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Resurrecting forgotten crops: Food-based products from potential underutilized crops a path to nutritional security and diversity

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ABSTRACT

Underutilized crops, often overlooked in mainstream agriculture, possess significant potential to address global challenges in food security, nutrition, and sustainable agriculture. These crops, including quinoa, amaranth, buckwheat, teff, millets, bambara groundnut, winged bean, lablab bean, moringa, and jackfruit, are rich in essential nutrients, bioactive compounds, and possess significant environmental adaptability. Despite their nutritional and pharmaceutical benefits, their commercialization has been limited due to historical neglect, yield variability, and underdeveloped supply chains. This review explores their nutritional and phytochemical profiles and emphasize their potential for innovative food applications and future smart foods. These crops are increasingly used to develop gluten-free bakery items, protein-rich snacks, meat analogues, fermented beverages, and functional foods. Additionally, this review discusses challenges such as fragmented data, limited consumer awareness, policy gaps and highlights strategies to overcome these obstacles. This review not only serves as a resource for researchers, policymakers, and industry leaders but also provides actionable insights to mainstream these crops to promote more diverse, sustainable, and resilient food systems.

1. Introduction

Underutilized crops, often referred to as “neglected” or “orphan” crops, include a broad range of plants that have historically received limited attention from mainstream agricultural practices, scientific research, and global food markets. Major underutilized crops included quinoa, amaranth, buckwheat, teff, minor millets, bambara groundnut, winged bean, lablab bean, moringa, and jackfruit, all of which possess significant nutritional and functional benefits globally. These crops have been overshadowed by globally dominant staple crops such as wheat, rice, and maize, which have formed the backbone of modern agricultural systems and global food supply chains (Li et al., 2020). While staple crops have undergone extensive breeding, commercialization, and technological development, underutilized crops have remained largely confined to regional or traditional uses, with minimal support from agricultural policies or research institutions (Hunter et al., 2019). . The historical neglect of these crops can be attributed to several factors. For instance, during the Green Revolution, the focus was primarily on improving the yield and productivity of a few staple crops (wheat and rice) to meet the growing food demands of an ever-expanding global population. This led to the marginalization of numerous indigenous and regionally important crops that did not align with large-scale, industrial farming systems (Eliazer Nelson et al., 2019). The widespread adoption of high-input monoculture systems further reduced the cultivation and conservation of these crops, thus leading to a decline in their genetic diversity and traditional farming knowledge. Additionally, global trade and market dynamics favored the widespread cultivation and commercialization of selected few crops that were easily transported, stored, and

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processed, thus leaving underutilized crops on the fringes of agricultural development. Despite their historical neglect, many underutilized crops possess unique agronomic traits, such as resilience to extreme environmental conditions (cold, heat and drought tolerance) and low water requirements. These traits make them valuable in the context of climate change and sustainable farming practices, particularly in regions prone to drought, poor soils, and unpredictable weather patterns. Moreover, these crops often play an important role in traditional farming systems and local diets, thus contributing to the cultural identity, dietary diversity, and food security of indigenous communities (Adelabu and Franke, 2023; Panda et al., 2023; Singh et al., 2022).

In recent years, there has been a growing recognition of the nutritional, environmental, and economic potential of underutilized crops, leading to a resurgence of interest in their cultivation and use in modern food systems. This renewed focus is driven by several global challenges, including the need to diversify food systems, address malnutrition, promote sustainable agriculture, and reduce the environmental impact of conventional farming practices (Hunter et al., 2019; Li et al., 2020; Panda et al., 2023). Underutilized crops play a vital role in traditional agroecosystems and indigenous food systems by supporting ecological sustainability, nutritional diversity, and cultural preservation. They improve soil fertility, suppress pests, and reduce dependence on synthetic inputs through agroecological practices such as intercropping, crop rotation, and mixed farming. Their drought tolerance and ability to thrive in nutrient-deficient soils make them essential for smallholder farmers in regions with erratic rainfall and poor soil conditions. These crops are rich in essential nutrients, low-glycemic index carbohydrates, resistant starch, and bioactive compounds, which help regulate glycemic response, support gut microbiota, and lower the risk of non-communicable diseases such as type 2 diabetes and cardiovascular disorders. Many of these crops are rich in essential nutrients such as protein, vitamins, minerals, and antioxidants, which are often lacking in conventional staple crops (Singh et al., 2022). For example, quinoa (*Chenopodium quinoa* L.), an ancient grain from the Andean region, is a complete protein, containing all nine essential amino acids (Younis et al., 2023). Owing to the adequate recommendations for improving the agronomic and environmental sustainability, the cultivation of quinoa has expanded from South America to Africa, Europe, Asia and North America (Taaime et al., 2023). Similarly, amaranth (*Amaranthus* spp.) and buckwheat (*Fagopyrum esculentum* L.) are pseudo-cereals that are high in protein, fiber, and micronutrients, making them excellent alternatives for gluten-free diets (Ahmed et al., 2014; Sarker et al., 2024). Amaranth is native to Africa, however, its cultivation is expanded to tropical and subtropical regions, and Central and South America (Managa and Nemadodzi, 2023). Buckwheat on the other hand is cultivated in Russia, China, Ukraine and India where considerable number of new cultivars with improved characteristics have been registered and released (Graziano et al., 2022).

