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Exploring the Potential of Amaranth in ensuring food and nutritional security

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Abstract

Amaranth, a pseudo-cereal, has gained prominence as a famine reserve crop due to its remarkable adaptability to harsh climatic conditions. This adaptability enables it to provide food and nutritional security in climate-vulnerable regions. Amaranth is a nutrient-dense food source, rich in protein, antioxidants, and low in glycemic index. These qualities make it an excellent choice for sustaining human health. Additionally, amaranth offers various health benefits, including anti-cancer properties, anti-helminthic effects, immune system regulation and regulation of cardiovascular health. Amidst the global challenges posed by food security, nutritional security, climate change, and agrarian sustainability, the adoption of climate-resilient and nutrient-rich crops is imperative. Amaranth's contributions to climate-resilient agriculture and nutritional enhancement are significant. The increasing poverty burden and nutritional insecurity among the impoverished necessitate the adoption of amaranth not only to address existing issues but also to promote crop diversification in vulnerable regions and attaining sustainable growth.

Keywords: Food security, nutritional security, famine reserves, climate resilient, pseudocereal

Introduction

Nutrient and food security have remained a persistent challenge for developing regions worldwide, despite the remarkable technological advancements achieved since the dawn of civilizations. Famines and food shortages have persisted as recurring societal issues. It is estimated that 27.7% of African regions, 7% of Asian regions, 1.2% of North American and European regions, and 6.4% of South American regions face difficulties in meeting their fundamental needs, particularly in terms of food access (FAO Report, 2019). To address this crisis, the United Nations introduced 17 Sustainable Developmental Goals (SDGs) in 2015, which came into effect on January 1, 2016. SDG 2 aims to establish a world devoid of hunger by 2030, while SDG 3 focuses on ensuring the well-being of all through access to nutritious food. A global assessment reveals that approximately 828 million individuals worldwide are affected by food insecurity, with varying levels of malnutrition ranging from chronic to acute (FAO Report, 2022). One of the dietary inefficiencies that remain unabated in rural homes are the invisible starvation and the direct consequences are the poor health of the population which gets reflected in poor economic outcome of the population (Yang *et al.*, 2024) ^[76]. Most of the upcoming nations' economies are pessimistic about the prospects of agriculture; under this scenario, the agriculture sector is under pressure to generate 70% of the food required to meet the growing population by 2050 or earlier. The global community must adopt a more structured and revised agricultural system. Stakeholders can mitigate food insecurity through crop diversification and the inclusion of underutilized, neglected, and climate-smart crops such as amaranth, teff (*Eragrostis tef*), quinoa (*Chenopodium quinoa*), and spider plant (*Cleome gynandra*) among others.

As the global population expands, the challenge of meeting food demands intensifies. A potential solution to this crisis lies in elevating the prominence of underutilized crops within the agricultural landscape. These crops possess not only nutritional value but also demonstrate enhanced resilience to biotic and abiotic stressors. Regrettably, the majority of global dietary requirements are currently met by a limited number of crops, leaving a significant gap in

ensuring adequate nutritional intake for the population. Underutilized crops encompass a diverse range of natural and cultivated flora species that lack substantial market acceptance (Kasolo *et al.*, 2018) [27]. As the global population expands, the challenge of meeting food demands intensifies. A potential solution to this crisis lies in elevating the prominence of underutilized crops within the agricultural landscape. These crops possess not only nutritional value but also demonstrate enhanced resilience to biotic and abiotic stressors. Regrettably, the majority of global dietary requirements are currently met by a limited number of crops, leaving a significant gap in ensuring adequate nutritional intake for the population. Underutilized crops encompass a diverse range of natural and cultivated flora species that lack substantial market acceptance (Kasolo *et al.*, 2018) [27]. They are often referred to as minor crops, promising crops, or orphan crops (Tyagi *et al.*, 2018) [68].

One of the underutilized and undervalued crop species is *Amaranthus* sp., a dicotyledonous pseudo-cereal originating in Mesoamerica. It is one of the New World's oldest crops. *Amaranthus* belongs to the Amaranthaceae family, and the word "amaranth" is derived from Greek, meaning "everlasting" or "unwithering." Traditionally, the crop has been utilized for food, fiber, oil production, and medicinal purposes. Historically, the amaranth held immense significance among the Inca, Maya, and Aztec civilizations. It was an integral part of their diet, alongside corn and beans. Based on human consumption, amaranth is classified into grain amaranth and vegetable amaranth (Mlakar *et al.*, 2010) [33]. However, the global patronage of *Amaranthus* began when US National Academy of Science carried out a research project Entitled Underexploited Tropical Plant with Promising Economic Value (National Academy Press, 1984) [40], and amaranth was selected among the 36 of world's most promising crops and identified as a major potential crop; since then, extensive studies are conducted to improve the nutritional and agronomic potential of the crop (Ulbricht *et al.*, 2009) [69]. *Amaranthus* having the ability to thrive in drought and stress condition including the ability to show resistance to biotic as well as abiotic stress has placed this crop in as a cultivated crop of immense importance. Therefore, shifting of production practices towards underused and orphan crop of amaranth can provide security in vulnerable regions with regards to nutrition and wholesome food.

