.: research avenues for improved nutritional value and yield in leafy amaranths in sub-Saharan Africa. Euphytica. 2014;197:303–17. https://doi.org/10.1007/s10681-014-1081-9.
23. Baldermann S, Blagojević L, Frede K, Klopsch R, Neugart S, Neumann A, et al. Are neglected plants the food for the future? Crit Rev Plant Sci. 2016;35:106–19. https://doi.org/10.1080/07352689.2016.1201399.
24. Ogwu MC. Value of *Amaranthus* [L.] species in Nigeria. Nutritional value of amaranth. London: IntechOpen; 2020. p. 1–21.
25. Ecker O, Weinberger K, Qaim M. Patterns and determinants of dietary micronutrient deficiencies in rural areas of East Africa. 2010. https://resolver.sub.uni-goettingen.de/purl?gro-2/61326.
26. Emire S, Arega M. Value added product development and quality characterization of amaranth (*Amaranthus caudatus* L.) grown in East Africa. Afr J Food Sci Technol. 2012;3:129–41.
27. Rastogi A, Shukla S. Amaranth: a new millennium crop of nutraceutical values. Crit Rev Food Sci Nutr. 2013;53:109–25. https://doi.org/10.1080/10408398.2010.517876.
28. Ebert AW, Wu T, Wang S. Vegetable amaranth (*Amaranthus* L.). Intl Cooperators' Guide AVRDC–The World Vegetable Center Publication; 2011.
29. Grundy MM, Momanyi DK, Holland C, Kawaka F, Tan S, Salim M, et al. Effects of grain source and processing methods on the nutritional profile and digestibility of grain amaranth. J Funct Foods. 2020;72: 104065. https://doi.org/10.1016/j.jff.2020.104065.
30. Mlakar SG, Bavec M, Turinek M, Bavec F. Rheological properties of dough made from grain amaranth–cereal composite flours based on wheat and spelt. Czech J Food Sci. 2009;27:309–19. https://doi.org/10.17221/61/2009-CJFS.
31. Akin-Idowu PE, Odunola OA, Gbadegesin MA, Ademoyegun OT, Aduloju AO, Olagunju YO. Nutritional evaluation of five species of grain amaranth—an underutilized crop. Int J Sci. 2017;3:18–27.
32. Olaniyi J. Evaluation of yield and quality performance of grain amaranth varieties in the Southwestern Nigeria. Res J Agron. 2007;1:42–5.
33. Peiretti P. Amaranth in animal nutrition: a review. Livestock Dev. 2018;30:1–20.
34. Kadereit G, Borsch T, Weising K, Freitag H. Phylogeny of Amaranthaceae and Chenopodiaceae and the evolution of C4 photosynthesis. Int J Plant Sci. 2003;164:959–86. https://doi.org/10.1086/378649.
35. Ruth ON, Unathi K, Nomali N, Chinsamy M. Underutilization versus nutritional–nutraceutical potential of the *Amaranthus* food plant: a mini-review. Appl Sci. 2021;11:6879. https://doi.org/10.3390/app11156879.
36. Noori M, Talebi M, Nasiri Z. Seven *Amaranthus* L. (Amaranthaceae) taxa flavonoid compounds from Tehran province, Iran. Int J Modern Bot. 2015;5:9–17. https://doi.org/10.5923/j.ijmb.20150501.02.
37. Stetter MG, Zeitler L, Steinhaus A, Kroener K, Biljecki M, Schmid KJ. Crossing methods and cultivation conditions for rapid production of segregating populations in three grain amaranth species. Front Plant Sci. 2016;7:816. https://doi.org/10.3389/fpls.2016.00816.
38. Joshi DC, Sood S, Hosahatti R, Kant L, Pattanayak A, Kumar A, et al. From zero to hero: the past, present and future of grain amaranth breeding. Theor Appl Genet. 2018;131:1807–23. https://doi.org/10.1007/s00122-018-3138-y.
39. Stetter MG, Schmid KJ. Analysis of phylogenetic relationships and genome size evolution of the *Amaranthus* genus using GBS indicates the ancestors of an ancient crop. Mol Phylogenet Evol. 2017;109:80–92. https://doi.org/10.1016/j.ympev.2016.12.029.