In addition to their macronutrient content, many underutilized crops are abundant in bioactive compounds, such as flavonoids, phenolics, and carotenoids, which have been shown to provide various health benefits, including antioxidant, anti-inflammatory, and cardioprotective effects. For instance, moringa (*Moringa oleifera* L.) leaves are rich in vitamins (A, C, and E), as well as calcium and potassium, making them a potent source of nutrition, especially in regions with high rates of malnutrition (Islam et al., 2021). Being a drought tolerant species, moringa is mainly grown in tropical countries such as Namibia in sub-Saharan Africa (Horn et al., 2022). These crops can also address specific nutritional deficiencies that are prevalent in many parts of the world. Sorghum (*Sorghum bicolor* L.) and other minor millets (such as foxtail millet, proso millet, finger millet, barnyard millet, etc.) are key sources of energy and micronutrients for millions of people in sub-Saharan Africa and South Asia. These grains are particularly well-suited to regions with harsh climatic conditions, where the cultivation of conventional crops may be less viable. The inclusion of these crops in global food systems can help improve dietary diversity and combat micronutrient deficiencies, thereby contributing to better public health outcomes (Amadou et al., 2013; Arya and Bisht, 2022; Kaur et al., 2024a; Ravichandra et al., 2023).

In the face of global environmental challenges, such as climate change, soil degradation, and water scarcity, underutilized crops offer promising solutions for sustainable agriculture. Many of these crops are naturally adapted to grow in marginal environments with limited inputs, making them well-suited for resource-poor regions. For example, finger millet (*Eleusine coracana* L.) and teff (*Eragrostis tef* L.) are the drought-tolerant grains that can thrive in arid and semi-arid conditions, requiring significantly less water than staple crops like wheat or rice (Ferede et al., 2020; Kaur et al., 2024a). Finger millet is cultivated in Uganda, Nigeria, Ethiopia, including East and South Africa, and different parts of India (Abioye et al., 2022). Teff, having its origins in Ethiopia has been now cultivated in North America, China, India, Australia, the United Kingdom and other countries in Africa (e.g., Cameroon and Uganda) (Barretto et al., 2020). Furthermore, underutilized crops often exhibit higher genetic diversity than conventional crops, which can enhance their resilience to pests, diseases, and changing environmental conditions. This genetic diversity is important in the era of climate change, as it allows for the selection of crop varieties that are better adapted to future climatic stresses. The cultivation of underutilized crops also contributes to the conservation of biodiversity, both in agricultural systems and in natural ecosystems, by promoting the use of a wider variety of plant species (Li et al., 2020; Shorinola et al., 2024; Wani et al., 2021). By incorporating these crops into farming systems, smallholder farmers can benefit from increased food security and income diversification, as these crops can provide multiple harvests or be used for different purposes (e.g., food, fodder, and bioenergy). In addition to their nutritional and environmental benefits, underutilized crops hold significant economic potential. As consumer demand for healthy, sustainable, and ethically produced food products continues to rise, there is increasing market interest in novel food products derived from these crops. Several underutilized crops, such as quinoa (*Chenopodium quinoa* L.) and fonio (*Digitaria exilis* L.), have gained popularity in global markets as "superfoods" due to their unique nutritional profiles and health-promoting properties. Quinoa seeds (also called as golden grains) is rich in the high-quality protein, dietary fiber, vitamin B, magnesium, potassium, and calcium, making it a powerhouse ingredient in health-focused food products (Singh et al., 2022; Younis et al., 2023). Moringa, often called the “miracle tree,” is rich in vitamins, minerals, and antioxidants, making it a versatile ingredient for health-focused food products like powders, teas, and supplements (Islam et al., 2021). Jackfruit (*Artocarpus heterophyllus*) is a nutrient-rich fruit known for its versatility, often used as a plant-based meat substitute in various food products, due to its high fiber content, vitamins, and unique texture (Ranasinghe et al., 2019).

The commercialization of underutilized crops creates income opportunities for smallholder farmers by accessing niche markets for climate-resilient, nutrient-rich foods. It enhances food security and rural livelihoods by promoting diverse cropping systems and reducing dependence on high-input staples. Value addition and agro-processing generate employment, strengthen local economies, and improve market access. Government initiatives like Agri-Business Incubators support farmers with technical training, funding, and market linkages, thus enabling the production of value-added products such as gluten-free flour, protein-rich snacks, and functional beverages. This expands market reach and enhances economic viability. Food-based companies are increasingly exploring the potential of these crops to create functional foods, gluten-free products, and plant-based protein alternatives that meet the demands of health-conscious consumers (Farooq et al., 2023; Knez et al., 2024; Li and Siddique, 2020; Revoredo-Giha et al., 2022). For example, buckwheat noodles (soba), amaranth snacks, and teff-based baked goods have gained traction in markets catering to gluten-free and plant-based diets (Alcorta et al., 2021; Sofi et al., 2023). Furthermore, winged bean (*Psophocarpus tetragonolobus*) and lablab bean (*Lablab purpureus*) are underutilized legumes with superior nutritional profiles, containing high levels of protein, vitamins, and minerals. These crops hold significant potential for creating innovative food-based products, such as protein-rich snacks, flours, and plant-based dairy alternatives, making them valuable contributors to sustainable diets and global nutritional security (Mohanty et al., 2020a; Pandey et al., 2023).

The present review explores the selected underutilized crops, including quinoa, amaranth, buckwheat, teff, minor millets, bambara groundnut, winged bean, lablab bean, moringa, and jackfruit. It highlights their rich nutritional and phytochemical profiles and discusses the development of food-based products from these crops and explores the challenges, opportunities, and future directions in commercializing these crops. This review is a valuable resource for policymakers and research professionals, providing insights that can inform policy decisions and guide future research. It emphasizes the potential of these crops to contribute to sustainable agriculture and global food security, encouraging investment in their development.

