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From humble beginnings to nutritional powerhouse: the rise of amaranth as a climate-resilient superfood

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Abstract

The present review article explores the multifaceted journey of amaranth, a once humble crop that is rising to prominence as a nutritional powerhouse and climate-resilient superfood. It delves into the nutritional marvels of amaranth, highlighting its triumph over other crops and its unique health benefits, including fortifying health defences and offering gluten-free alternatives. The resilience of amaranth in the face of climate challenges is emphasized, showcasing its ability to thrive in adversity, defy soil adversities, fuel soil vitality, and act as a pest-proof champion. The article also underscores the rising importance of amaranth in global food security, addressing malnutrition, and promising enhanced yields. The review further explores the innovative adventures and opportunities in amaranth cultivation, including revolutionary breeding techniques, genomic advancements, mechanization, and market potential. The call to action emphasizes the need to embrace the extraordinary potential of amaranth, ignite a revolution in its cultivation, integrate it into culinary practices, and chart future research frontiers. The review concludes by unmasking challenges and outlining implications for future research and policy, solidifying amaranth's position as a vital component in transforming food systems, and ensuring food and nutritional security.

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Introduction

The intensification of modern agricultural practices has led to a decline in the nutritional value of staple grains and increased their vulnerability to pests, posing significant challenges to global food security. Amidst this crisis, alternative crops like amaranth offer promising solutions. Despite its moniker as the 'poor man's crop', amaranth stands out for its resilience and versatility. It thrives in poor soils, endures extreme climatic conditions, and resists pests, making it a sustainable and economically viable crop for resource-constrained farmers[1].

Nutritionally, amaranth is exceptional. It is rich in protein, fiber, essential minerals (calcium, magnesium, potassium, and phosphorus), and vitamins A, C, and E. It is a complete protein with all necessary amino acids, particularly lysine, distinguishing it from other cereals[2]. Such nutrient density makes amaranth an affordable and valuable food source, particularly for populations facing protein-energy malnutrition and micronutrient deficiencies.

Historically, amaranth has been a dietary staple for ancient civilizations like the Aztecs, Mayans, and Incas, cultivated since at least 4000 BC in Latin America[3]. It was domesticated independently in Mesoamerica and the Andes, resulting in diverse landraces and uses today[4].

Although global trade statistics for amaranth are limited, significant production occurs in countries like Mexico, Argentina, Bolivia, Peru, the United States, India, China, and various African nations[5]. In India, amaranth cultivation is expanding, particularly in regions facing water scarcity, such as Gujarat[6]. Several improved varieties, such as GA-1, GA-2, Suvarna, and PRA series, have been developed, enhancing yield, and adaptability[7].

Amaranth outperforms traditional staple crops like maize and wheat in poor soil conditions and water use efficiency due to its C4 photosynthetic pathway, extensive root system, and pest resistance[8]. Its genetic diversity offers further opportunities for breeding varieties suited to climate change-induced stressors[9].

Despite these advantages, amaranth remains underutilized due to a lack of awareness, improved varieties, and market development. Addressing these gaps through breeding, optimized cultivation practices and consumer education could promote its wider adoption. This review aims to provide a comprehensive analysis of amaranth's potential as a climate-resilient superfood, exploring its historical significance, nutritional benefits, and role in sustainable agriculture. This article delves into innovative cultivation techniques and breeding advancements, positioning amaranth as a pivotal crop for addressing global food security challenges in the face of climate change.

The review aims to illuminate the following fields of research:

• Amaranth's role as a climate-resilient and nutritious crop.

• Its nutritional profile and adaptability to harsh environments.

• Health benefits and contributions to sustainable agriculture.

• Ongoing breeding efforts for improved varieties.

Harnessing the health benefits of amaranth

Amaranth offers several health benefits due to its rich nutritional profile. It is a good source of essential vitamins, minerals, and antioxidants that support overall well-being. Amaranth is an excellent addition to a healthy diet because it may aid digestion, strengthen the immune system, and reduce the risk of developing chronic diseases (Fig. 1).

Fortifying health defenses

Amaranth, an ancient grain with a rich history, boasts a remarkable nutritional profile that contributes to its potential health benefits. The seeds and leaves of amaranth are packed with essential nutrients, including high-quality proteins containing all essential amino acids, particularly lysine, often deficient in other cereals[10]. The abundance of protein, coupled with a rich array of vitamins, minerals, and dietary fiber, sets amaranth apart from many other grains, promoting overall well-being and potentially reducing the risk of chronic diseases like cardiovascular disease, type 2 diabetes, and obesity[11].

Beyond its exceptional nutritional value, amaranth also contains an impressive array of bioactive compounds, including betalains, carotenoids, and flavonoids, which contribute to its vibrant pigmentation and potent antioxidant properties[12]. These compounds have been linked to various health benefits, including anti-inflammatory and anticancer activities[12,13]. Amaranth's high mineral content, particularly calcium, iron, and zinc, further enhances its nutritional value and potential health benefits.

Recent research has shed light on amaranth's potential role in metabolic health. Studies suggest that amaranth may help low density lipoproteins (LDL) or bad cholestrol and total cholesterol levels[14]. Additionally, evidence suggests that amaranth could positively influence blood sugar and insulin levels[15]. A study involving Mexican patients with poorly controlled diabetes demonstrated that amaranth consumption led to weight and BMI reduction in obese patients, along with decreased serum markers for obesity and cardiovascular risk[16]. These potential benefits are likely attributed to the synergistic action of fiber, antioxidants, and other beneficial plant compounds present in amaranth[17].

Compared to other grains, amaranth stands out as a nutritional powerhouse. It surpasses quinoa in protein, iron, and calcium content per serving, and significantly outperforms rice in protein, fiber, and most micronutrients. For individuals with gluten sensitivities, amaranth offers a valuable alternative to wheat, often providing a higher fiber concentration and specific nutrients.

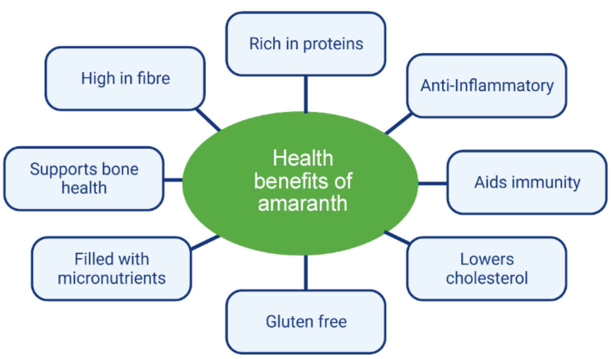

Fig. 1 Health benefits of amaranth.

A gluten-free alternative

Celiac disease and non-celiac gluten sensitivity have recently increased the demand for gluten-free alternatives. Amaranth emerges as a promising option due to its nutritional profile and absence of gluten. Amaranth's gluten-free status benefits people with celiac disease, an autoimmune illness caused by gluten, a protein complex found in wheat, barley, and rye[18]. Unlike these grains, amaranth does not contain gluten, making it a safe and nutritious food choice for individuals with celiac disease. One of the significant advantages of amaranth as a gluten-free alternative is its high protein content. The protein content in amaranth is higher than that of many other grains. It also provides a complete protein profile, including the essential amino acid lysine, usually deficient in many cereals. A study of 1,309 amaranth accessions found a total protein (7.84%−18.01%) and essential amino acids such as lysine (0.66−11.12 g/16 g N), methionine (0.35−4.80 g/16 N), and half cystine (0.12−8.32 g/16 N)[19]. Amaranth also contains high levels of dietary fiber, associated with multiple health benefits, including improved digestion, blood glucose control, and cardiovascular health[20]. Including high-fiber foods like amaranth in a gluten-free diet can help alleviate common nutritional deficiencies associated with this diet.

Moreover, amaranth is rich in essential micronutrients, such as iron, calcium, and magnesium, often lacking in conventional gluten-free products[19]. Furthermore, the textural properties of amaranth may pose challenges in gluten-free baking. Gluten plays a crucial role in providing elasticity and volume to baked goods, qualities that are difficult to replicate with gluten-free grains. More research is needed to improve the textural properties of amaranth-based gluten-free products.