40. Trugo LC, Finglas PM. Encyclopedia of food sciences and nutrition. Amsterdam: Academic Press; 2003. p. 1498–506.
41. Assad R, Reshi ZA, Jan S, Rashid I. Biology of amaranths. Bot Rev. 2017;83:382–436. https://doi.org/10.1007/s12229-017-9194-1.
42. Hancock JF. Agriculture in the Americas before the European conquest. In: World Agriculture before and after 1492: legacy of the columbian exchange. Cham: Springer; 2022. p. 31–50. https://doi.org/10.1007/978-3-031-15523-9_4.
43. Stallknecht G, Schulz-Schaeffer J. Amaranth rediscovered. New York: New Crops Wiley; 1993. p. 211–8.
44. National Research Council, Policy and Global Affairs, Development S and Cooperation. Lost crops of Africa: volume II: vegetables. National Academies Press; 2006.
45. Orona-Tamayo D, Valverde ME, Paredes-López O. Chia—the new golden seed for the 21st century: nutraceutical properties and technological uses. In: Sustainable protein sources. Amsterdam: Elsevier; 2017. p. 265–81. https://doi.org/10.1016/B978-0-323-91652-3.00005-8.
46. Qumbisa N, Ngobese N, Kolanisi U. Potential of using *Amaranthus* leaves to fortify instant noodles in the South African context: a review. Afr J Food Agric Nutr Dev. 2020;20:16099–111. https://doi.org/10.18697/ajfand.92.18690.
47. Department of Agriculture, Forestry, and Fisheries. Amaranth—production guidelines. Republic of South Africa; 2014.
48. Van Averbeke W, Jansen van Rensburg W, Slabbert M, Chabalala M, Faber M, Van Jaarsveld P, et al. African leafy vegetables. Nutritional value and water use of African leafy vegetables for improved livelihoods WRC report TT535/12 Water Research Commission, Pretoria; 2012. p. 39–67.
49. Emmanuel OC, Babalola OO. Amaranth production and consumption in South Africa: the challenges of sustainability for food and nutrition security. Int J Agric Sustain. 2022;20:449–60. https://doi.org/10.1080/14735903.2021.1940729.
50. Gotor E, Irungu C. The impact of Bioversity International's African leafy vegetables programme in Kenya. Impact Assess Project Apprais. 2010;28:41–55. https://doi.org/10.3152/146155110X488817.
51. Rosentrater KA, Evers A. Introduction to cereals and pseudocereals and their production. In: Kent's technology of cereals: an introduction for students of food science and agriculture. Elsevier: Duxford; 2018. p. 1–76.
52. Jacobsen S, Mujica A, Ortiz R. The global potential for quinoa and other Andean crops. Food Rev Int. 2003;19:139–48. https://doi.org/10.1081/FRI-120018880.
53. Alemayehu FR, Bendevis M, Jacobsen S. The potential for utilizing the seed crop amaranth (*Amaranthus* spp.) in East Africa as an alternative crop to support food security and climate change mitigation. J Agron Crop Sci. 2015;201:321–9. https://doi.org/10.1111/jac.12108.

54. Schippers R. African indigenous vegetables: an overview of the cultivated species 2002; 2002. http://r4d.dfid.gov.uk/Output/179575/.
55. Grubben G. Vegetables. vol. 2. Prota; 2004.
56. Omami EN. Responses of amaranth to salinity stress. 2007. http://hdl.handle.net/2263/26640.
57. Aderibigbe O, Ezekiel O, Owolade S, Korese J, Sturm B, Hensel O. Exploring the potentials of underutilized grain amaranth (*Amaranthus* spp.) along the value chain for food and nutrition security: a review. Crit Rev Food Sci Nutr. 2022;62:65. https://doi.org/10.1080/10408398.2020.18253239.
58. Wolosik K, Markowska A. *Amaranthus cruentus* taxonomy, botanical description, and review of its seed chemical composition. Nat Prod Commun. 2019;14:193457819844141. https://doi.org/10.1177/1934578X19844141.