2. Nutritional and phytochemical composition of underutilized crops

Quinoa, a highly nutritious pseudocereal, contains a rich profile of macronutrients and micronutrients. It has a notable protein content of 16.3 %, complemented by 7 % lipids, 74 % carbohydrates, 3.8 % ashes, and 3.8 % fiber (USDA, 2011). Additionally, quinoa is an excellent source of minerals, particularly iron, making it a valuable food for addressing micronutrient deficiencies. Amaranth, another pseudocereal, has nutritional composition similar to rice and beans. It contains 14.6 % protein, 6.04 % fat, and 68.1 % carbohydrates, with good amount of essential amino acids namely methionine (15.8 mg per g) and lysine (55.8 mg per g) (Sattar et al., 2024). Its fatty acid profile includes palmitic, oleic, and linoleic acids, which comprise 1.4 % of its total fatty acids (Table 1).

Buckwheat is a gluten-free, nutrient-rich pseudocereal, suitable for individuals with celiac disease. It contains 13.07 % protein, 56 % carbohydrates, 2.52 % fat, 11.94 % fiber, and 1.67 % ash. Buckwheat provides a calorie content comparable to that of other cereals and legumes, at 383 calories per 100 g, and has high amount of unsaturated fatty acids (74.5 % to 79.3 %), along with vitamins A, E, B complex, and C (Sofi et al., 2023). Teff, valued for its greater nutritional composition when compared to other grains such as maize and wheat, has 9.37 % protein, 85.6 % carbohydrates, 9.8 % fiber, and 4.4 % lipids. Additionally, its flavonoid and phenolic content ranges from 0.62 to 1.16 mg RE and 1.41–2.19 mg gallic acid equivalent per g, separately (Forsido et al., 2013; Gebru et al., 2021).

Millets are staple crops throughout Asia and Africa's semi-arid regions, and they are classified into major and minor types. Sorghum, pearl millet, and finger millet are examples of major millets, whereas minor millets include little millet, kodo millet, barnyard millet, foxtail millet, and proso millet. Sorghum contains 10.4 % protein, 72.6 % carbohydrates, and 1.9 % fat, providing a significant energy source (349 kcal/100 g), along with phosphorus (222 mg per 100 g), iron (4.1 mg per 100 g) and calcium (25 mg per100 g) (Slama et al., 2020). Pearl millet is notable for high content of protein (12–16 %) and lipid (4–6 %), whereas finger millet contains 6–8 % protein and 1.5–2 % fat, with an abundance of amino acids such as lysine, arginine, and methionine. (Hithamani and Srinivasan, 2014; Nakarani et al., 2021). Minor millets are notable for their carbohydrate content per 100 g of sample, such as little millet (65.55 g), kodo millet (66.19 g), and foxtail millet (60.09 g). Kodo millet and little millet also offer a high dietary fiber content of 37 % and 38 %, respectively, making them advantageous for the health of the digestive system (Shah et al., 2021).

Fonio, cultivated in West African countries, has a unique nutritional profile with low moisture (9.5 %) and fat content (0.34 %), yet provides 21.5 % protein. It surpasses other cereals in mineral content (4.3 %), making it a nutritious alternative to wheat flour (Ananth et al., 2023; Koroch et al., 2013). Bambara groundnut (*Vigna subterranea*) is considered a balanced food, containing 64.4 % carbohydrates, 23.6 % protein, 1.4–9.7 % fat, and 1.4–10.3 % dietary fiber. It is particularly high in lysine, complementing cereals that are typically low in this amino acid (Tan et al., 2020a). A valuable source of protein, winged bean has a high protein composition of 28.43–31.13 %, 34.53–39.76 % carbohydrates, and 4.55–4.98 % ash (Adegboyega et al., 2019).

Moringa, commonly called as "miracle plant, is valued for the diverse uses of its parts, including leaves, seeds, and roots. Its nutritional composition includes 56.50 % carbohydrates, 28.50 % protein, 2.33 % fat, 56.257 mg GAE/g total phenolic content (TPC) and 29.33 mg GAE/g total flavonoid content (TFC) (Saleh et al., 2024). Jackfruit is abundant in carotene, carbohydrates, and ascorbic acid and the seeds offering more nutrients than the pulp. The young fruit contains 9.4–11.5 % carbohydrates, 0.1–0.60 % fat, 2.0–2.6 % protein, and 2.6–3.6 % dietary fiber (Ranasinghe et al., 2019). Lastly, lablab bean, a valuable source of vegetable protein, offers 23–28 % protein and is high in carbohydrates (60.74 g/100 g), lipids (1.69 g/100 g), and minerals such as iron (5.10 mg per 100*g*), calcium (130 mg per 100*g*), magnesium (283 mg per 100*g*), and copper (1.335 mg 100*g*) (Naeem et al., 2020).

3. Food-based products from underutilised crops

3.1. Quinoa

Quinoa seeds offer a wonderful substitute element in baked items, greatly augmenting their nutritious content. Replacing a portion of wheat flour with whole-quinoa-seed flour leads to dough that possesses enhanced nutritional characteristics. This is due to quinoa's elevated protein content, a more well-rounded amino acid composition, and increased levels of dietary fiber and phytochemicals (Mu et al., 2023). The recipes that were based on quinoa had a more even distribution of amino acids, with lysine levels that were notably greater compared to what is usually seen in cereals. The lysine levels ranged from 2.83 to 9.40 g/100 g of protein (Pathan and Siddiqui, 2022). Quinoa-based pasta offers enhanced nutritional advantages in comparison to regular pasta, while also maintaining exceptional cooking quality and displaying an attractive color. Quinoa pasta demonstrates increased durability after being cooked, while yet keeping excellent quality. Quinoa pasta is a highly promising market product that offers excellent nutritional and functional quality (Itusaca-Maldonado et al., 2024). Substituting rice flour with quinoa flour and papaya powder enhances the nutritional content of cookies by increasing their protein, amino acid, fiber, and beta-carotene levels. This modification improves the nutritional composition of gluten-free cookies and supports the objective of creating healthier food options (Hussien et al., 2023). By including quinoa flour into recipes, the overall dietary fiber content is multiplied by approximately five, enabling the gluten-free shortbreads to be labeled as a significant source of fiber. Incorporating quinoa flour into the formulation significantly increases the polyphenol content of the shortbreads by approximately five times, resulting in a higher antioxidant capacity. In addition, the gluten-free biscuits that were tested contain a high concentration of amino acids, including those that are necessary for the body (Bravi et al., 2024).