Amaranth's resilience to climate change

Amaranth offers a compelling solution to the agricultural challenges posed by climate change. It thrives in diverse climates and soil types, including water-scarce regions, marginal lands, and areas facing extreme temperatures. Amaranth's deep root system, efficient water use, heat tolerance, and short growing cycle ensure reliable yields even in unpredictable conditions, making it a valuable asset for sustainable food production.

This exceptional adaptability allows amaranth to address specific challenges exacerbated by climate change. In drought-prone regions, amaranth's water-saving mechanisms and deep roots support its cultivation[21]. It also withstands heat stress and exhibits remarkable salt tolerance, enabling farmers in coastal areas to grow amaranth successfully despite rising sea levels[22]. Moreover, amaranth grows in low-fertility and marginal soils, expanding its potential for cultivation in challenging environments.

Beyond its resilience, amaranth contributes to climate change mitigation through carbon sequestration (Fig. 2) and improved soil health. Its rapid growth cycle offers additional benefits for farmers.

While amaranth holds significant potential, continued research and development are needed to realize its benefits fully. These measures include genetic improvement and establishing standardized agronomic practices[19,23]. Investing in amaranth can build more resilient and sustainable agricultural systems in a changing world.

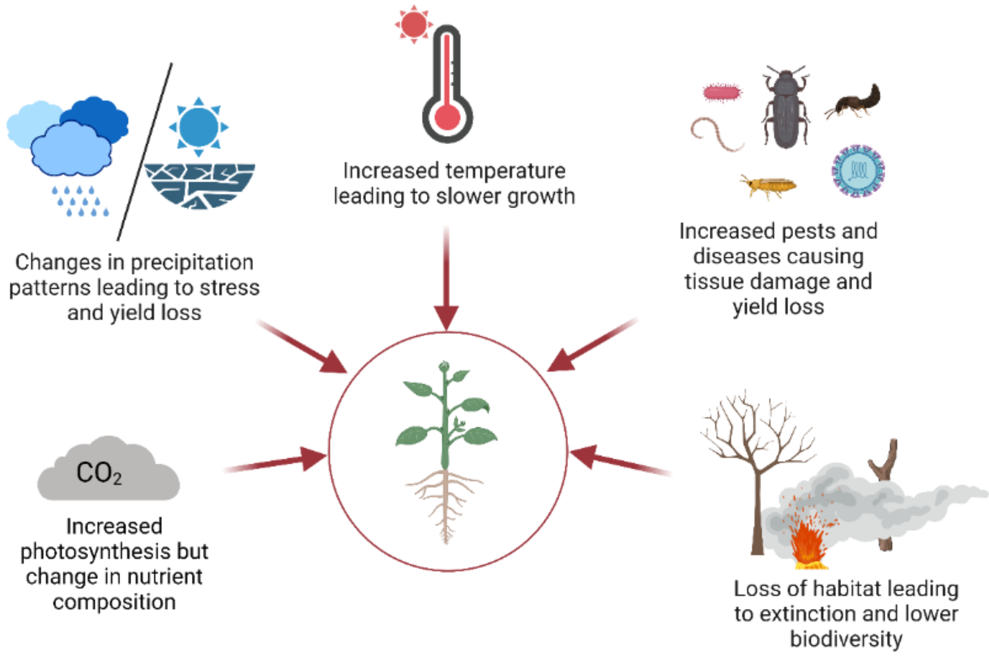

Fig. 2 Effect of climate change on plants.

The soil and water alchemist that defies soil adversities

Water scarcity, exacerbated by climate change, represents one of the most significant global challenges to sustainable agricultural development. As such, there is a critical need for agrarian systems to improve water use efficiency, a measure of how effectively a plant uses water for growth and productivity. The genus *Amaranthus* provides a fascinating study area in this context due to its inherent water-use efficiency. Amaranth species demonstrate a significant degree of tolerance to drought conditions, primarily due to their efficient water use (Fig. 3). This attribute makes them appropriate for farming in water-scarce deserts and semiarid climates.

A key factor contributing to amaranth's high water use efficiency is its C4 photosynthetic pathway. The C4 pathway, characterized by the initial fixation of CO_2 into a four-carbon compound, is known to be more efficient than the C3 pathway under conditions of water scarcity, high temperatures, and high light intensity, as it allows for higher rates of photosynthesis with lower water loss through transpiration[24]. The feature confers a distinct advantage on amaranth in the face of climate change-induced alterations in precipitation patterns. Moreover, the extensive root system of amaranth species allows for efficient water uptake, even from dry soils[24], which is particularly beneficial in arid regions, where access to deep soil water reserves is crucial for plant survival. Amaranth species also demonstrate adaptive morphological features that enhance their water use efficiency (WUE). These include small, narrow leaves and the presence of a thick cuticle, which reduce water loss through transpiration[25]. The genetic diversity within the amaranth genus further contributes to its WUE. The wide genetic variation provides opportunities for selecting and breeding amaranth varieties that are particularly efficient in water use[9].

Amaranth species demonstrate a remarkable ability to adapt to various soil conditions, including poor soil quality, making them ideal candidates for cultivation in degraded lands. The ability of amaranth to grow in soils with low fertility is primarily attributed to their extensive root system, which allows for the effective exploration of soil resources[26]. The C4 metabolism of amaranth allows it to thrive in nitrogen-poor soils.

Furthermore, studies have shown that *A. hypochondriacus* exhibits a high tolerance to aluminum toxicity, a common issue in acidic soils[27]. The grain amaranth plant displays a unique tolerance to aluminum (Al) toxicity, elucidated by its unique secretion of organic acids (OAs) from its roots in response to Al stress. The OAs secreted include both oxalate and citrate. The dual secretion is noteworthy as some plant species secrete only a single type of OA under Al stress. The secretion pattern of these two acids are different. Oxalate secretion starts immediately after the onset of Al stress (pattern I response), whereas citrate secretion gradually increases over time, indicating a pattern II response. The study suggests that oxalate is crucial in neutralizing Al toxicity at the early stages. Notably, the secretion of OAs is specific to Al stress and is not stimulated by other metals[27]. Investigating amaranth's physiological and biochemical processes is crucial for understanding how the plant adapts to poor soil quality. Studies suggest that the capacity of amaranth to grow in nutrient-deficient soils can be attributed to its efficient nutrient uptake mechanisms and ability to form symbiotic relationships with beneficial soil microbes[28].

Additionally, some species of amaranth have developed the ability to synthesize and accumulate compatible solutes that help the plant adjust osmotically under nutrient-stress conditions. These solutes, such as proline and glycine betaine, protect cellular structures and stabilize the enzymes under stress conditions[29].

Amaranth's value extends beyond its ability to thrive in poor conditions. Species like *Amaranthus mangostanus* L. increase soil organic carbon (SOC), a critical factor in fertility[30]. Higher SOC improves soil quality, benefiting from better aeration, water infiltration, and a thriving microbial community that