Amaranth: A Profile

Amaranth, belonging to the genus *Amaranthus*, is a diverse group of plants known for their nutritional value and adaptability to various environmental conditions. This profile explores the botany and taxonomy of amaranth species, focusing on their classification, origin, distribution, and morphological and agronomic characteristics.

Botany and Taxonomy

Classification, Origin, and Distribution

The genus *Amaranthus* is divided into three subgenera: *Acnida*, *Albersia*, and *Amaranthus* (Mosyakin *et al.*, 1996) [34]. However, the scientific community considers taxonomic categorization within the *Amaranthus* genus to be a challenging endeavor due to the absence of clearly distinguishing traits. The widespread usage of synonyms has been attributed to similarities in the huge number of species, small, difficult-to-see diagnostic parts, intermediate (hybrid) forms, and extensive geographical distribution (Jacobsen *et al.*, 2003) [24]. Due to the requirement for micro classification or infrageneric classification, the *Amaranthus* genus has been artificially classified into the

following, primarily based on usages (Das., 2012) [12]:

- **Vegetable *Amaranthus*:** *Amaranthus tricolor* var. *tricolor*, *Amaranthus tricolor* var. *tristis* (Weerasekara and Waisundara., 2020) [74]
- **Grain *Amaranthus*:** *Amaranthus hypochondriacus*, *Amaranthus caudatus*, *Amaranthus cruentus* (Weerasekara and Waisundara., 2020) [74]
- **Weed *Amaranthus*:** *Amaranthus spinosus*, *Amaranthus viridis*, *Amaranthus retroflexus* (Weerasekara and Waisundara., 2020) [74].

Amaranthus species

Amaranthus has approximately 400 species (Rastogi and Shukla 2013) [50], with only a few now being cultivated. The overall number of species established to date has yet to be determined (Jacob *et al.*, 2003) [24]. The genus includes leafy vegetable amaranth, grain amaranth, decorative, and weedy amaranth. Alemayehu *et al.* (2015) [5] identified three main seed amaranth types: *A. caudatus* L., *A. hypochondriacus* L., and *A. cruentus*, with *A. tricolor* classified as decorative. *A. blitum* (slender amaranth), *A. lividus*, *A. dubius* (spleen amaranth), *A. spinosus*, *A. thunbergia*, and *A. graecizans* yield leafy amaranth (Schippers 2002) [53]. *A. graecizans* and *thunbergii* are typical types found in Sub-Saharan Africa (Alemayehu *et al.*, 2015) [5]. The main species farmed for seed and vegetable purpose are:

Amaranthus caudatus (red amaranth, flower amaranth, and pendant amaranth) is typically found in Southern Nigeria, where the grains range from white to brown to red (NC State Extension, 2019). The sun-loving shrub, known for its thick red flower, can reach a height of 160 cm (Ogwu, 2020) [42].

Amaranthus dubius (spleen amaranth, pigweed) is an annual, erect herbaceous plant (30-150 cm tall) with spike-like or paniculate inflorescences and broad, dark-green leaves (Ogwu, 2020) [42]. It was most likely introduced to Nigeria by early European visitors, and it thrives in a variety of soils and temperatures. It is grown throughout the country for its delicious leaves, seeds, and stems.

Amaranthus hypochondriacus, often known as Prince's feather. The plant is mostly farmed for grain in South America and Asia, with output centered in Mexico's Morelos, Puebla, and Guerrero states (Velez-Jimenez *et al.*, 2014). It is ornamental in Africa, save for trial places in Zimbabwe and South Africa (Schippers, 2002) [53]. The plant is 40-200 cm tall, frequently red-tinted, with forked, plump stems and multicellular hairs. The leaves are alternating, lobed or unlobed, and the flowers are usually deep crimson, purple, or beetroot red, with uncommon yellow or green variants. Seeds range in hue (white to dark reddish brown) and size (1-1.4 mm), with lustrous surfaces (Ogwu, 2020) [42]. It matures in 75-90 days and is day-neutral.

Amaranthus spinosus (spiny amaranth, prickly pigweed) is a thorny weed that grows as a ruderal and in the wild. In Nigeria, it is consumed as food and cattle feed. Its leaves are hairless, sometimes lustrous, with sharp spines. Most likely introduced from the Americas (Schonbeck, 2012) [54].

Amaranthus thunbergii (wild spinach, pigweed) is popular in Northern Nigeria as a green vegetable and seasoning agent. The hairless, angular stem grows up to 55 cm and produces small axillary clusters of greenish, unisexual blooms. The species is native to Africa but was imported to Nigeria (Kirby, 2013) [29].