A study found that the utilization of legume protein isolates/concentrates, such as lupin protein isolates, in conjunction with pseudocereal flours like quinoa, holds significant promise for the development of snack products. This method improves the nutritional value of protein-rich extrudates and decreases the hardness of snacks when the protein concentration is 70 % (Martin et al., 2022). Furthermore, (Zapana et al., 2020) successfully generated puffed quinoa treats by the amalgamation of a gun and extrusion puffing approach. Compared to microwave puffed quinoa, this method produced high-quality snacks that retained the nutritional properties and ensured optimal absorption of organic matter and proteins. In addition to the nutritional advantages, the incorporation of non-traditional grains also affects the physical

Table 1
Summarized nutritional and phytochemical profiles of underutilized crops.

Crop	CHO (%)	Protein (%)	Fats (%)	Ash (%)	Dietary fiber	Amino acids	Fatty acids % (% of TFA)	Phytochemicals	Vitamins	Minerals	References
Quinoa	74.0	16.3	7.0	2.7	7.0 mg	His 2.73 g, Lys 6.19 g Thr 4.02 g, Val 5.23 g Leu 6.67 g, Ile 3.38 g Phe+Tyr 7.31 g	C (16:0)–10 % C (18:1)–19.7–29.5 % C (18:2)- 49.0–56.4 % C (18:3)- 8.7–11.7 % (% of TUSFA)	Flavonoids 36.2–288 mg Phenolics 30.3–202 mg Phytosterols 0.3–180 mg	Thiamin 0.29–0.38 mg Riboflavin 0.30–0.39 mg niacin (Niacin) (Niacin) 0.56–1.56 mg Pyridoxine 0.487 mg Ascorbic acid 2.44–4.64 mg Tocopherol 0.4–1700 µg	Fe 40 mg/g K 3370 mg/g Mg 2510 mg/g Ca 41 mg/g Zn 31 mg/g	USDA, 2011; Poonia et al., 2024; Mu et al., 2023
Amaranth	68.1	14.6	6.04	2.40	6.7mg	His 2 g/16 g N Lys 4.8 g/16g N Thr 5.1 g/16g N Val 5.1 g/16g N Leu 6.5 g/16g N Ile 3.9 g/16g N Phe+Tyr 9.1 g/16g N	Palmitic acid 7.38 mg Oleic acid 23.78 mg Linoleic acid 13.53 mg Linolenic acid 0.71 mg	Total flavonoids 91.94 µg RE/ g Phenolics content 138.96 µg GAE/g	Retinol 2 mg Ascorbic acid 4.2 mg Tocopherol 1.19 mg Folate 8 2 mg	Fe 7.61 mg P 557 mg K 508 mg	Sattar et al., 2024
Buck wheat	56	13.07	2.52	1.67	11.94 %	His 2.73 g/100g Lys 6.19 g/100g Thr 4.02 g/100g Val 5.23 g/100g	Palmitic acid 13.64 % Oleic acid 43.94 % Linoleic acid 31.81 % Linolenic acid 1.67 %	TPC 123–3149 mg RE/100g TFC 6–507.6 mg RE/100g	Thiamine 0.22 mg Riboflavin 0.1 mg niacin (Niacin) (Niacin) 1.8 mg Pantothenic acid 1.1 mg Pyridoxine 0.17 mg Tocopherol 140.1 µg/g Ascorbic acid 5mg	Fe 40 mg/g K 3370 mg/g Mg 2510 mg/g Ca 410 mg/g Zn 31mg/g	Sofi et al., 2023
Teff	85.6	9.37	4.4	–	9.8 %	His 3.2 g/16N Lys 3.7 g/16N Thr 4.3 g/16N Val 5.5 g/16N Leu 8.5 g/16N Ile 4.1 g/16N Phe+Tyr 9.5 g/16N	Oleic acid 29 % Linoleic acid 50 % (% of TUSFA)	TPC 161.27–460.7 mg GAE per 100g TFC 130.44–244.3 mg QE per 100g	niacin (Niacin) (Niacin) 3.363 mg Pyridoxine 0.482 mg Phylloquinone 1.9 µg Retinol 9 IU Tocopherol 0.08 mg	Fe 7.63 mg P 429 mg K 427 mg Ca 180 mg Zn 3.63 mg Mg 184 mg Na 12 mg	Gebru et al., 2021
Millets											
Pearl millet	61.78	10.96	5.43	137	11.49 %	His 2.15 g Iso 3.45 g Leu 8.52 g Lys 3.19 g Met 2.11 g Phe 4.82 g Thr 3.55 g Val 4.79 g	MUFAS 1047 mg SFAS 875 mg	TPC 269–420 mg GAE/100 g	Thiamine 0.25 mg Riboflavin 0.20 mg niacin (Niacin) (Niacin)e 0.86 mg Folic acid 36.11 mg	Fe 6.42 mg Al 2.21 mg Ca 27.35 mg Cu 0.54 mg	Dayakar et al., 2017; Shah et al., 2021
Sorghum	67.68	09.97	1.73	1.39	10.22 %	His 2.07 g Iso 3.45 g Leu 12.03 g Lys 2.31 g Met 1.52 g Phe 5.10 g	MUFAs acids 314 mg SFAs 163 mg	TPC 2.20 mg GAE/g TPC 0.84 mg Catechin/g	Thiamin 0.35 mg Riboflavin 0.14 mg niacin (Niacin) (Niacin) 1.34 mg	Fe 3.95 mg Al 2.56 mg Ca 27.60 mg Cu 0.45 mg	Dayakar et al., 2017; Slama et al., 2020