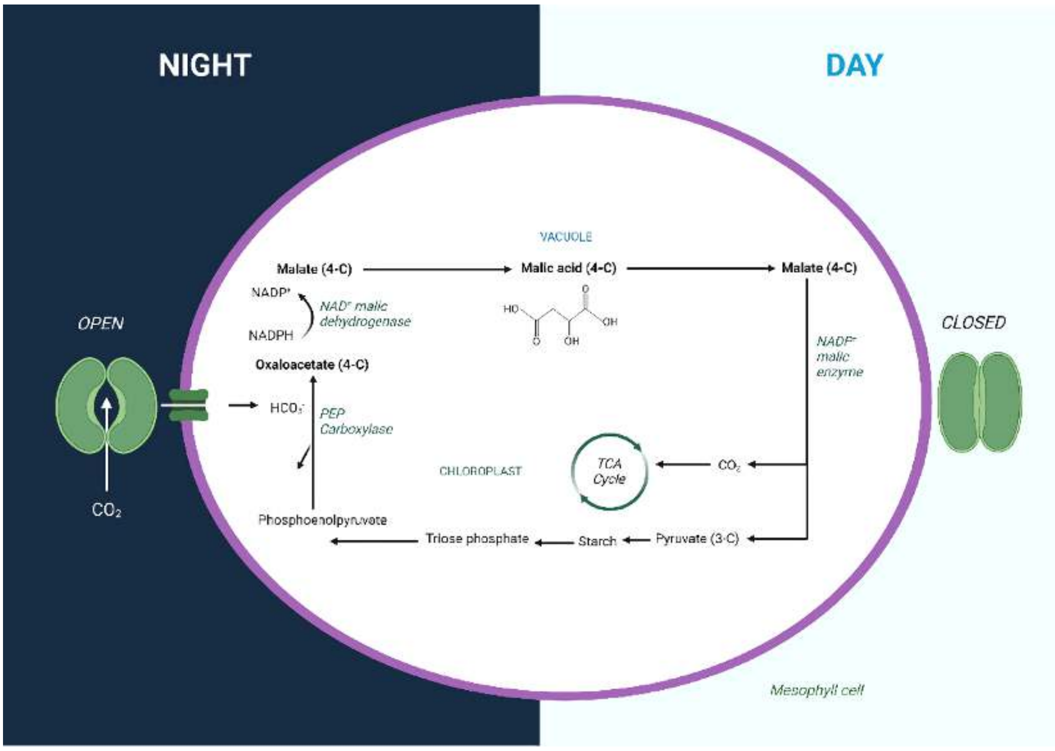

Fig. 3 Water use efficiency of amaranth.

breaks down organic matter into humus, a stable form of carbon[31]. This effect reduces reliance on synthetic fertilizers and increases carbon sequestration, mitigating climate change. Amaranth's deep taproot system and abundant biomass further enhance these benefits[31]. The advantages extend beyond SOC, with research noting improved soil biological activity and favoring beneficial fungi linked to better soil structure and carbon storage[32]. Research also suggests amaranth can form associations with beneficial nitrogen-fixing bacteria like *Azospirillum*, reducing reliance on synthetic nitrogen fertilizers and increasing soil nitrogen, a key component of organic matter[33]. Additionally, as a cover crop, amaranth suppresses weeds, prevents soil erosion, and protects topsoil, all contributing to a thriving soil ecosystem likely to see gains in organic matter over time[34].

In drought-prone regions of India, farmers have successfully used amaranth to enhance soil fertility while taking advantage of the crop's drought tolerance[32]. Several factors influence the rate of organic carbon accumulation, including soil type, climate, and farm management practices. Building soil organic carbon is a long-term process, and amaranth's benefits are most pronounced when used consistently in rotations or as a component of a farming system that prioritizes soil health.

A pest-proof champion

Pest infestations pose a significant threat to global crop production, a problem exacerbated by climate change, which is expected to increase pest populations. Amaranth has shown considerable pest resistance, making it a promising crop for regions with high pest pressure. This resistance is attributed to secondary metabolites such as phenolic compounds and saponins, which deter pests and protect against pathogens[35]. Additionally, physical traits like trichomes hinder insect pests. Genetic variation within the amaranth genus allows for the selection and breeding of pest-resistant varieties[36]. Amaranth's rapid growth and prolific seed production also enable it to withstand and recover from pest damage effectively[37].

Achieving agricultural sustainability

Amaranth has shown remarkable resilience to poor soil conditions, distinguishing it as a candidate crop for areas where soil fertility is compromised. The plant's inherent ability to tolerate poor soils can be attributed to several factors, including its efficient nutrient uptake and utilization mechanisms and robust root system. One of the vital aspects of amaranth soil tolerance is its phosphorus uptake efficiency of 30 kg P/ha[38]. Plants need the macronutrient phosphorus. However, it is typically in short supply in different types of soil. Amaranth has demonstrated a superior ability to extract phosphorus from the soil, particularly from low-phosphorus soils, compared to other staple crops[39]. Such ability is partially due to its extensive root system, which allows for more extensive soil exploration and nutrient uptake.

Furthermore, amaranth species possess a remarkable ability to thrive in soils with high salinity levels. Salt stress is a significant issue, especially in arid and semi-arid regions, reducing crop productivity. However, studies have shown that some amaranth species can tolerate high salinity levels, suggesting a potential for their use in salt-affected soils[1]. More research is needed to determine how exactly amaranth achieves its salt tolerance. An experiment reported increased water use efficiency with increasing salinity levels ranging from 3.9 g in *A. tricolour* to 6.7 g dry mass in *A. cruentus* per kg water. Specific leaf area decreased with salinity[40]. Amaranth also displays a notable ability to tolerate heavy metal-contaminated soils.

Heavy metal contamination is a growing concern due to increased industrial activities and the use of contaminated irrigation water. Some amaranth species have been found to accrue significant quantities of heavy metals in their tissues, suggesting their potential application in the phytoremediation of contaminated soils[41]. Nonetheless, the effects of heavy metal accumulations on persons must be thoroughly studied.

Agronomic practices can further enhance amaranth's soil tolerance. For example, applying organic amendments, such as compost or manure, can improve soil fertility and enhance the growth and productivity of amaranth[42]. Moreover, conservation tillage practices can help maintain soil structure and enhance water retention, supporting amaranth growth in poor soils.

While the soil tolerance of amaranth is well-documented, further research is needed to fully understand the underlying mechanisms and exploit the trait for crop improvement. Specifically, more research is needed on the plant's molecular and physiological responses to poor soil conditions, which could involve studies on the role of root architecture, nutrient uptake mechanisms, and stress response pathways in soil tolerance. Moreover, breeding programs could aim to develop improved amaranth varieties with enhanced soil tolerance traits, which could be achieved through conventional breeding methods or modern biotechnological tools, such as genetic engineering or marker-assisted selection.

A solution to global food security

Amaranth is increasingly recognized for its potential to address global food security challenges. With its high protein content and ability to thrive in diverse environments, amaranth offers a sustainable solution for feeding a growing population. Its resistance to climate change and culinary versatility make it a valuable crop that has the potential to contribute substantially to global food security efforts.

Combating malnutrition

Amaranth offers a wide range of vitamins and minerals, including vitamins C and E, folate, calcium, iron, magnesium, and zinc[2]. With a protein content ranging from 15% to 18%, amaranth surpasses most traditional cereals and provides a well-balanced amino acid profile, particularly rich in lysine, an essential amino acid typically deficient in other grains[43]. This high-quality protein, combined with the grain's digestibility makes amaranth a valuable plant-based protein source[2].

Amaranth is also rich in dietary fiber, providing approximately 7 g per 100 g serving, which supports gut health and may help prevent chronic diseases[44]. It is abundant in phytonutrients like phenolic compounds, squalene, and tocotrienols, which have antioxidant, anti-inflammatory, and anti-cancer properties[45].

Amaranth seeds have a balanced distribution and high bioavailability of amino acids, and cooking can increase the bioavailability of its antioxidants[46]. However, the bioavailability of calcium in amaranth may be hindered by oxalates, while minerals like magnesium, zinc, and manganese are more readily absorbed[47]. To maximize nutrient absorption, methods such as soaking, sprouting, or fermenting should be used, and pairing amaranth with vitamin C-rich foods can enhance iron absorption[48].

According to the USDA Nutrient Database, amaranth grain has a low moisture content (11.29%) compared to other grains and is a good source of protein (13.56%), carbohydrates (65.25%), lipids (7.2%), and fiber (6.7%). It contains essential minerals like iron, zinc, magnesium, manganese, potassium, and calcium, providing 371 calories per 100 g[49].

The concept of Recommended Dietary Allowance (RDA) is crucial in nutrition science, providing guidelines on essential nutrients needed for good health. Amaranth grain offers significant energy, contributing to dietary needs, but the bioavailability of its nutrients can be influenced by compounds like phytates and oxalates that bind to minerals, reducing their absorption[50]. Processing techniques such as soaking, sprouting, and fermenting can reduce anti-nutrient levels, enhancing mineral bioavailability[50]. Additionally, combining amaranth with vitamin C-rich foods boosts the absorption of non-heme iron[51].