Amaranthus tricolor (also known as Joseph's coat or Chinese spinach) is a colorful ornamental and edible plant with red, yellow, and green leaf. It can grow up to 125 cm in moist conditions and tolerates scorching summers (Shukla *et al.*, 2006) [57]. *Amaranthus viridis* (green amaranth, African spinach) is a

densely branching plant with edible ovate leaves that grow to 60-80 cm tall. It is a prevalent weed grown in Nigeria and the most popular weedy amaranth. It originated in East Asia (Tony *et al.*, 2012) [66].

Origin and distribution

Approximately 400 species of *Amaranthus* are found across temperate, subtropical, and tropical regions globally, with around 20 species cultivated or growing wild in India, a major center of distribution alongside tropical America (Suma *et al.*, 2002). Grain types of *Amaranthus* are native to South and Central America, while others are native to Europe, Asia, Africa, and Australia (Rastogi & Shukla, 2013) [50].

Amaranthus originated in Central America, and evidence of cultivation dating back to 6700 BC (Mposi, 1999) [35]. From 1400 to 1500 AD, the Aztecs called it "huautli" and used it as a staple diet and in religious ceremonies. For ritual purposes, the seeds often were combined with honey, sweets, and, sometimes human blood for ritual purpose (National Research Council 1984) [40]. After the Spanish conquest in the early 1500s, efforts to suppress Aztec culture led to a decline in its cultivation, though limited use continued for about 50 years. Today, it is still grown in small quantities in the region to make "alegría" a honey-based confection. *Amaranthus* was introduced to Spain in the sixteenth century and had spread throughout Europe, Russia, Africa, and Asia by the nineteenth century. By the mid-1990s, South Asia was the only region where output was growing. Research into its high-quality protein composition resumed in the United States in the 1970s (Brenner *et al.*, 2010) [9]. Today, it is cultivated worldwide, keeping both historical and contemporary relevance (Mposi, 1999) [35].

Morphology

Amaranthus is characterized by an annual or occasionally short-lived perennial life cycle and a herbaceous growth habit with prostrate to upright stems (Weerasekara & Waisundara, 2020) [74]. Its alternating leaves range from ovate to linear, with notched or indented apices and smooth edge. Flowers are irregular and grouped in compound dichasia within inflorescences. Monoecious plants include *A. albus*, *A. blitum*, *A. caudatus*, *A. hybridus*, *A. powellii*, *A. retroflexus*, and *A. spinosus*, whereas dioecious plants include *A. tuberculatus*, *A. palmeri*, and *A. rudis* (Costea & Tardif, 2003) [11]. The inflorescences are terminal and/or axillary, with three to five tepals and stamens. Monoecious species are primarily self- or wind-pollinated. The fruit is either a utricle or a pyxidium, and the seeds are small (0.9-1.7 mm in diameter), with 1000 seeds weight between 0.6 and 1 g. Wind, water, and birds are the primary dispersers of seeds, which have a long germination period and produce prolifically. The basal chromosomal count is 16 or 17 (Steckel, 2004) [60]. Furthermore, this genus uses C4 photosynthesis, setting it apart from closely related genera (Sage *et al.*, 2007) [52]. Morphological descriptions of *Amaranthus*, particularly blooms and inflorescences, are sometimes discordant among floristic and taxonomic research (Weerasekara and Waisundara., 2020) [74]. Within each species, different races are distinguished by branching patterns, height, inflorescence size and shape, days to maturity, seed size, seed color, and other physical characteristics (Brenner *et al.*, 2010) [9].

Morphological Characteristics

Growth Habit

Amaranthus species often have an upright growth habit. For

example, a study on Malawian amaranth accessions found that all examined accessions had an erect plant growth habit (Nyasulu *et al.*, 2021) [41].

- **Leaves:** *Amaranthus* leaves come in a variety of forms and colors, including oval, oblong, elliptical, and ovate. A research analyzing 293 amaranth accessions found considerable changes in leaf blade coloring and form between distinct clusters, also the presence of leaf blotch helped in differentiation of amaranth species from one another (Thapa *et al.*, 2018).
- **Inflorescence:** *Amaranthus* species have a variety of inflorescence colors, including green, light green, and purple, with spiky or smooth structures. In the Malawian study, accessions had diverse inflorescence hues and spininess, showing great morphological variety (Nyasulu *et al.*, 2021) [41].
- **Seeds:** Seed color in *Amaranthus* species varies, with common colors being black and brown. The same study observed that most accessions had black seeds, while one had brown seeds, highlighting the genetic diversity within the species (Nyasulu *et al.*, 2021) [41].