59. Velez-Jimenez E, Tenbergen K, Santiago P, Cardador-Martínez MA. Functional attributes of amaranth. Austin J Nutr Food Sci. 2014;2:1–6.
60. Grubben GJ, Denton OA. Plant resources of tropical Africa. PROTA Foundation; 2004.
61. Omari F, Njiru E, Mutisya D, Karoki M, Rutto R, Mokua R, et al. Grain amaranth training manual.
62. Berkelaar D, Alemu J. Grain amaranth. Christian Reformed World Relief: Nairobi; 2006. p. 2–3.
63. Alege G, Daudu S. A comparative foliar epidermal and morphological study of five species of the genus *Amaranthus*. Eur J Exp Biol. 2014;4:1–8.
64. Das S. *Amaranthus*: a promising crop of future. Singapore: Springer; 2016.
65. Palada M. Suggested cultural practices for vegetable amaranth. International Cooperators Guide; 2003. https://www.example.edu/paper.pdf.
66. Department of Agriculture, Fisheries, and Forestry. Amaranthus: production guidelines. South Africa; 2010.
67. Weber L, Kauffman C, Bailey N, Volak B. Amaranth grain production guide. Rodale Research Center; 1987.
68. Makinde E, Ayeni L, Ojeniyi S. Morphological characteristics of *Amaranthus cruentus* L. as influenced by Kola Pod Husk, organomineral and NPK fertilizers in Southwestern Nigeria. N Y Sci J. 2010;3:130–4.
69. Cheng A. Shaping a sustainable food future by rediscovering long-forgotten ancient grains. Plant Sci. 2018;269:136–42. https://doi.org/10.1016/j.plantsci.2018.01.018.
70. Qiu Y, Liu G. Production guide of vegetable amaranth for Florida: HS1407, 2/2021. EDIS 2021; 2021. https://edis.ifas.ufl.edu/.
71. de Oliveira CM, Ribeiro Júnior WQ, de Camargo AJA, Frizzas MR. First record of damage by an insect pest in a commercial amaranth crop in Brazil. Scientia Agricola. 2012;69:271–4. https://doi.org/10.1590/S0103-90162012000400006.
72. Myers R. Grain amaranth: a lost crop of the Americas. Small Farm Today. 2004. https://scholar.google.com/scholar?cluster=11766753328472495898&hl=en&as_sdt=0,5.
73. Topwal M. A review on amaranth: nutraceutical and virtual plant for providing food security and nutrients. Acta Sci Agric. 2019;3:9–15.
74. Punia Bangar S, Sharma N, Singh A, Phimolsiripol Y, Brennan CS. Glycaemic response of pseudocereal-based gluten-free food products: a review. Int J Food Sci Technol. 2022;57:4936–44. https://doi.org/10.1111/ijfs.15890.
75. Woomer JS, Adedeji AA. Current applications of gluten-free grains—a review. Crit Rev Food Sci Nutr. 2021;61:14–24. https://doi.org/10.1080/10408398.2020.1713724.
76. Alba E, Polignano G, Notarnicola L. Yield stability in a set of amaranth entries in southern Italy [*Amaranthus* spp.-Apulia]. Ital J Agron (Italy). 1997. https://hdl.handle.net/11563/1106.
77. Chan HT. Handbook of tropical foods. 1983. https://www.cabidigitallibrary.org/action/doSearch?do=Handbook+of+tropical+foods.
78. Dixit AA, Azar KM, Gardner CD, Palaniappan LP. Incorporation of whole, ancient grains into a modern Asian Indian diet to reduce the burden of chronic disease. Nutr Rev. 2011;69:479–88. https://doi.org/10.1111/j.1753-4887.2011.00411.x.
79. Olorunnisomo O, Ayodele O. Effects of intercropping and fertilizer application on the yield and nutritive value of maize and amaranth forages in Nigeria. Grass Forage Sci. 2009;64:413–20. https://doi.org/10.1111/j.1365-2494.2009.00706.x.