Amaranth has proven effective in addressing malnutrition. An Integral Nutritional Recovery Program (INRP) using amaranth flour showed significant improvements in children's weight/height, muscle mass, and fat mass[52]. Studies in Uganda and Kenya have demonstrated that incorporating grain amaranth into local diets can significantly enhance nutrient intake and improve child nutrition[53,54]. Community-based projects in rural Uganda focusing on cultivating amaranth have positively impacted children's growth and micronutrient status[55].

Amaranth also presents a cost-effective alternative to traditional therapeutic foods for severe malnutrition. Replacing milk powder with locally sourced amaranth can reduce production costs and increase accessibility[56]. In broader food security initiatives, the inclusion of amaranth in school food programs and public distribution networks in Karnataka, India, has enhanced the nutritional status of millions of children and the general public under the National Food Security Act of 2013[57].

Potential for food and nutritional security

Given its high nutritional value, resilience to harsh environmental conditions, and adaptability to poor soils, amaranth has immense potential to contribute to food and nutritional security, particularly in regions plagued by malnutrition and climate change-induced food shortages. Amaranth, due to its robust nutritional profile and adaptability to various environmental conditions holds immense potential to contribute significantly to global food and nutritional security. As previously mentioned, the crop's nutrient composition, including high-quality protein, essential amino acids, fiber, vitamins, and minerals, contributes to its reputation as a nutritious food source. Amaranth's grain protein content surpasses many cereals and pseudo-cereals, with a commendable balance of essential amino acids, particularly lysine, which is deficient in many grain crops[58]. Additionally, the leaves are a valuable source of vitamin C and carotenoids[59].

As stated earlier, the gluten-free grains of amaranth are an ideal food source for individuals with gluten intolerance or celiac disease[60]. One of the aspects enhancing the potential of amaranth for food and nutritional security is its adaptability. Amaranth can tolerate various environmental conditions, including drought and salinity, making it a suitable crop for areas affected by climate change. Moreover, amaranth's fast growth rate and high yield further reinforce its potential to contribute to food security. The crop's potential for multiple harvests within a growing season and its versatility in usage - as fresh vegetables, grains, or forage - offers an effective strategy to address food shortage challenges in vulnerable regions.

Potential for increased yields

The potential of amaranth as a resource-efficient crop with high nutritional value is well-recognized. However, there are still significant opportunities for improving yield and optimizing cultivation practices, which could further enhance the role of amaranth in global food security. The genetic diversity of amaranth, with over 60 recognized species, presents considerable opportunities for plant breeding and improvement. Conventional breeding methods and modern biotechnological approaches can be employed to develop high-yielding, disease-resistant varieties with superior nutritional profiles. For instance, there is potential for selecting and breeding amaranth varieties with higher protein content, improved protein quality, or increased levels of specific micronutrients. Developing varieties with enhanced resistance to pests and diseases could reduce the need for chemical inputs and promote more sustainable farming practices.

Advances in genomics and molecular breeding could further accelerate the genetic improvement of amaranth. High-throughput sequencing technologies may make finding genes and genetic markers linked to desired traits easier. They can be used in marker-assisted selection (MAS) or genetic engineering. For instance, a recent study identified several candidate genes associated with grain yield and quality in *A. cruentus*, which could be targeted in future breeding programs[1]. Regarding cultivation practices, research is needed to determine the optimal conditions for amaranth growth and productivity. Factors to be considered include planting density, irrigation regime, fertilization, and pest management. It is also crucial to adapt these practices to different agroecological conditions and farming systems, considering the wide adaptability of amaranth to diverse environments.

Given the tolerance of amaranth to poor soil conditions and variable climate, there is potential for expanding its cultivation in marginal lands or areas affected by climate change, which may require the development of suitable agronomic practices and farming systems. For instance, the research could explore the potential of amaranth in agroforestry systems, intercropping, or conservation agriculture, which could contribute to both productivity and sustainability.

Innovations in amaranth research and cultivation

Amaranth cultivation presents both challenges and opportunities for farmers and agricultural stakeholders. While the crop demonstrates resilience to adverse weather conditions and pests, its low market demand, and limited infrastructure for processing and distribution pose challenges. However, with increasing awareness of the grain's nutritional value and potential health benefits, coupled with investment in research and development, there is an opportunity to overcome these obstacles and promote sustainable amaranth cultivation for a more secure and diversified food system.

Some of the challenges of amaranth cultivation are discussed below.

Improving agronomic traits

Amaranth has been recognized as a promising crop for improving food security in arid regions. However, its wider adoption is hindered by several challenges related to yield improvement and agronomic practices. One major challenge in amaranth cultivation is the inconsistency in yields, primarily due to a lack of suitable varieties for diverse environments. Traditional landraces often fail to deliver stable, high yields under varying environmental conditions, discouraging farmers from adopting amaranth cultivation. Breeding programs should focus on creating amaranth cultivars with greater production stability in various settings to solve the problem. For instance, marker-assisted selection can expedite breeding by identifying genetic markers associated with yield-related traits[61]. Further, agronomic methods must be optimized for maximum output, including planting and harvesting at optimal times, fertilizing, and pest management. Another challenge relates to the high susceptibility of amaranth to various pests and diseases, which can significantly reduce crop yield[62]. Developing resistant varieties through genetic improvement is critical to overcoming the hurdle. Additionally, integrated pest management strategies incorporating biological control agents and botanical pesticides can reduce the dependence on synthetic pesticides, thus promoting sustainable amaranth cultivation[63].

In light of changing climate patterns and increasing global food demand, enhancing amaranth through genetic improvement and optimized agronomic practices has become a critical area of research. Genetic improvement of amaranth is underway through the following methods. Figure 4 shows the methods for genetic improvement of amaranth crops.

Revolution through conventional breeding

Genetic improvement is essential for enhancing amaranth's potential. Conventional breeding has successfully improved yield and adaptability, while biotechnological methods like CRISPR/Cas9 offers the potential for rapid, targeted improvements in yield and stress tolerance. Alongside genetics, agricultural practices greatly influence amaranth productivity. Crop rotation (particularly with legumes), intercropping, and balanced fertilization all plays a significant role. However, challenges like limited genomic knowledge and a lack of standardized agronomic practices hinder progress.

Amaranth's inherent drought tolerance makes it an excellent candidate for cultivation in marginal lands[1]. Developing tailored agronomic practices, including efficient irrigation and soil management will be crucial to capitalize on this trait and enhance food security in water-scarce regions.

Historically, amaranth breeding has emphasized grain varieties. Less attention has been given to developing vegetable amaranth, particularly species like *A. cruentus*, *A. dubius*, *A. caudatus*, and *A. hypochondriacus*, specifically in East Africa[64]. The increasing demand for dual-use amaranth cultivars necessitates collaboration with smallholder farmers to develop varieties that allow multiple leaf harvests followed by a final grain harvest. Expanding breeding efforts nationwide would increase their availability. While progress has been made in enhancing growth rate, taste, nutritional quality of leaves, and resilience, a broader approach encompassing the diverse range of amaranth species is needed to meet global market demands thoroughly.