Physiology

Amaranthus is a dicotyledonous herbaceous plant that uses a C4 photosynthetic pathway to produce its initial photosynthetic product (Wang *et al.*, 1999) [73]. It belongs to the NAD-malic enzyme (NAD-ME) subgroup of C4 metabolism, which is distinguished by Kranz anatomy in leaves, cotyledons, and bracts. This structure allows for efficient CO₂ usage through mitochondrial decarboxylation of malate in bundle sheath cells, which improves adaptation to changing temperatures and moisture levels (Costea & Tardif, 2003) [11]. *Amaranthus* thrives in temperatures ranging from 25°C to 40°C and outperforms C3 plants such as wheat and soybeans under high light and low moisture conditions thanks to its water-efficient C4 pathway (Spreeth *et al.*, 2004) [59]. Certain species, such as *A. palmeri*, *A. retroflexus*, and *A. rudis*, show enhanced growth and invasiveness as temperatures rise, underlining their potential influence in a changing environment (Hyvönen, 2011) [23]. The plant's drought endurance is linked to its C4 mechanism, deep root system, dormant aptitude, and ability to resume transpiration after rehydration (Myers 1996) [38]. Higher temperatures increase plant height, dry matter accumulation, and leaf area expansion (Flint & Patterson, 1983) [17]. *Amaranthus* flowering depends on photoperiod, with most species blooming during short-day circumstances (<12 hours) or water stress (Palada, 2003) [44]. Elevated chlorophyll content, reduced biomass, and changes in specific leaf area all indicate moderate shade tolerance. These traits provide insights for developing crop-weed competition models (Brainard *et al.*, 2005) [8].

Nutritional Composition

Amaranth (*Amaranthus hypochondriacus*), a member of the Amaranthaceae family, is well-known for its nutrient-dense seeds, which are high in macronutrients like proteins, dietary fiber, and lipids, as well as micronutrients like vitamins and minerals (Table 1 to 5). Over the last two decades, substantial study has emphasized the seed's high protein content, which ranges from 13% to 19%, as well as an extraordinary balance of important amino acids (Venskutonis and Kraujalis, 2013) [71]. Amaranth seeds are also high in lipids, starch, and antioxidants (Jahaniaval *et al.*, 2000) [25].

Table 1: Nutrient composition and energy content of amaranth grain (USDA, 2016)

Component	Amaranth grain (value per 100 g)
Protein	13.56
Lipid	7.02
Carbohydrate	65.25
Dietary fiber	6.70
Water	11.29
Energy	371;1554
Ash	2.88

Table 2: Minerals composition of amaranth grain (USDA, 2016)

Component	Amaranth grain (g per 100g)
Minerals	
Calcium	159 mg
Copper	0.53 mg
Iron	761 mg
Magnesium	248 mg
Manganese	3.33 mg
Phosphorus	557 mg
Potassium	508 mg
Sodium	4 mg
Zinc	2.87 mg
Selenium	18.7 mcg

Table 3: vitamins composition of amaranth grain (USDA, 2016)

Component	Amaranth grain (g/100g)
Vitamins	
Ascorbic acid	4.20 mg
Riboflavin	0.20 mg
Folate	82 mcg
Niacin	0.92 mg
Thiamine	0.12 mg
Vitamin A	2IU
Pantothenic acid	1.46 mg
Vitamin B-6	0.59 mg
Vitamin E (alpha-tocopherol)	1.19 mg
Vitamin E (beta -tocopherol)	0.96 mg
Vitamin E (delta-tocopherol)	0.69 mg
Choline	69.8 mg
Betaine	67.6 mg
Lutein	28 mcg

Table 4: Essential amino acid profile of amaranth grain [USDA, 2016]

Component	Amaranth grain (g/100g)
Arginine	1.06
Histidine	0.39
Isoleucine	0.58
Lysine	0.88
Leucine	0.75
Methionine	0.23
Phenylalanine	0.54
Threonine	0.56
Tryptophane	0.18
Valine	0.68

Table 5: Fatty acid composition of amaranth grain oil (USDA, 2016).

Component	Amaranth grain (g/100g)
Palmitic acid (C16:0)	1.154
Stearic acid (C18:0)	0.223
Oleic acid (C18:1)	1.671
Linoleic acid (C18:2)	2.736
Linolenic acid (C18:3)	0.042

Nutraceuticals in amaranth

Amaranth, rediscovered in 1980 for its remarkable nutritional value, is a gluten-free pseudocereal with a high protein content (13-19% DM) and enhanced lysine and sulfur amino acids (Venskutonis & Kraujalis, 2013) [71]. Grain amaranths (*A. cruentus*, *A. caudatus*, and *A. hypochondriacus*) have health benefits such as lower blood pressure, liver support, and antioxidant properties due to phenolic components (Sharma & Bhat, 2009) [56]. Amaranth oil, high in unsaturated fatty acids and squalene, helps with antioxidant therapy and hyperglycemia management (Sulaiman & Andini, 2020) [62]. Betacyanins and betalains in *A. spinosus* are natural pigments that have anti-inflammatory and anti-aging characteristics (Kalinova *et al.*, 2009; Stintzing *et al.*, 2004) [26, 61]. Bioactive compounds like rutin, quercetin, lunasin, tocopherols, and lectins have demonstrated anticarcinogenic, cholesterol-lowering, and immunosuppressive effects (Sulaiman & Andini, 2020).