(continued on next page)

Table 1 (*continued*)

Crop	CHO (%)	Protein (%)	Fats (%)	Ash (%)	Dietary fiber	Amino acids	Fatty acids % (% of TFA)	Phytochemicals	Vitamins	Minerals	References
						Thr 2.96 g Val 4.51 g			Folic acid 34.66 mg		
Finger millet	66.82	07.16	1.92	2.04	11.18 %	His 2.37 g Iso 3.70 g Leu 8.86 g Lys 2.83 g Met 2.74 g Phe 5.70 g Thr 3.84 g Val 5.65 g	MUFAs 585 mg SFAs 317 mg	TPC 10.2 mg/100g TFC 62.23–74.05 mg/100g	Thiamin 0.26 mg Riboflavin 0.14 mg Naicin 1.34 mg Folic acid 36.20 mg	Fe 4.62 mg Al 3.64 mg Ca 364 mg Cu 0.67 mg	Hithamani and Srinivasan, 2014; Nakarani et al., 2021
Kodo millet	6619	08.92	2.55	1.72	06.39 %	His 2.14 g Iso 4.55 g Leu 11.96 g Lys 1.42 g Met 2.69 g Phe 6.27 g Thr 3.89 g Val 5.49 g	MUFAs 297 mg SFAs 246 mg	TPC 175.94 mg GAE per g TFC 16.48 mg RE per g	Thiamin 0.29 mg Riboflavin 0.20 mg niacin (Niacin) (Niacin) 1.49 mg Folic acid 39.49 mg	Fe 2.34 mg Al 1.07 mg Ca 15.27 mg Cu 0.26 mg	Dayakar et al., 2017; Pujari and Hoskeri, 2022
Little millet	65.55	08.92	2.55	1.72	06.39 %	His 2.35 g Iso 4.14 g Leu 08.08 g Lys 2.42 g Met 2..21 g Phe 6.14 g Thr 4.24 g Val 531 g	MUFAs 868 mg SFAs 589 mg	TPC 24 mM FAE per 100 g, TFC 87–33 mg/100g	Thiamin 0.26 mg Riboflavin 0.05 mg niacin (Niacin) (Niacin) 1.29 mg Folic acid 36.20 mg	Fe 1.26 mg Ca 16.07 mg Cu 0.34 mg	Dayakar et al., 2017; Shah et al., 2021
Foxtail millet	60.09	12.30	4.30	3.3	8.0 %	His 130 mg Lys 140 mg Arg 220 mg Cys 100 mg Met 180 mg Iso 480 mg Leu 1032 mg Thr 193 mg Phe 330 mg Try 60 mg	Palmitic acid 6.40 mg Stearic acid 6.30 mg Oleic acid 13.0 mg Linoleic acid 66.50 mg	TPC 28.2–59 mg RE/100g TFC 25–88 mg/100g	Thiamin 0.59 mg Riboflavin 0.11 mg niacin (Niacin) (Niacin) 3.20 mg	Fe 3.5 mg P 300 mg Ca 31 mg Zn 60.6 mg	Dayakar et al., 2017; Shah et al., 2021
Barnyard millet	65.55	06.20	2.20	–	–	–	Oleic acid 53.80 mg Palmitic acid 10.80 mg Linoleic acid 34. 90 mg	TPC 43 mg /100g TFC 29–58 mg/100g	Thiamin 0.33 mg Riboflavin 2.0 mg niacin (Niacin) (Niacin) 0.10 mg	Fe 17.4 mg Ca 18.3 mg Zn 57.4 mg	Dayakar et al., 2017; Shah et al., 2021
Fonio	0.6	21.5	0.34	4.3 %	59.4 %	His 2.02 mg Thr 2.62 mg Lys 6.42 mg Met 0.45 mg Val 7.26 mg Leu 1.18 mg Iso 1.18 mg Phe 3.9 mg Try 59.23 mg	–	TPC 134.42 mg/100g TFC 3.79 mg/100g	Thiamin 0.17 mg Riboflavin 0.22 mg niacin (Niacin) (Niacin) 1.15 mg	Fe 21 mg K 277.08 mg Ca 19.60 mg Mg 156.60 mg Zn 1.6 mg Na 1.4 mg	Ananth et al., 2023; Jocelyne et al., 2020; Koroch et al., 2013; Sadiq et al., 2015; Zu et al., 2020
Bambara groundnut	64.4	23.6	1.4–9.7	2.4–3.4	1.4–10.3 %	Lysine 80.2 mg Leucine 102.1 mg Asp 146.1 mg	Palmitic acid 21 % Oleic acid 23 % Linoleic acid 36 %	TPC 706.9 mg CE/100g Quercetin 0.007–6.39 mg/g Catechin	α-Tocopherol 0.38 mg	Fe 2–9 mg P 81–563 mg K 1545–2200 mg Mg 32–335	Maphosa et al., 2022; Ramatsetse et al., 2023; Tan et al., 2020a; D. Yao et al., 2015

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Table 1 (*continued*)