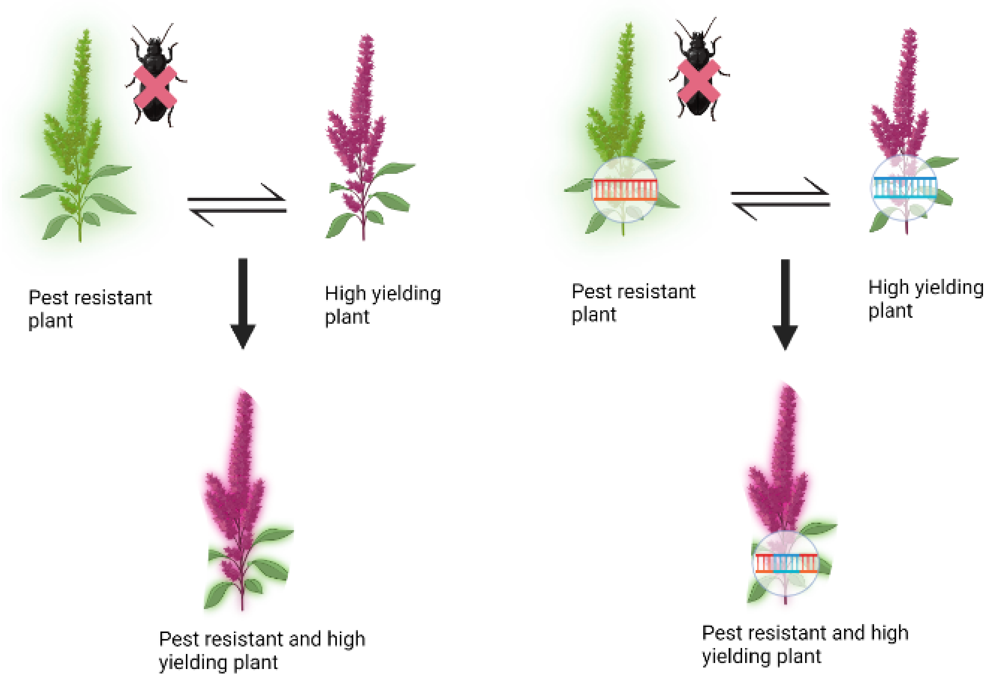

Fig. 4 Amaranth crop improvement through, (a) breeding, and (b) genetic engineering.

Transforming possibilities: agrobacterium-mediated advancements

Amaranth is an economically significant crop renowned for its high nutritional value and resilience to harsh environments, holds promise for future crop improvement programs. However, inherent challenges, such as genotype-dependent response, insufficient selectivity markers, and low transformation efficiency, have made amaranth genetic transformation less straightforward than in model plants. To counter these challenges, *Agrobacterium*-mediated transformation, a technique praised for its precise and consistent DNA transfer ability, has been employed extensively in plant genetic engineering. One research study used *Agrobacterium tumefaciens* strains EHA 105 and LBA 4404 to focus on transforming *A. tricolor* L. The research optimized various transformation factors, leading to a significant yield of transformed shoots. The subsequent generations of the plant confirmed the robustness of transformation, which exhibited Mendelian inheritance patterns for kanamycin resistance, a direct result of the integrated transgene[65]. In another study, *A. rhizogenes* was used to transform *A. tricolor*, underscoring the influence of factors such as bacterial suspensions and explant sources on the transformation rate. The study led to a high incidence of hairy root emergence and showed that these transformed roots could regenerate shoots[66].

Furthermore, in the case of *A. spinosus* L., the inoculation with various strains *of A. rhizogenes* led to *in vitro* rhizogenesis. The research confirmed the presence of the rolB gene and demonstrated the production of characteristic opines, offering the potential for pharmaceutical use and crop protection[65]. Moreover, a comprehensive study shed light on the potential of modern genetic engineering techniques to enhance various amaranth species[67]. The research was committed to examining the regeneration and genetic transformation across multiple species and varieties. Another research targeted the development of a protocol for root genetic transformation in grain amaranthus species and their supposed ancestor, *A. hybridus*. The study concluded that the transformation efficiency was species-dependent and identified an optimal protocol for producing embryogenic calli from transformed roots. The work also proposed a solution to the genetic transformation recalcitrance typically observed in grain amaranth[68]. A separate study targeted developing an amaranth transformation system *via Agrobacterium*-mediated transformation. The research successfully introduced the genes encoding neomycin phosphotransferase type II (NPTII) and β-glucuronidase (GUS) into mature embryo explants with a disarmed *Agrobacterium* strain containing the plasmid pGV2260(pEsc4). Southern blot hybridization confirmed the presence of the transgenes in the genome of transformed amaranth plants and their progeny. The study also demonstrated tissue-specific and light-inducible expression of the introduced genes, driven by a pea chlorophyll a/b-binding protein promoter (AB80). These findings offer invaluable insights into the genetic transformation and expression regulation in *A. hypochondriacus*, potentially contributing to its use as an alternative crop and a model system for studying photosynthetic pathways and their interactions[69].

Tapping miRNA magic in amaranth varietal development

MicroRNAs (miRNAs) are a class of small, non-coding RNA molecules, about 20–24 nucleotides long, which play crucial roles in post-transcriptional gene regulation. They have been implicated in various biological processes, including plant development, stress response, and disease resistance making them an exciting area of research in crop improvement[70].

In amaranth, miRNAs could be leveraged to develop new varieties with enhanced traits, such as improved nutritional content, higher yield, or increased resilience to environmental stressors. A study on amaranth identified miRNAs potentially involved in responding to various types of stress, such as cold, heat, and drought. For example, miR159 played an essential role in regulating target genes in amaranth, while the combined function of miR397, miR398, and miR408 was found effective for oxidoreductase gene regulation. Additionally, miR0005 is an abundant and specific type of a large group of amaranth that could be crucial for regulating seed yield and tolerance towards environmental stresses caused by high temperatures[71]. Furthermore, understanding the role of miRNAs in amaranth's stress response mechanisms could be invaluable in breeding varieties resistant to climate change impacts. A group of miRNAs in amaranth were found to differentially expressed under heavy metal and drought conditions, suggesting their involvement in drought and heavy metal tolerance[72].

Unlocking potential with CRISPR-Cas9 technology

Amaranth, encompassing over 60 species of flowering plants flourishes across various habitats from tropical to temperate regions. It is lauded for its impressive nutritional profile, being a rich source of proteins, vitamins, minerals, dietary fibers, and health-beneficial phytochemicals[73]. However, the cultivation of this valuable crop faces challenges such as susceptibility to various pests, diseases, and environmental stressors that can potentially cause significant yield losses.

Herein, the application of gene-editing technology, particularly CRISPR-Cas9, promises to redefine the cultivation of amaranth. CRISPR-Cas9 can precisely target and modify genes to boost disease resistance, increase yield, and enhance the crop's nutritional content. The technology is not foreign to amaranth, but it presents real opportunities for its application. CRISPR-Cas9 has been employed in other crops, enhancing their yield and resistance by altering genes crucial for plant architecture, grain size, and disease resistance[74]. Such genetic targets also exist in amaranth, presenting opportunities for similar modifications.

Furthermore, research has unveiled several genes in amaranth associated with characteristics like grain size, plant height, and environmental stress resistance[75]. Through CRISPR-Cas9, these genes can be targeted and modified, thereby improving yield and possibly strengthening the crop's adaptability to climate change, a growing issue with implications for global food security. In addition to resistance and yield enhancement, CRISPR-Cas9 also holds promise in boosting the nutritional content of amaranth.

Despite these advancements in genetic technology, traditional agronomic practices still profoundly influence crop yield. Techniques such as crop rotation, intercropping, and judicious use of fertilizers significantly impacts amaranth yield. Research suggests CRISPR-Cas9 can align crops with specific agronomic practices to maximize their potential yield[75]. Genetic engineering can also enhance amaranth compatibility with certain companion crops within intercropping systems or increase its resilience to diverse soil types, enabling farmers to fully exploit the benefits associated with these agronomic practices without the inherent limitations of the crop. The CRISPR-Cas9 system has been applied to amaranth for various purposes, including disease resistance, herbicide tolerance, nutritional enhancement, and yield improvement[75].

Enhancing productivity through mechanization

The cultivation of amaranth presents unique difficulties regarding mechanization. Most amaranth production still relies on manual labor, and the small size of the plants and seeds makes mechanization difficult, which limits the crop's commercial viability. Given the relative novelty of amaranth as a commercial crop, machinery has been limited in development tailored to its specific needs.

The typical grain size of amaranth and its unique plant architecture introduces particular challenges for mechanized harvesting. Unlike cereal crops such as wheat or maize, where extensive machine harvesting is practiced, amaranth's small grain size and the scattered panicle arrangement make mechanical harvesting more complicated and less efficient[76]. Furthermore, amaranth plants are prone to lodging, causing the plant to lean or fall, further complicating mechanical harvesting. Also, the biological and morphological diversity among different amaranth species adds another complexity to developing universal mechanization techniques.