80. Wanjala W, Onyango A, Makayoto M, Onyango C. Indigenous technical knowledge and formulations of thick (ugali) and thin (uji) porridges consumed in Kenya. Afr J Food Sci. 2016;10:385–96. https://doi.org/10.5897/AJFS2016.1521.
81. Agong S. *Amaranthus caudatus* L. In: Brink M, Belay G, editors. Prota 1: cereals and pulses. Prota: Wageningen; 2006.
82. He H-P, Cai Y, Sun M, Corke H. Extraction and purification of squalene from *Amaranthus* grain. J Agric Food Chem. 2002;50:368–72. https://doi.org/10.1021/jf010918p.
83. He H-P, Corke H. Oil and squalene in *Amaranthus* grain and leaf. J Agric Food Chem. 2003;51:7913–20. https://doi.org/10.1021/jf010918p.
84. Alvarez-Jubete L, Auty M, Arendt EK, Gallagher E. Baking properties and microstructure of pseudocereal flours in gluten-free bread formulations. Eur Food Res Technol. 2010;230:437–45. https://doi.org/10.1007/s00217-009-1184-z.
85. Venskutonis PR, Kraujalis P. Nutritional components of amaranth seeds and vegetables: a review on composition, properties, and uses. Compr Rev Food Sci Food Saf. 2013;12:381–412. https://doi.org/10.1111/1541-4337.12021.
86. Akinsola A, Onabanjo O, Idowu M, Ade-Omowaye B. Traditional complementary foods: a critical review. Greener J Agric Sci. 2017;7:226–42. https://doi.org/10.15580/GJAS.2017.9.092217137.
87. Anigo K, Ameh D, Ibrahim S, Danbauchi S. Nutrient composition of commonly used complementary foods in North western Nigeria. Afr J Biotechnol. 2009;8(17).
88. Baral M, Datta A, Chakraborty S, Chakraborty P. Pharmacognostic studies on stem and leaves of *Amaranthus spinosus* Linn. Int J Appl Biol Pharm Technol. 2011;2:41–7.
89. Aphalo P, Martínez EN, Añón MC. Amaranth sprouts: a potential health promoting and nutritive natural food. Int J Food Prop. 2015;18:2688–98. https://doi.org/10.1080/10942912.2015.1004585.
90. Khanam UKS, Oba S. Bioactive substances in leaves of two amaranth species, *Amaranthus tricolor* and *A. hypochondriacus*. Can J Plant Sci. 2013;93:47–58.
91. Kraujalis P, Venskutonis PR, Kraujalienė V, Pukalskas A. Antioxidant properties and preliminary evaluation of phytochemical composition of different anatomical parts of amaranth. Plant Foods Hum Nutr. 2013;68:322–8. https://doi.org/10.4141/cjps2012-117.
92. Iyer N. Everyday superfoods. New Delhi: Bloomsbury Publishing; 2021.
93. Parihar M, Kumar A, Bisht JK, Bhinda MS, Shyamnath RPM, Mondal T, et al. Reviving the forgotten food network of potential crops to strengthen nutritional and livelihood security in North Western Himalayas. Indian J Agron. 2021;66:S44–59.

94. Babayev H, Mehvaliyeva U, Aliyeva M, Feyziyev Y, Guliyev N. The study of NAD-malic enzyme in *Amaranthus cruentus* L. under drought. Plant Physiol Biochem. 2014;81:84–9. https://doi.org/10.1016/j.plaphy.2013.12.022.
95. Kauffman CS, Weber LE. Grain amaranth. In: Advances in new crops. Timber Press: Portland; 1990. p. 127–39.
96. Soriano-García M, Aguirre-Díaz IS. Nutritional functional value and therapeutic utilization of amaranth. In: Nutritional value of amaranth. London: IntechOpen; 2019.
97. Taylor JR, Belton PS, Beta T, Duodu KG. Increasing the utilisation of sorghum, millets and pseudocereals: developments in the science of their phenolic phytochemicals, biofortification and protein functionality. J Cereal Sci. 2014;59:257–75. https://doi.org/10.1016/j.jcs.2013.10.009.