Crop	CHO (%)	Protein (%)	Fats (%)	Ash (%)	Dietary fiber	Amino acids	Fatty acids % (% of TFA)	Phytochemicals	Vitamins	Minerals	References
						Glu 209.5 mg		0.01–2.34 mg/g Myricetin 0.062–1.80 mg/g Keampferol 0.05–2.18 mg/g		mg Ca 30–128 mg	
Winged bean	37.34	29.88	17.76	4.78	4.74 %	His 0.99–4.2 g Lys 4.20–8.29 g Thr 1.4–6.9 g Arg 3.53–7.54 g Val 3.87–6.4 g Leu 6.2–11.1 g Iso 4.02–6.16 g Phe 2.2–5.79 g Try 3.2–5.3 g	Palmitic acid 36.27–39.3 % Stearic acid 13.5–15.5 % Oleic acid 15.3–17.7 5 Linoleic acid 12.3–14.3 % Linolenic acid 3.6–5.2 5	TPC 48.4–143.5 mg GAE/100g TFC 9.1–37.0 mg crude extract/100 g	Thiamin 0.08–1.7 mg Riboflavin 0.2–0.5 mg niacin (Niacin) (Niacin) 0.1–4.6 mg Folic acid 25.6–63.5 mg Tocopherol 22.8 mg	K 1110–1800 g P 200–610 g S 380 g Ca 80–370 g Mg 110–255 g	Bepary et al., 2023; Mediawati and Triatmi Andri Yanuarini, 2023
Moringa	56.50	28.50	2.33	9.33	3.0 %	His 30.88 µg/ml Lys 27.67 µg/ml Thr 36.77 µg/ml Val 22.1 µg/ml Leu 20.50 µg/ml Ile 31.8 µg/ml	Palmitic acid 8.87–12.2 % Oleic acid 66.5–74.8 % Linoleic acid 0.62–2.97 %	TPC 56.257 mg GAE/g TFC 29.33 mg GAE/g	niacin (Niacin) (Niacin) 1.5 mg Ascorbic acid 8.6 mg Tocopherol 77mg	Fe 379.56 ppm K 17,838.65 ppm P 4058.41 ppm Ca 28,387.96 ppm Mg 7116.78 ppm Mn 51.74 ppm	Saleh et al., 2024
Jackfruit	9.4–11.5	2.0–2.6	0.1–0.6	0.9	2.6–3.6 %	His 3.49 mg Thr 6.50 mg Val 7.16 mg Met 0.43 mg Lys 1.19 mg Leu 4.58 mg Iso 6.48 mg Phe 5.97 mg	Palmitic acid 39.85 % Oleic acid 3.30 % Linoleic acid 30.19 % Linolenic acid 3.73 %	TPC 23.28 mg GAE/g TFC 35.4 mg RE/g	Thiamin 0.105 mg Riboflavin 0.055 mg niacin (Niacin) (Niacin) 0.92 mg Pantothenic acid 0.235 mg Pyridoxine 0.329 mg Folic acid 24 µg Ascorbic acid 13.8 mg	Fe 0.23 mg P 21 mg K 448 mg Mg 29 mg Mn 0.043 mg Na 2 mg Zn 0.13 mg	Adan et al., 2020; Ranasinghe et al., 2019; Srivastava and Singh, 2020; Azeez et al., 2015; Amadi et al., 2018; Ojwang et al., 2015
Lablab bean	60.74	23.90	1.69	2.91	21.56 %	Lys 5.73 % His 2.89 % Thr 3.11 % Val 4.91 % Met 1.32 % Leu 7.02 % Iso 3.61 % Phe 5.26 % Try 3.18 %	Palmitic acid 11.58 % Oleic acid 8.94 % Linoleic acid 12.49 % Linolenic acid 16.06 % Docosapentaenoic acid 11.37 %	TPC 253.67 mg GAE per Kg TFC 124.15 RE per 100 g seed	Retinol 0.1 U Thiamin 1.130 mg Riboflavin 0.136 mg niacin (Niacin) (Niacin) 1.610 mg Pyridoxine 0.155 mg Folic acid 23 µg	Fe 5.10 mg Ca 130 mg Mg 283 mg Cu 1.335 mg Zn 9.30 mg	Habib et al., 2017a; Hossain et al., 2016; Naeem et al., 2020; Shaahu et al., 2015

*C (16:0): Palmitic acid; C (18:0): Stearic acid; C (18:1): Oleic acid; C (18:2): Linoleic acid; C (18:3): Linolenic acid; TFA: Total Fatty Acids; TUSFA: Total Unsaturated Fatty Acids; MUFAs: Monounsaturated Fatty Acids; SFAs: Saturated Fatty Acids; IU: International Unit; U: Units; TPC: Total Phenolics Content; TFC: Total Flavonoid Content; GAE: Gallic Acid Equivalents; FAE: Ferulic Acid Equivalents; CE: Catechin Equivalents; RE: Rutin Equivalents.

attributes of meals. An important outcome noticed when adding quinoa flour at concentrations ranging from 20 to 50 %, in combination with amaranth and kaniwa, is the alteration of internal architecture. As a result, this causes a decrease in pore size, an increase in hardness, and a reduction in crunchiness (Ramos Diaz et al., 2015). The snacks seen in the market are predominantly made out of corn or rice starch.

Nevertheless, these snacks possess little nutritional worth as a result of their elevated calorie concentration and absence of vital nutrients (Saldanha Do Carmo et al., 2019). Therefore, a new quinoa probiotic food can be a healthier option for a snack. The market for functional foods is primarily dominated by probiotic bacteria (De Almada et al., 2016).

Quinoa seeds have been used to meat recipes as components or used as alternatives for fat. Quinoa seed flour and starch are used into meat recipes to improve the overall health benefits of the end product. Typically, these ingredients are employed in amounts of <15 % (Mu et al., 2023). Research has demonstrated that the use of quinoa seed flour in meat products does not have any adverse impact on their physical, chemical, or sensory characteristics. In fact, it can enhance their resistance to oxidation (Verma et al., 2019). A recent study (Felix et al., 2021) showed that quinoa seed flour concentrations exceeding 200 g/kg had the ability to create gels with textures like sausages. This finding holds potential for the development of vegan meat substitutes. Another study found that using quinoa seed starch in chicken meatballs was more successful in avoiding water loss during cooking and freeze-thaw cycles, leading to higher acceptance compared to using quinoa seeds alone (Park et al., 2021).