Amaranth cultivation's limited mechanization restricts its production's scalability, making it less competitive as a commodity crop. The situation increases production costs as labor-intensive practices, such as manual harvesting, are often required. Moreover, the lack of mechanization can influence post-harvest losses, as manual harvesting and processing usually lead to grain loss or damage. Such losses are critical in regions where amaranth could contribute significantly to food security. The mechanization of amaranth cultivation remains a challenging yet crucial aspect of the crop's commercial viability. It impacts production efficiency and cost-effectiveness and influences harvested grains' quality and quantity.

Future research should be geared toward developing efficient mechanization solutions for amaranth cultivation, which includes the design of machinery for planting, cultivation, and harvesting stages. Additionally, breeding programs should consider traits that facilitate mechanization, such as plant architecture that is more suitable for machine harvesting. By addressing these issues, we can enhance the potential for amaranth as a sustainable and profitable crop in modern agriculture.

Market potential and culinary integration

Captivating consumers

Despite its nutritional value and health benefits, amaranth faces both cultivation and consumer acceptance challenges. Limited consumer awareness is a major obstacle. Educational campaigns highlighting amaranth's benefits and convenient products like breakfast cereals and snack bars could increase its appeal. Amaranth's high protein and unique amino acid profile make it ideal for fortifying foods for vulnerable populations, while its bioactive compounds offer potential for health-promoting functional foods. Underdeveloped markets also hinder amaranth cultivation. Farmers lack established supply chains, discouraging production. Cooperative marketing groups and supportive policies could create reliable demand. Meeting international quality standards opens the door to global trade, especially as the demand for nutritious, sustainable foods grows. Value-added products like amaranth oil (with its squalene content) and nutraceuticals from leaf extracts offer further market opportunities as shown in Fig. 5.

Value-added products and market expansion

Amaranth grain can be utilized in a variety of food systems. Its uses include porridge, bread, pasta, and breakfast cereals. A healthful snack can also be made by popping the grain, like how popcorn is prepared. Gluten-free amaranth flour is a

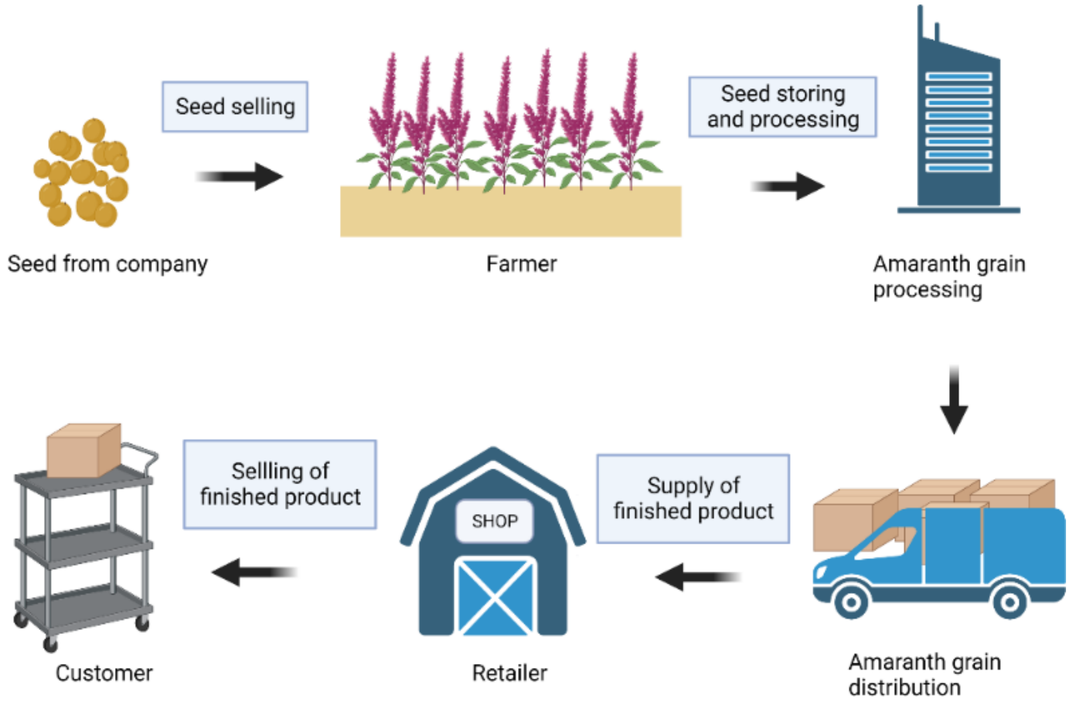

Fig. 5 Schematic representation of an ideal supply chain of amarnath.

suitable alternative for those with celiac disease or gluten intolerance.

Amaranth grains have a significant application in the bakery and confectionery sector. Gluten-free bread formulations incorporating amaranth flour have enhanced nutritional profiles and improved texture and sensory attributes compared to conventional bread. In addition to gluten-free applications, there is growing interest in the potential of amaranth grains as a functional food ingredient for the nutritional enrichment of food products with nutraceutical benefits. Another promising area is the utilization of amaranth in developing extruded food products. Amaranth grains in extrusion cooking systems have been found to enhance product quality and nutritional profiles while maintaining satisfactory sensory attributes. Extrusion of amaranth grains also results in resistant starches with health benefits such as blood glucose regulation and improved gut health[77]. However, with increasing research and development in processing technologies and consumer education, amaranth grains in food systems could be more widely realized, offering consumers a nutritious and sustainable food choice.

Culinary applications of amaranth

Amaranth has diverse culinary applications, enhancing both traditional and contemporary dishes worldwide. In its grain form, amaranth is a versatile ingredient. It can be cooked into a savory or sweet porridge, often combined with fruits, spices, nuts, vegetables, or cheese, making it a staple in regions such as Central and South America, India, and Africa. Additionally, it serves as a gluten-free substitute for polenta, providing a nutritious base for various dishes globally. Amaranth milk, created by combining the grains with other flours, is utilized in making dairy-free crackers.

Amaranth grains also find their place in pilafs and stir-fries, replacing rice or quinoa to add unique flavors and nutritional benefits, particularly in Asia and the Middle East. They can be used to make gluten-free and protein-rich falafel, vegetarian burger binders, and even creamy risotto, presenting a novel alternative to traditional risotto in Italy. In the Middle East, amaranth substitutes bulgur wheat in tabbouleh salad, creating a refreshing variation. In the Caribbean and India, amaranth is mixed with vegetables, spices, and herbs to make savory fritters and pakoras.

Fermented amaranth products are increasingly popular due to their probiotic, vitamin, and mineral content. Examples include fermented mashes, a health food staple worldwide, and traditional beverages like Chicha de Amaranto from the Andes, amaranth pozol from Mexico, and Kunu from Nigeria. Amaranth is also sautéed, stir-fried, or added to soups and stews globally, contributing its nutritional benefits to various dishes.

Amaranth flour is extensively used in gluten-free baking, either alone or blended with other flours, and serves as a thickener for soups and stews. It forms the base of gluten-free crackers and is used in desserts like amaranth pudding in India, flavored with cardamom, saffron, and nuts. Amaranth also enhances the nutritional profile of energy bars and gluten-free sourdough bread. Innovative applications include fermented milk drinks and lacto-fermented beverages, which are rich in probiotics and bioactive compounds. In Ethiopia, an amaranth-teff blend is used to make injera, a traditional flatbread.

The leaves of the amaranth plant are consumed raw in salads, providing texture and nutritional value, particularly in Asia, Africa, and the Caribbean[78]. The wide array of culinary applications underscores amaranth's versatility and global appeal as a nutritious food source.

Call to action: embracing the amaranth revolution

Amaranth's resilience and nutritional profile offers a promising solution for food security and malnutrition. However, to fully harness its potential, we must address key challenges and invest in targeted research.