98. Kaur S, Singh N, Rana JC. *Amaranthus hypochondriacus* and *Amaranthus caudatus* germplasm: characteristics of plants, grain and flours. Food Chem. 2010;123:1227–34. https://doi.org/10.1016/j.foodchem.2010.05.091.
99. Makobo N, Shoko M, Mtaita T. Nutrient content of vegetable amaranth (*Amaranthus cruentus* L.) at different harvesting stages. World J Agric Sci. 2010;6:285–9.
100. Andini R, Yoshida S, Ohsawa R. Variation in protein content and amino acids in the leaves of grain, vegetable and weedy types of amaranths. Agronomy. 2013;3:391–403. https://doi.org/10.3390/agronomy3020391.
101. Shukla S, Bhargava A, Chatterjee A, Srivastava A, Singh S. Genotypic variability in vegetable amaranth (*Amaranthus tricolor* L.) for foliage yield and its contributing traits over successive cuttings and years. Euphytica. 2006;151:103–10. https://doi.org/10.1007/s10681-006-9134-3.
102. Baraniak J, Kania-Dobrowolska M. The dual nature of amaranth—functional food and potential medicine. Foods. 2022;11:618. https://doi.org/10.3390/foods11040618.
103. Akçin T, Yalçin S. Nutrition contents of the some wild edible plants in Central Black Sea Region of Turkey. Int J Nat Eng Sci. 2007;1:11–3.
104. Chivenge P, Mabhaudhi T, Modi AT, Mafongoya P. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-Saharan Africa. Int J Environ Res Public Health. 2015;12:5685–711. https://doi.org/10.3390/ijerph120605685.
105. Nascimento AC, Mota C, Coelho I, Gueifão S, Santos M, Matos AS, et al. Characterisation of nutrient profile of quinoa (*Chenopodium quinoa*), amaranth (*Amaranthus caudatus*), and purple corn (*Zea mays* L.) consumed in the North of Argentina: proximates, minerals and trace elements. Food Chem. 2014;148:420–6. https://doi.org/10.1016/j.foodchem.2013.09.155.
106. Bakhru H. Foods that heal: the natural way to good health. Orient Paperbacks; 1995. www.orientpaperbacks.com.
107. Kachiguma NA, Mwase W, Maliro M, Damaliphetsa A. Chemical and mineral composition of amaranth (*Amaranthus* L.) species collected from central Malawi. J Food Res. 2015;4:92. https://doi.org/10.5539/jfr.v4n4p92.
108. Juan R, Pastor J, Alaiz M, Vioque J. Electrophoretic characterization of *Amaranthus* L. seed proteins and its systematic implications. Bot J Linn Soc. 2007;155:57–63. https://doi.org/10.1111/j.1095-8339.2007.00665.x.
109. Narwade S, Pinto S. Amaranth—a functional food. Concepts Dairy Vet Sci. 2018;1:1–4. https://doi.org/10.32474/CDVS.2018.01.000112.
110. Mendonça S, Saldiva PH, Cruz RJ, Arêas JA. Amaranth protein presents cholesterol-lowering effect. Food Chem. 2009;116:738–42. https://doi.org/10.1016/j.foodchem.2009.03.021.
111. Plate AY, Arêas JA. Cholesterol-lowering effect of extruded amaranth (*Amaranthus caudatus* L.) in hypercholesterolemic rabbits. Food Chem. 2002;76:1–6. https://doi.org/10.1016/S0308-8146(01)00238-2.
112. Kigel J. Development and ecophysiology of amaranths. In: Amaranth: biology, chemistry, and technology. Boca Raton: CRC Press; 1994. p. 39–73. https://doi.org/10.1201/9781351069601.
113. Morales D, Miguel M, Garcés-Rimón M. Pseudocereals: a novel source of biologically active peptides. Crit Rev Food Sci Nutr. 2021;61:1537–44. https://doi.org/10.1080/10408398.2020.1761774.
114. Abolaji G, Olooto F, Ogundele D, Williams F. Nutritional characterization of grain amaranth grown in Nigeria for food security and healthy living. Agrosearch. 2017;17:1–10. https://doi.org/10.4314/agrosh.v17i2.1.