Quinoa seed milk has a far lower glycemic index (GI) than rice milk, with values of 52 and 79 respectively (Pineli et al., 2015). This suggests that quinoa seeds could be a viable option for achieving sensory quality standards. The production of whole meal quinoa yoghurt involved the introduction of *Weissella cibaria* MG1 bacteria into pasteurized wholemeal quinoa milk at a concentration of 1 × 107 CFU/ml. The pasteurization process involved heating the quinoa milk to 110 °C for 10 min (Zannini et al., 2018). Due to its abundant starch content, quinoa is a flexible ingredient for developing valuable food items. Moreover, it is progressively employed for manufacturing non-dairy milk substitutes (Huang et al., 2021; Jeske et al., 2018)). Quinoa seeds are the most commonly utilized pseudocereal in brewing, as stated by the Food and Agriculture Organization (FAO). Both ungerminated quinoa seeds and quinoa flakes are employed in the manufacturing of beer. Research has demonstrated that incorporating 30 % quinoa seed flakes into the brewing process substantially improves foam stability, despite the fact that quinoa has a lower soluble nitrogen level. The enhanced quality can be due to the abundant presence of soluble proteins in quinoa, which give rise to substantial nitrogenous components at the molecular level. The addition of quinoa seed flakes to beer led to a greater sensory appeal in comparison to beer made solely from malt (Kordialik-Bogacka et al., 2018). In addition, a study assessed the suitability of quinoa seed protein for the process of wine phenolic fining (Pino-Ramos et al., 2022). According to their research, the protein present in quinoa seeds, whether used in amounts of either 30 g/h L or 50 g/h L, was just as successful as commercially available fining agents in lowering the cloudiness of red wine. This indicates that the protein found in quinoa seeds could be a practical substitute for animal protein in the process of wine fining.

3.2. Buckwheat

Buckwheat flour is a multifaceted component that has been observed to improve the sensory characteristics of many baked goods. Research suggests that buckwheat flour can be used as a substitute for wheat flour in biscuits, bread, and other baked goods without negatively affecting their acceptability. For example, biscuits made with 30 % or 40 % buckwheat flour were shown to be highly acceptable in sensory assessments (Filipcev et al., 2011; Filipčev et al., 2011). Furthermore, the addition of 30 % buckwheat flour to wheat bread resulted in enhanced antioxidant and sensory characteristics, leading to a high level of acceptance among consumers (Chlopicka et al., 2012). The addition of 10 % to 40 % buckwheat flour to regional bakery items such as Turkish bread and rolls improved their sensory attributes. Research has demonstrated that substituting wheat flour with buckwheat flour in baked goods enhances their antioxidant levels without significantly affecting their sensory attractiveness. The inclusion of whole-grain buckwheat flour in wheat bread enhances its antioxidant capabilities. Additionally, the incorporation of buckwheat hemicellulose into wheat-buckwheat bread enhances its physical characteristics (Starowicz et al., 2018). The bread containing buckwheat hemicellulose, despite its dark crumb color, was highly received by consumers. Additionally, the use of buckwheat flour improved the bread's visual appeal and color (Lin et al., 2009). The ideal ratios of buckwheat flour in gluten-free cakes, cookies, and muffins are 30 %, 10 %, and 20 % respectively (Dossa et al., 2023). The addition of buckwheat flour to durum semolina spaghetti enhances its volume, firmness, and ability to stick together (Chillo et al., 2008). It also has a beneficial impact on sensory attributes like smell, taste, shiny look, and color. The addition of 20 % buckwheat flour to instant noodles enhances both their texture and color (Choy et al., 2013). Buckwheat flour imparts a distinct nutty and earthy taste to bread, while simultaneously improving its nutritious composition. It can also be included into cakes, muffins, and various other baked items. The sensory characteristics of these baked goods are affected by the quantity of buckwheat flour utilized. Higher quantities result in a more pronounced buckwheat flavor and scent, although the texture may become more compact and weightier. Therefore, buckwheat flour is a highly valuable component in bread goods due to its distinctive flavors and nutritional advantages over the other crops.

The popularity of buckwheat sprouts is growing steadily because of their numerous health advantages. These sprouts, produced by germinating the seeds of the gluten-free buckwheat plant, contain high levels of flavonoids and anthocyanins, which are powerful antioxidants. The compounds present in them include rutin, isoorientin, vitexin, isovitexin, cyanidin 3-O-glucoside, and cyanidin 3-O-rutinoside (Kim et al., 2007; Liu et al., 2007; Nakamura et al., 2013). Incorporating buckwheat sprouts into one's diet can be a highly effective method to optimize these advantages. Nevertheless, there is a requirement for comprehensive details on the process of integrating buckwheat sprouts into food items. Only a limited number of research have examined the utilization of them as a component (Kim et al., 2004). Tartary buckwheat sprouts are a viable substitute for buckwheat flour in steamed bread recipes (Sturza et al., 2020). Nevertheless, the intense bitterness and astringency of the sprouts restricted their usage to minimal amounts (8 %) as higher concentrations had adverse impacts on consumer satisfaction.

Buckwheat beer is a gluten-free drink that is produced using buckwheat malt and other components that do not contain gluten. It is specifically intended for those with celiac disease or gluten intolerance who are unable to consume regular beers. Researcher demonstrated that buckwheat beer can attain sensory acceptance and quality comparable to that of barley beer (Sofi et al., 2023). The beer contains buckwheat malt, which is made by malting and kilning buckwheat groats. The biochemical characteristics of buckwheat groats have a substantial influence on both malt and beer production (Phiarais et al., 2010). In the manufacturing of buckwheat beer, the malting and mashing processes are carefully adjusted to ensure that the beer has the appropriate sensory characteristics. A recent study (Dabija et al., 2022) has demonstrated that buckwheat beer surpasses quinoa and other gluten-free pseudocereal beers in terms of carbonation levels and flavor purity. Nevertheless, the abundant presence of polyphenols and amino acids in buckwheat can intensify the impression of bitterness in the brew.