Amaranth's water use efficiency, while promising, requires further exploration. We need to understand the mechanisms behind its efficient water uptake, how to optimize its C4 photosynthetic pathway under varying conditions, and the role of morphological features in minimizing water loss. Additionally, amaranth's genetic diversity presents opportunities for breeding water-efficient varieties, but identifying responsible genes is crucial.

Utilizing amaranth for malnutrition also poses challenges. Anti-nutritional factors can hinder nutrient bioavailability, but traditional processing methods offer mitigation. Research should focus on enhancing yield, mitigating anti-nutrient effects, increasing consumer acceptance, and developing educational initiatives around amaranth cultivation and utilization. While amaranth is a valuable gluten-free alternative, challenges like consumer unfamiliarity and distinct flavor need to be addressed. This may involve promoting mixed-grain products for wider acceptance. To maximize amaranth's potential, genetic improvement is key. Limited commercial varieties necessitate strategic breeding programs focused on yield, disease resistance, and nutritional value. Optimization of cultivation practices, including planting density, irrigation, nutrient management, and pest control, will further boost productivity.

Innovation in post-harvest processing and storage is crucial for efficiency and year-round availability. Research into amaranth's nutritional and health benefits, consumer preferences, and socio-economic factors will guide product development, pricing, and integration into food systems.

A collaborative, multidisciplinary approach involving farmers, consumers, and stakeholders is essential. This arrangement ensures research is relevant and impactful, ultimately leading to the most effective use of amaranth for food security and nutritional well-being.

Encouraging the heterozygosity

Amaranth, a highly diverse and heterozygous crop, presents significant challenges for breeding due to its genetic variation. This variation, while advantageous for adaptability and disease resistance, complicates efforts to maintain stable characteristics across generations. The crop's wind-pollinated nature exacerbates this issue by making it difficult to control the outcrossing rate, leading to high heterozygosity and variability in desired agronomic traits[36].

The plant's structural characteristics, such as highly branched nature, further contribute to yield variability. Additionally, the presence of chaff and variable seed sizes, influenced by their position on the plant, pose processing challenges and impacts the commercial viability of amaranth[79]. Despite its nutritional and agronomic potential, these issues hinder the crop's full domestication and commercial exploitation.

While the genetic diversity of amaranth offers the potential for significant genetic improvement, the lack of effective tools for controlled hybridization and a limited understanding of its molecular genetics remain substantial barriers. However, advances in genomic research, including whole-genome sequencing and marker-assisted selection, hold promise for addressing these challenges. These technological advancements could help harness amaranth's genetic diversity, leading to the development of stable, high-yielding, and climate-resilient varieties. This progress would significantly enhance the acceptance and utilization of amaranth as a nutritionally rich crop, thereby supporting its broader agricultural and commercial adoption.

Balancing weedy relatives and gene flow

Amaranth is closely related to several weedy species that can cross-pollinate and introduce unwanted traits, which poses a risk of crop-to-weed gene flow, complicating the development of genetically modified amaranth varieties. The phenomenon of gene flow, especially from the weedy relatives to the cultivated varieties of amaranth has significant implications on the agricultural and ecological aspects. The weedy relatives of cultivated amaranth species are persistent pests in agricultural lands, often presenting a formidable challenge to farmers. These weedy types, such as *A. retroflexus* and *A. palmeri*, have a growth habit similar to the cultivated types and can easily invade crop fields. Consequently, they compete for resources and may significantly reduce the yield[80]. The close genetic relationship between the weedy and cultivated species also enables interspecific hybridization, further exacerbating the problem.

Gene flow between cultivated amaranth and its weedy relatives poses another challenge. It is a two-way process where genes from the cultivated types can transfer to the weed types and vice versa. The resulting hybrid offspring can potentially exhibit enhanced weediness or invasiveness[81]. For instance, the herbicide resistance traits observed in some amaranth weed species are suspected to have originated from cultivated varieties[82]. Gene flow can also lead to genetic pollution of the cultivated amaranth, thereby reducing its quality. The loss of desirable traits or acquisition of undesirable traits from weedy relatives could impede efforts to improve amaranth cultivars. Additionally, the spread of transgenes from genetically modified amaranth into its weedy relatives could have far-reaching ecological impacts, with potential consequences for biodiversity.

Reducing anti-nutritional factors

Despite its rich nutritional profile, amaranth also contains antinutritional factors (ANFs) that could limit its potential as a sustainable food source. ANFs reduce the body's ability to absorb or utilize essential nutrients. In amaranth, these include oxalates, phytates, and specific proteins that can interfere with digestion. Oxalates in amaranth can bind to calcium and form insoluble crystals, potentially leading to kidney stones[83]. Phytates, conversely, can chelate essential minerals such as iron, zinc, and calcium, reducing their bioavailability[2]. Additionally, specific proteins in amaranth, such as amaranthine and amarantins, can inhibit the activity of digestive enzymes, thus impeding protein digestion[84].

Despite these challenges, several opportunities exist to mitigate these ANFs' effects and enhance amaranth's nutritional value. Traditional processing methods, such as soaking, germination, and fermentation, have effectively reduced the levels of ANFs[85]. For instance, germination activates endogenous enzymes that can degrade phytates, thus improving mineral bioavailability. Similarly, fermentation can produce organic acids that solubilize minerals bound by phytates[86].

In addition, recent advancements in food technology provide novel ways to address the antinutritional factors in amaranth. High-pressure processing, for instance, has been shown to reduce the levels of oxalates in food[87]. Moreover, applying enzymatic treatments using phytases and proteases can degrade phytates and denature antinutritional proteins, respectively[88]. Another approach to reducing ANFs in amaranth is through genetic improvement. For example, breeding programs could select varieties with lower ANF content or varieties in which the ANFs are more susceptible to degradation during processing[82]. Figure 6 shows the methods for the removal of antinutritional factors from amaranth.

Minimizing seed shattering for efficient harvesting

Amaranth naturally shatters its seed to disperse them. While the trait is suitable for a wild plant, it is a problem for farmers who can lose a significant portion of their crop before they can harvest it. Seed shattering represents one of the most considerable challenges in amaranth cultivation. The phenomenon occurs when mature seeds detach from the parent plant, which, while a natural survival mechanism in wild species, has significant implications for cultivated crops, leading to yield losses Amaranth species, particularly grain amaranth (*A. hypochondriacus*, *A. cruentus*, and *A. caudatus*), are notable for their tendency toward seed shattering. Seed loss depends on the variety, environmental conditions, and cultivation practices. The seed-shattering concerns have prompted the development of various strategies. One of the most promising steps is selective breeding, which aims to produce varieties that maintain seed adherence longer, thus reducing seed shattering[76]. However, the strategy has often come with trade-offs. For instance, improved adherence can sometimes increase susceptibility to disease or pests[89].

The genetic aspects of seed shattering are currently an area of intense research. A gene termed 'sh4', initially discovered in rice, has been shown to influence seed shattering significantly, and homologs of this gene have been identified in other species[90]. If similar genes could be identified in amaranth, it could open up new possibilities for genetic modification or selective breeding strategies.

Genome sequencing of amaranth species could provide the necessary insights for identifying these critical genes. Genomes of *A. caudatus*, *A. cruentus*, and *A. hypochondriacus*[91]; *A. tuberculatus*, *A. hybridus*, and *A. palmeri*[92] have been sequenced. However, the genes responsible for seed shattering are not definitively identified. Another promising avenue for addressing the seed-shattering issue is through agricultural practices. Timing of harvest, irrigation management, and usage of certain growth regulators can reduce seed loss due to shattering.

Economic viability and market potential of amaranth cultivation

Amaranth cultivation is economically viable due to its adaptability to various climatic conditions and low input requirements. Research indicates that amaranth can be grown successfully in marginal soils with minimal fertilizers and pesticides, significantly reducing production costs[93]. This resilience makes it particularly attractive for smallholder farmers in resource-constrained environments, where traditional crops may fail under adverse conditions. The cost-effectiveness of amaranth cultivation is further enhanced by its high-yield potential. Studies show that the total biomass yield of amaranth can range from 100 to 500 quintals per hectare, which is comparable to or even surpasses traditional cereals like maize and wheat[94].