Antioxidant properties of amaranth

To present, 75 betalains have been found in 17 of Caryophyllales' 34 families, with no known occurrences outside of this order (Khan & Giridhar, 2015;) [28]. Most plants in the Amaranthaceae family contain betalains in various organs, which have ecological roles such as attracting pollinators and maybe providing stress relief, however data is sparse. While red beetroot (*Beta vulgaris*) is still the predominant commercial source of betalains, amaranths have been suggested as alternatives (Cai *et al.*, 2005) [10]. Betalains are natural food colorants with health benefits such as antioxidants and anticancer qualities (; Gengatharan *et al.*, 2015). They can neutralize free radicals, which may help prevent cancer and cardiovascular disease (Gengatharan *et al.*, 2015) [18]. Betalains have antimalarial activity (Hilou *et al.*, 2006) [21] and antibacterial properties against *Salmonella typhimurium* and *Bacillus cereus* (Velićanski *et al.*, 2011) [70]. As a result, amaranth stands out as an important crop for both nutritional and nutraceutical purposes.

Lysine content

Amaranth grain and leaves are popular due to their nutritional content. Grains contain approximately 15% protein (Adhikarya *et al.*, 2020), and their amino acid composition is wellbalanced, with a high lysine content (Segura-Nieto *et al.*, 1992) [55]. Lysine is the limiting amino acid in most cereal crops, including wheat, sorghum, and rice, but it is abundant in amaranth; the first limiting amino acid in amaranth is leucine (Adhikarya *et al.*, 2020), and it is also prevalent in the majority of our staple foods. Therefore, amaranth is considered a complete protein supply when ingested with another cereal.

Squalene content

Squalene, a unique triterpene molecule with biological and pharmacological implications, participates in cholesterol manufacturing (Popa *et al.*, 2015) [48]. Regular eating has been associated to lower cholesterol levels (Chan *et al.*, 1996) and the prevention of chemically induced breast and colon cancer (Adhikarya *et al.*, 2020). Consuming more squalene-rich olive oil has been linked to a lower prevalence of heart disease in the Mediterranean region (Keys, 1995; Owen *et al.*, 2000). Squalene is produced via cholesterol production as well as dietary sources such as plant oils, with olive and amaranth oils being particularly abundant (León-Camacho *et al.*, 2014). Grain amaranths, particularly *A. cruentus* (2.26-5.67%), *A. hypochondriacus* (3.6%), and *A. tricolor* (6.1%), have been found as viable natural sources (Adhikarya *et al.*, 2020).

Comparison of Amaranth Nutrients With Other Crop

Table 6: Nutrients comparison of vegetable amaranth with spinach and other leafy vegetables (per100g) (Rastogi and shukla 2013) ^[50]

Component	Amaranth	Spinach	Basella	Chard
Protein	3.5 g	3.2 g	1.8 g	2.4 g
Ascorbic acid	80mg	51 mg	102 mg	32 mg
Fiber	1.3g	0.6 g	0.7 g	0.8 g
Carotenoids	6100 IU	8,100 IU	8,000 IU	6,500 IU
Fat	0.5g	0.3 g	0.3 g	0.3 g
Carbohydrate	6.5g	4.3 g	3.4 g	4.6 g
Calcium	267 mg	93 mg	109 mg	88mg
Iron	3.9 mg	3.1 mg	1.2 mg	3.2
Potassium	411mg	470 mg	----	550 mg