115. Raw P. Composition of Foods Raw, Processed, Prepared USDA National Nutrient Database for Standard Reference, Release 28 (2015) Documentation and User Guide. United States 2015.
116. Angeli F, Spanevello A, De Ponti R, Visca D, Marazzato J, Palmiotto G et al. Electrocardiographic features of patients with COVID-19 pneumonia. Eur J Intern Med 2020;78:101–6.
117. Ogrodowska D, Zadernowski R, Czaplicki S, Derewiaka D, Wronowska B. Amaranth seeds and products—the source of bioactive compounds. Pol J Food Nutr Sci. 2014;64:165–70. https://doi.org/10.2478/v10222-012-0095-z.
118. Skwarylo-Bednarz B, Stepniak PM, Jamiolkowska A, Kopacki M, Krzepilko A, Klikocka H. Amaranth seeds as a source of nutrients and bioactive substances in human diet. Acta Scientiarum Polonorum Hortorum Cultus. 2020;19:153–64. https://doi.org/10.24326/asphc.2020.6.13.
119. Ríos-Hoyo A, Romo-Araiza A, Meneses-Mayo M, Guttiérrez-Salmeán G. Prehispanic functional foods and nutraceuticals in the treatment of dyslipidemia associated to cardiovascular disease: a mini-review. Int J Vitam Nutr Res. 2017;87:58–98. https://doi.org/10.1024/0300-9831/a000290.
120. Devasagayam T, Tilak J, Boloor K, Sane KS, Ghaskadbi SS, Lele R. Free radicals and antioxidants in human health: current status and future prospects. Japi. 2004;52:4.
121. Lopez JM. Amaranth seeds: a promising functional ingredient for gastronomy—a review. Sarhad J Agric. 2024;40:39–53. https://doi.org/10.17582/journal.sja/2024/40.1.39.44.
122. Alegbejo JO. Nutritional value and utilization of Amaranthus (*Amaranthus* spp.)—a review. Bayero J Pure Appl Sci. 2013;6:136–43. https://doi.org/10.4314/bajopas.v6i1.27.
123. Ekesa BN. Selected superfoods and their derived super diets. In: Superfood and functional food—the development of superfoods and their roles as medicine. Croatia: IntechOpen; 2017. p. 95–114. https://doi.org/10.5772/67239.
124. Soetan K, Oyewole O. The need for adequate processing to reduce the anti-nutritional factors in plants used as human foods and animal feeds: a review. Afr J Food Sci. 2009;3:223–32.
125. Fasuyi A, Dairo F, Adeniji A. Protein supplementary quality of tropical vegetable (*Amaranthus cruentus*) leaf meal in broiler starter diets: bionutritional evaluation. Int J Agric Res. 2007;2:976–86.

126. Gemede HF, Ratta N. Antinutritional factors in plant foods: potential health benefits and adverse effects. Int J Nutr Food Sci. 2014;3:284–9. https://doi.org/10.11648/j.ijnfs.20140304.18.
127. Valencia-Chamorro S. Quinoa: overview. Encycl Food Grains. 2016;1:341–8.
128. Akin-Idowu PE, Ademoyegun OT, Olagunju YO, Aduloju AO, Adebo UG. Phytochemical content and antioxidant activity of five grain amaranth species. Am J Food Sci Technol. 2017;5:249–55. https://doi.org/10.12691/ajfst-5-6-5.
129. Beta T, Duodu K. Bioactives: antioxidants. 2016.
130. Briend A, Prinzo ZW. Dietary management of moderate malnutrition: time for a change. Food Nutr Bull. 2009;30:S265–6. https://doi.org/10.1177/15648265090303S301.
131. Francis G, Kerem Z, Makkar HP, Becker K. The biological action of saponins in animal systems: a review. Br J Nutr. 2002;88:587–605. https://doi.org/10.1079/BJN2002725.
132. Addisu S, Assefa A. Role of plant containing saponin on livestock production; a review. Adv Biol Res. 2016;10:309–14. https://doi.org/10.5829/idosi.abr.2016.309.314.