Additionally, amaranth's short growing cycle—typically 4–5 months—allows for multiple harvests within a year, providing a steady income stream for farmers. This rapid turnaround time is particularly beneficial in regions with distinct growing seasons, enabling farmers to maximize land use and productivity. Moreover, the nutritional profile of amaranth enriched can

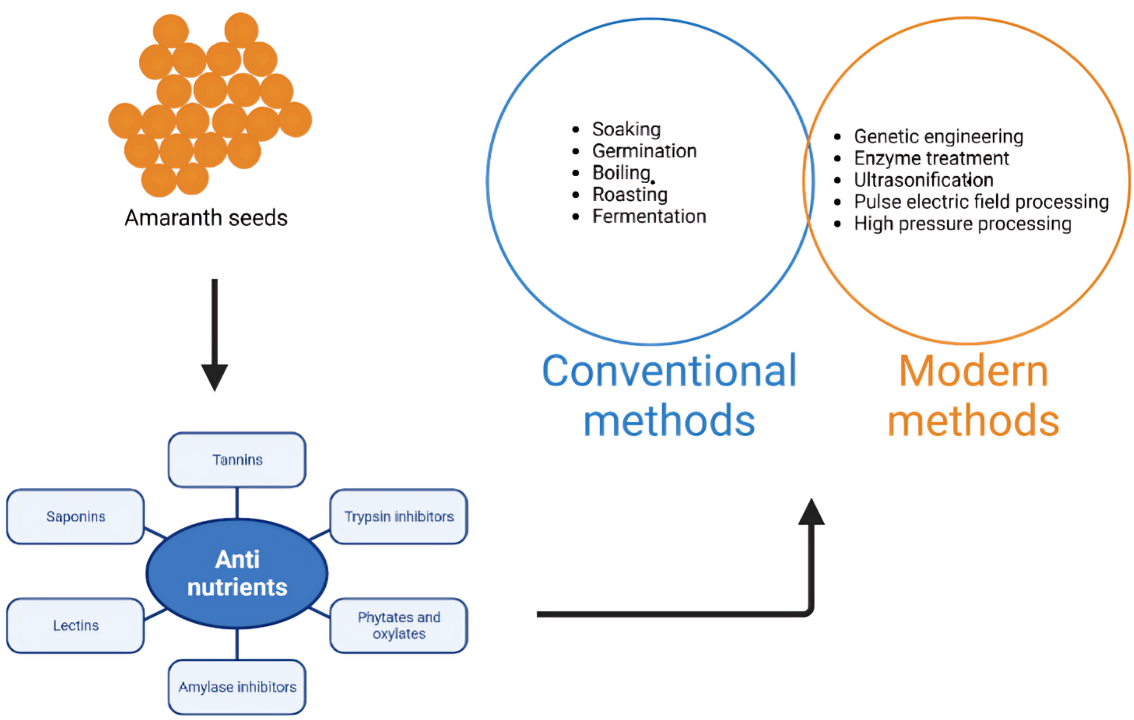

Fig. 6 Methods for removal of antinutrients from amaranth.

command higher market prices, further boosting its economic appeal.

The market potential for amaranth is substantial, driven by its nutritional benefits and increasing consumer demand for healthy and sustainable food sources. Amaranth's gluten-free nature makes it particularly popular in health-conscious markets and among individuals with gluten intolerance. The grain's superior amino acid profile, especially its high lysine content, positions it as a valuable ingredient in health foods and nutritional supplements. The global health food market, which is expanding rapidly, presents a significant opportunity for amaranth producers.

Furthermore, amaranth has shown promising potential in international markets. Countries such as Mexico, Argentina, and the United States are leading producers, with growing interest from African and Asian nations[5]. South Africa, for instance, has emerged as a major supplier of amaranth seeds to Europe, with exports increasing significantly in recent years[95]. This growing international demand underscores the crop's market viability and potential for generating foreign exchange earnings.

To capitalize on this market potential, strategic investments in value chain development, including processing and packaging facilities are crucial. Developing robust supply chains that ensure consistent quality and supply will help tap into lucrative export markets. Additionally, raising awareness about amaranth's health benefits and culinary versatility can drive domestic consumption, creating a stable demand base that supports local farmers and agribusinesses[96]. Promoting amaranth through targeted marketing campaigns and integrating it into national food security strategies can further enhance its market potential and economic impact.

Propelling amaranth's cultivation and utilization

Amaranth's nutritional value and adaptability make it a potent tool for enhancing food security and health. We need to expand its cultivation and utilization to realize its full potential. Developing improved amaranth varieties is crucial. Despite genetic diversity, commercial varieties often lack yield potential and disease resistance. Breeding programs can address this issue, creating high-yielding, disease-resistant, and locally adapted varieties[97]. International projects focus on varieties for drought-prone areas and smallholder farmers, highlighting amaranth's role in addressing food insecurity.

Alongside varietal development, agronomic research can optimize cultivation practices. Farmer training in all aspects of amaranth production and knowledge-sharing through extension services can empower growers.

We need streamlined post-harvest processing to boost utilization for consistent quality. Most importantly, newer product development from amaranth is crutial. New products like cereals, snacks, amaranth flour, or oil will broaden its appeal. Fortified foods could leverage amaranth's nutrients. Consumer awareness campaigns, sensory studies, and an understanding of market pricing are essential for widespread adoption. Policies incentivizing cultivation and integrating amaranth into public programs will create market demand and normalize this valuable crop.

Policy recommendations for amaranth cultivation

To maximize the potential of amaranth as a climate-resilient superfood, it is essential for policymakers to implement strategic measures that promote its cultivation, research, and market development. Firstly, national and regional agricultural policies should prioritize funding for amaranth research and development. This funding should support breeding programs aimed at enhancing yield, nutritional content, and stress resistance using advanced techniques like CRISPR-Cas9 and miRNA regulation[98]. Additionally, establishing research centers dedicated to study amaranth's agronomic traits and potential health benefits can drive innovations that improve cultivation practices and product quality.

Secondly, governments should incentivize farmers to adopt amaranth cultivation through subsidies, training programs, and access to quality seeds. Subsidies for purchasing seeds and inputs, as well as financial support for transitioning to amaranth from less resilient crops, can encourage adoption[99]. Training programs should educate farmers on best practices for growing amaranth, managing pests organically, and optimizing water use. Extension services can play a crucial role in disseminating this knowledge, ensuring that smallholder and resource-constrained farmers can benefit from the crop's resilience and nutritional advantages.

Furthermore, to develop a sustainable market for amaranth, policies should focus on enhancing market access and consumer awareness. Governments can facilitate the establishment of cooperatives and farmers' markets, providing platforms for small-scale producers to sell their products directly to consumers. Additionally, public awareness campaigns highlighting amaranth's nutritional benefits and culinary versatility can stimulate demand. Integrating amaranth into school feeding programs and public institutions can further promote its consumption. International trade policies should also be reformed to reduce tariffs and non-tariff barriers, fostering global trade and allowing producers from developing countries to access lucrative markets[5]. By adopting these comprehensive policy measures, governments can ensure that amaranth becomes a key component of sustainable and resilient food systems.

Conclusions

Amaranth is a highly nutritious and climate-resilient crop with significant potential to address global food and nutritional security, especially in the context of climate change. Its rich content of protein, vitamins, minerals, and fiber, along with its gluten-free nature makes it a valuable alternative for individuals with dietary restrictions. The crop's adaptability to poor soils, pest resistance, and efficient water use underscore its importance in sustainable agriculture. However, challenges such as yield improvement, genetic diversity management, limited mechanization and consumer awareness need to be addressed to fully harness amaranth's potential. Advances in plant breeding technologies offer promising solutions to these issues, but further research and policy efforts are crucial to ensure the successful integration of amaranth into global food systems.

Author contributions

The authors confirm contribution to the paper as follows: draft manuscript preparation: Yadav A; critical reviewing and revising: Yadav K. Both authors reviewed the results and approved the final version of the manuscript.

Data availability

All data synthesized and analyzed during this review are available within the article.

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Conflict of interest

The authors declare that they have no conflict of interest.

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