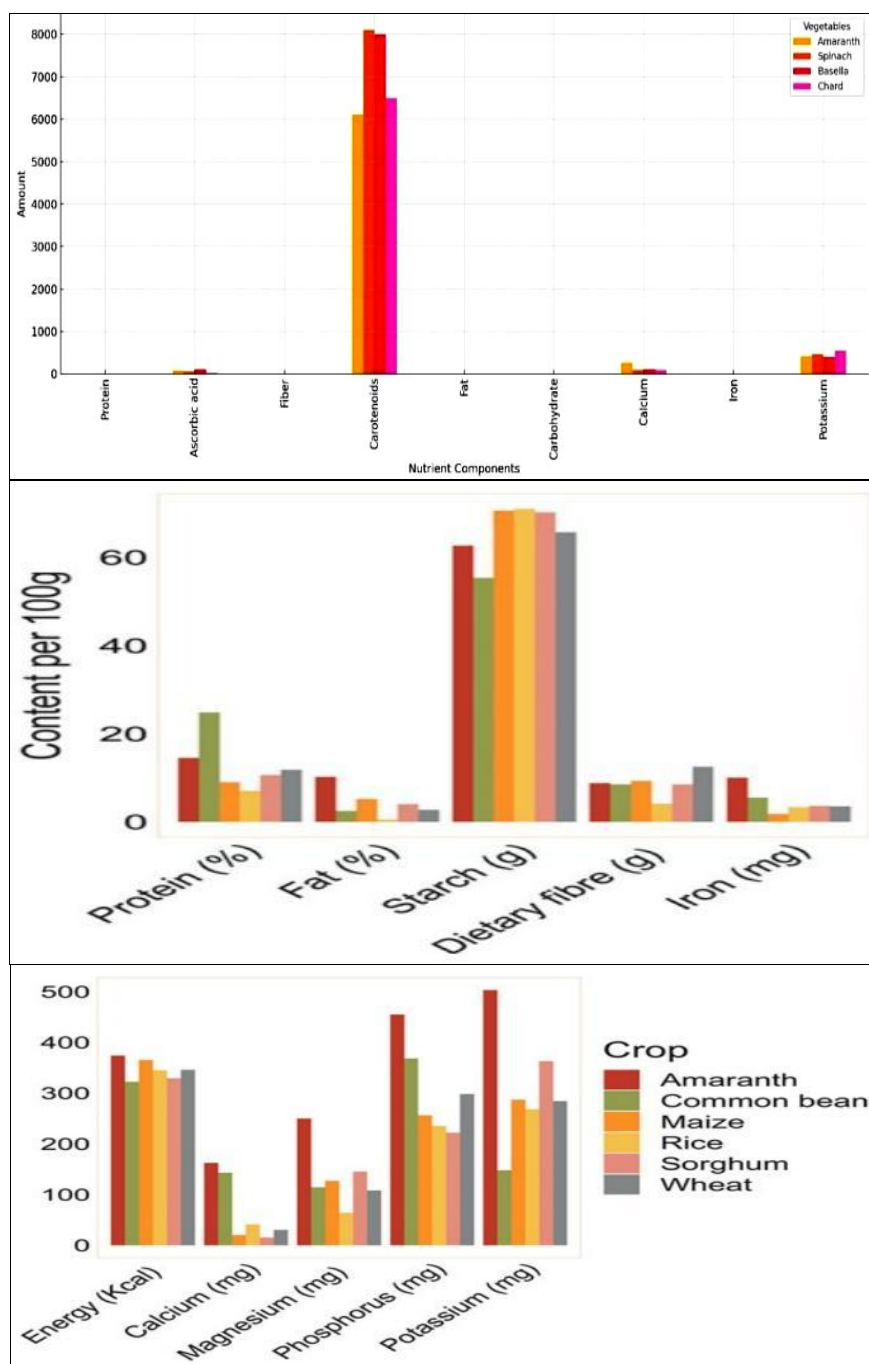


Fig 1: Nutrients comparison of vegetable amaranth with spinach and other leafy vegetables (per100g) (Rastogi and Shukla 2013) ^[50]

Comparison of nutrient content of amaranth and other crops. Values are per 100 g of seeds, units for each component are indicated in labels. (Data from Rastogi and Shukla 2013; Petry *et al.* 2015; Kumar *et al.* 2016) ^[50]

Use of amaranth.

Whole plant of amaranth is used for food and other purposes. Numerous techniques have been devised to expand the ingestion of amaranth into dietary habits of the population, seeds of amaranth are popped or boiled and eaten as rice (Topwal, 2019) ^[67]. Grain flakes are prepared using amaranth seeds and the most critical by-product of amaranth seeds is the flour. The flour is used for baking industry (Park *et al.*, 2020) ^[46]. Amaranth doesn't contain gluten; this trait makes them excellent for the manufacturing of food for the people who are allergic to gluten or having celiac disease (Woomer *et al.*, 2021) ^[75]. Also, efforts are made to prepare weaning food from amaranth grain which hold immense nutrient content that could be used to provide required nutrients to the growing infants (Akinsola *et al.*, 2017) ^[4]. Such weaning food made using amaranth can be then be made to mix with flour made from sorghum, chick pea, maize or of other grain in optimum mix to derive maximum benefits (Zebdewos *et al.*, 2015) ^[78]. As bakery product are taking prominent place among today's generation, efforts to generate bakery product such as biscuit using amaranth flour are being worked upon (Renu and Anirban, 2015) ^[51]. To bring crispiness flours made from maize, Chenopodium, quinoa flour and the acceptability of the product was fairly high due to nutritional advantage (Virginia and Ajit, 2014) ^[72]. Furthermore, the interest for functional beverage is increasing among the masses due to its convenience, appearance, ease of distribution and packaging (Pandal, 2017) ^[45]. Consequently, a non-alcoholic beverage using amaranth grains were prepared known as amaranth-Kunu having higher protein, fat and ash content (Aderibigbe *et al.*, 2020) ^[2]. The beverage drinks produced using amaranth will be a good alternative for low-nutrient beverages that are dominating the market.