133. Kregiel D, Berlowska J, Witonska I, Antolak H, Proestos C, Babic M, et al. Saponin-based, biological-active surfactants from plants. Appl Charact Surfactants. 2017;6:184–205. https://doi.org/10.5772/67239.
134. Cooper P, Rao K, Singh P, Dimes J, Traore P, Rao K, et al. Farming with current and future climate risk: advancing a 'hypothesis of hope' for rainfed agriculture in the semi-arid tropics. J SAT Agric Res. 2009;7:1–19.
135. Harrison A. Globalization and poverty: an introduction. In: Globalization and poverty. Chicago: University of Chicago Press; 2007. p. 1–32. https://doi.org/10.7208/9780226318004-002.
136. Chilonda P, Machethe C, Minde I. Poverty, food security and agricultural trends in southern Africa. Regional strategic analysis and knowledge support system for southern Africa (ReSAKSS-SA) ReSAKSS working paper. 2007. http://www.sa.resakss.org/.
137. Jones N, Bailey M, Lyytikainen M. Research capacity strengthening in Africa: trends, gaps and opportunities-appendices. 2007. https://scholar.google.com/scholar?cluster=16047851251791861607&hl=en&as_sdt=0,5.
138. Muromo F, Matunhu J, Madanzi T, Manjeru P, Isaac I. Market linkages: a way of sustaining the production of amaranth in Manjolo and Sikalenge Wards of Binga District of Matabeleland North Zimbabwe. World. 2021;9:37–41. https://doi.org/10.12691/wjar-9-1-6.
139. Maseko I, Mabhaudhi T, Tesfay S, Ncube B, Chimonyo V, Araya H, et al. Productivity of selected African leafy vegetables to varying water regimes. Rain-shelter conditions. Pre-and post-harvest response of selected indigenous leafy vegetables to water stress; 2019. p. 76. https://doi.org/10.1016/j.agwat.2018.06.012.
140. Mekonnen G, Woldesenbet M, Teshale T, Biru T. *Amaranthus caudatus* production and nutrition contents for food security and healthy living in Menit Shasha, Menit Goldya and Maji Districts of Bench Maji Zone, South Western Ethiopia. Nutr Food Sci Int J. 2018;7:23–30.
141. Newton J, Patterson L. Maine grown world crops specialty produce marketing plan. https://www.ceimaine.org/wp-content/uploads/2017/01/Appendix-4-Marketing-Plan.pdf.
142. Gao Y, Janes ME, Chaiya B, Brennan MA, Brennan CS, Prinyawiwatkul W. Gluten-free bakery and pasta products: prevalence and quality improvement. Int J Food Sci Technol. 2018;53:19–32. https://doi.org/10.1111/ijfs.13505.
143. Bvenura C, Kambizi L. Future grain crops. In: Future foods. London: Elsevier; 2022. p. 81–105. https://doi.org/10.1016/B978-0-323-91001-9.00032-3.
144. Gordon A. Exporting traditional fruits and vegetables to the united states: trade, food science, and sanitary and phytosanitary/technical barriers to trade considerations. In: Food safety and quality systems in developing countries. London: Elsevier; 2015. p. 1–15. https://doi.org/10.1016/B978-0-12-801227-7.00001-9.
145. Ainebyona R, Mugisha J, Kwikiriza N, Nakimbugwe D, Masinde D, Nyankanga RO. Economic evaluation of grain amaranth production in Kamuli district, Uganda. J Agric Sci Technol A. 2012;2:178.
146. Lotter D, Marshall M, Weller S, Mugisha A. African indigenous and traditional vegetables in Tanzania: production, post-harvest management, and marketing. Afr Crop Sci J. 2014;22:181–90.
147. Filho AMM, Pirozi MR, Borges JTDS, PinheiroSantAna HM, Chaves JBP, Coimbra JSDR. Quinoa: nutritional, functional, and antinutritional aspects. Crit Rev Food Sci Nutr. 2017;57:1618–30. https://doi.org/10.1080/10408398.2014.100181.