Role of amaranth in mitigating malnutrition.

Amaranth, a multi-purpose crop consumed for centuries by numerous cultures, possesses superior nutritional value compared to other crops. It is rich in essential nutrients, antioxidants, and bioactive compounds that contribute to achieving global nutritional security. Amaranth's high protein content and resilience to climate change make it a promising crop for sustaining the global food system.

In contrast to conventional cereal crops, amaranth stands out for its substantial content of wellbalanced protein, particularly lysine, which is often lacking in other grains. The combination of this high-quality protein with its high digestibility makes amaranth a valuable plant-based protein source (Zhang *et al.*, 2023) ^[79]. According to studies conducted in Uganda and Kenya, incorporating amaranth grain into locally available diets has demonstrated an increase in nutrient intake, thereby enhancing child nutrition (Tibagonzeka, 2014) ^[64]. Furthermore, amaranth has proven its efficacy in combating malnutrition, paving the way for the development of the Integral Nutritional Recovery Program (INRP) that utilizes amaranth flour to improve children's weight, height, fat mass, and muscle mass (López *et al.*, 2021) ^[30].

Amaranth presents a cost-effective alternative to conventional therapeutic foods for severe malnutrition. Its high protein, energy, and nutrient content in optimal quantities renders it a suitable replacement for milk (Nabuuma *et al.*, 2013) ^[39]. By

harnessing locally available amaranth, cost reductions can be achieved, and its accessibility can be enhanced across diverse regions. In a broader context, the integration of amaranth into school food programs and public distribution networks in Karnataka, India, has substantially improved the nutritional well-being of millions of children and the general population, as stipulated by the National Food Security Act of 2013 (Awan *et al.*, 2015) ^[7]. Furthermore, amaranth is a nutrient-dense grain, replete with micronutrients such as zinc, iron, vitamin C, and vitamin A. Among these micronutrients, iron holds particular prominence. Amaranth exhibits significantly higher iron levels compared to green leafy vegetables (Habtamu *et al.*, 2014) ^[20]. Moreover, the bioavailability of iron in amaranth surpasses that of other crops. Consequently, incorporating amaranth in regions susceptible to anemia presents a valuable strategy in combating this prevalent disease.

Enhancing food security

Amaranth, commonly referred to as the "super grain," is renowned for its exceptional potential in producing valuable food products. Its gluten-free nature makes it an ideal alternative for individuals with celiac disease. (Reference) The versatility of amaranth grain enables its production of a diverse range of products, contributing to its widespread appeal. At the household level, amaranth can be prepared as porridge (Mugalavai, 2013) ^[36]. Additionally, it can be roasted or popped to produce flour, which can be utilized alone or combined with other flours to create various products such as pasta, biscuits, and bread muffins (Emire and Arega, 2012) ^[14]. Given its potential, amaranth grain holds the promise of expanding the scope of the food processing industry and creating employment opportunities. This, in turn, can pave the way for sustainable development.

To ensure food security, efficient post-harvest practices must be implemented to sustain the entire value chain. Post-harvest loss of amaranth is estimated to be 5-13% in Sub-Saharan Africa (Tibagonzeka *et al.*, 2018) ^[65]. Like any other food grain, amaranth also requires post-harvest management of the grains to enhance nutritional content and command high market acceptance. Post-harvest operations encompass a wide range of practices, including drying, threshing, storage, and processing; each step requires due diligence to minimize grain quality loss effectively (Manikandan & Srimathi, 2014) ^[32]. In developing countries, harvesting is typically done manually, while in developed countries, combined harvesters are commonly used for the same purpose (Buzby & Bennette, 2011) ^[22]. The critical step following harvesting is drying, as the moisture content should be within the optimal range to protect the grains from fungal and other seed-inhabiting organisms. Therefore, to improve food security, the proper storage of the grain material needs to be implemented.

Other benefits of amaranth

Amaranth grains are renowned for their extensive range of health benefits. The peptides present in the grains exhibit hypercholesterolemic activity (Sisti *et al.*, 2019) ^[58], while the antioxidant properties of the grain protect against oxidative free radicals, thereby safeguarding the body. Furthermore, amaranth grain flour protein has been demonstrated to maintain gut microbiota (Olguín-Calderón *et al.*, 2019) ^[43], thereby enhancing the beneficial microbiome in the gut and contributing to overall health when consumed. Additionally, research has shown that amaranth grains possess anticancerous properties (Quiroga *et al.*, 2015) ^[49] and anti-fungal activity (Lozano-Grande *et al.*, 2020)

[31]. Studies conducted by the World Health Organization (WHO, 2019) [15] have highlighted the rising prevalence of hypertension, and the nutrients present in amaranth, particularly the seed-stored protein, have been shown to exhibit relatively good anti-hypertensive activity (Kamal *et al.*, 2021). This further elevates the nutrient-providing capacity of amaranth. Moreover, the anti-cancerous (Tanya *et al.*, 2020) and anti-diabetic (Zamudio *et al.*, 2022) [77] activities of amaranth have been extensively documented.

Constrains to amaranth production and utilization

Despite its high regard as a nature crop, the adoption of amaranth as the primary crop faces uncertainties and challenges along its value chain. The primary constraints in amaranth utilization are grain propagation, refinement, and distribution of grain and its derivatives (Mukuwapasi *et al.*, 2024) [37]. Consumer acceptance is also a significant concern in the marketing of amaranth grain. Among the input requirements, the unavailability of high-quality planting material poses a substantial challenge, particularly considering the constraints in amaranth production.

Another constraint to amaranth production is the gene flow to its weedy species. This is a two-way process in which genes flow from cultivated plants to weed species, reinforcing them to gain important resistance. This, in turn, creates superweeds. Conversely, gene flow from weed species to cultivated plants can lead to the loss of quality in the cultivated plants. (Aulakh *et al.*, 2024) [6]. In addition to the anti-nutritional factors present in the amaranth, the shattering character of grains are a menacing proem to farmers as it reduces the yield from the crop. This mechanism was evolved as an adaptive advantage to the crop, currently selective breeding strategies are involved for correction of the defect (Gomes *et al.*, 2024) [19]. Hence, concrete measures need to be developed for the subjugate the hinderance imposed by constraints of amaranth utilization.

Framework for Enhancing Amaranth Value Chain to Bolster Food and Nutritional Security

It is evident that amaranth has been recognized as a priority crop for value chain development among numerous underutilized crops in developing regions worldwide (reference). Despite its numerous positive attributes, amaranth faces several challenges in effectively harnessing its potential. The constraints in production can be effectively addressed through the establishment of a robust network of extension workers and the provision of training to farmers on the optimal application of fertilizers. This approach can encourage farmers in vulnerable regions to adopt amaranth cultivation (Aderibigbe *et al.*, 2022) [1].

The absence of adequate post-harvest technology for processing and packaging can be addressed through public-private partnerships. These partnerships facilitate the provision of market information to farmers while simultaneously ensuring the consumers access of high-quality products at competitive prices. The National Innovation Platforms established in countries such as Zimbabwe, Kenya, and Benin have made significant recommendations for the enhancement of the amaranth value chain. Among these most crucial recommendations are the creation of market access and consumer demand, the strengthening of the input system, the improvement of technology for planting and linkage with extension and research agents (Hall *et al.*, 2014).

Although research communities have consistently researched and promoted underutilized crops, there is an urgent need for a

concerted and coordinated effort to enhance the value of amaranth. This includes the urgent need to collect and preserve germplasm of these crops, followed by the selection of appropriate breeding strategies to develop high-quality varieties. Most advanced research and development activities in developed countries are supported by their government policies. The outcomes of these research projects will further advance research and aid in achieving a value chain development approach, thereby securing the needs of small-scale farmers. Additionally, such projects foster the creation of collaborative environments. (Devaux *et al.*, 2018) [13].

A comprehensive network for grain amaranth stakeholders is becoming increasingly necessary. The primary objective of this network should be the exchange of knowledge and resources, as well as the coordination of actions. This can be achieved through an innovation platform, which are multi-stakeholder platforms that facilitate the development and strengthening of technical and business relationships. Researchers should not only focus on generating novel knowledge and technologies, but also on utilizing this knowledge and technology to transform processes and enhance the capabilities of stakeholders. Farmers should be actively involved throughout the entire process, and the private sector should be engaged to influence their willingness to process and market amaranth products. Policy dialogues should be conducted to raise awareness and generate support, and donors should be partnered with for financial assistance. Additionally, further funding sources should be explored internally.

Conclusion

The amaranth species exhibits remarkable potential in alleviating malnutrition and lifestyle-related diseases. Its ability to attain food security and nutritional security in challenging terrains is boundless. The nutritional value of amaranth grains is exceptional as it has excellent source of essential nutrients, particularly in the face of ever-evolving climatic conditions. The crop's climate resilience nature makes it well-suited to the current global scenario. Given the growing population's demand for nutritious food, it is imperative to promote diverse food options, with amaranth grain emerging as a superior choice. The emphasis on sustainable practices associated with amaranth grain is highly commendable, as it ensures the well-being of future generations while simultaneously meeting the current demands. Efforts from government and private agencies can effectively address the constraints associated with production of grains, thereby unlocking the grain's limitless potential in meeting the needs of vulnerable regions.

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