Buckwheat honey is a dark-hued honey renowned for its unique taste and scent, distinguishing it from other types of honey. This honey is derived from the nectar that bees gather from the blossoms of the buckwheat plant, which is cultivated extensively in many regions across the globe. Buckwheat honey is typically characterized by its opulent and malted flavor, accompanied by a little bitter undertone. The sensory assessments emphasize the intricate aroma of the substance (Zhou et al., 2002), which is a blend of malt, caramelized sugar, vanilla, butter, floral fragrances, and fruity esters. The complexity of this can be due to the presence of volatile substances such as 3-methyl butanal, maltol, furaneol, vanillin, different esters, 2-phenyl ethanol, β-damascenone, and phenylacetaldehyde. Buckwheat honey is renowned for its distinctive flavor and scent, as well as its notable health advantages stemming from its many antioxidants, which contribute to its anti-inflammatory effects (Schramm et al., 2003).

3.3. Amaranth

Amaranth grain can be utilized independently or in conjunction with other grains to produce extruded meals, baked goods, breakfast dishes, and gluten-free products (Schoenlechner et al., 2010). However, it is necessary to mix it with wheat flour in order to make leavened bread (Sanz-Penella et al., 2013). Making bread by combining various mixtures of amaranth and wheat flours, resulting in a notable improvement in nutritious value as the proportion of amaranth climbed from 5 to 30 % (Emire and Arega, 2012). Researcher (Ayo, 2001) found that when amaranth flour was mixed with wheat flour in varying proportions of 0 to 55 %, it resulted in a decrease in loaf volume and made the bread undesirable when the substitution level reached 15 %. The inclusion of amaranth flour in goods leads to a substantial increase in protein, fat, ash, dietary fiber, and mineral content. However, it is important to note that this also results in elevated phytate levels, which might potentially decrease the bioavailability of minerals. In order to preserve the nutritional content and overall quality of the product, it is advised to restrict the usage of amaranth flour to a maximum of 20 % (Sanz-Penella et al., 2013). Another study found that bakery items such as breads, biscuits, and cookies are among the most widely processed foods worldwide (Caleja et al., 2016). Biscuits, composed mainly of lipids and wheat flour, possess excellent digestibility and are rich in energy. Amaranth grain flour can be used as a substitute for up to 35 % of wheat flour, with the optimal substitution rate being 25 % (Sindhuja et al., 2005). This substitution rate results in enhancements in color, flavor, and appearance. When cookies made entirely from grain of amaranth had sensory attributes that were deemed acceptable (Aderibigbe et al., 2022).

Amaranth has been employed to enhance the protein and nutritious content of weaning diets (Anaemene et al., 2024). The utilization of malted flour derived from sorghum and amaranth was employed to enhance the quality of the flour and reduce the presence of anti-nutritional components. The blend consisting of 90 % amaranth and 10 % sorghum,meets the criteria set by the World Health Organization (WHO) in 2007 for supplementary diets for infants aged 12 to 23 months who are not well breastfed. Amaranth grains were soaked and pre-gelatinized in order to produce flour (Mburu et al., 2012). When given to infants three times daily, the resulting porridge fulfilled their daily requirements for protein, phosphorus, iron, zinc, riboflavin, niacin (Niacin), manganese, and tocopherols. Households in both rural and urban regions can be targeted with marketing campaigns for complementary diets that incorporate grains and amaranth. These diets offer a balanced combination of protein and energy, making them beneficial for the growth of children.

Functional meals and beverages offer benefits for both physiological and nutritional systems. A beverage containing extruded amaranth grains was preferred over a beverage without amaranth (Milán-Carrillo et al., 2012). In Nigeria, the traditional sorghum-based beverage known as Kunu has been substituted with a revitalizing non-alcoholic drink made by fermenting grain amaranth for different durations. Based on sensory evaluations, it was determined that amaranth-kunu fermented for 48 h was more enjoyable to taste compared to sorghum-kunu. Additionally, it was discovered to contain a greater amount of protein, fat, and ash content (Ndukwe et al., 2023). The germination and extrusion procedures to create a beverage by combining amaranth and tea (Dabija et al., 2022). They found that the protein content of germinated grains was more than that of extruded seeds (Manassero et al., 2020). The athletic performance indicators of cycling athletes were assessed in a randomized crossover study after consuming either a commercial beverage or a beverage containing amaranth. The amaranth beverage's elevated caloric content (52.48 kcal/100 mL) in contrast to the lower caloric content (24 kcal/100 mL) of commercial beverages likely contributed to the performance difference (Espino-González et al., 2016).

Squalene is a vital chemical found in both plant and animal cells, renowned for its significant biological roles. The amaranth plant is widely acknowledged as the primary and most plentiful source of squalene produced from plants (Venskutonis and Kraujalis, 2013). Plant-derived squalene oil is extensively employed in the formulation of cosmetics and personal care items (Aderibigbe et al., 2022). Amaranth-derived squalene possesses potent antioxidant capabilities that shield the skin from oxidative harm induced by free radicals (Huang et al., 2009). Additionally, it stimulates skin rejuvenation, fortifies the skin's defensive barrier, improves moisture retention, and minimizes water depletion.

3.4. Teff

Prior to the production of different food products, teff grains are milled into fine-sized flour particles. Either the grain is cooked to make porridge and stir-fried dishes or processed to produce extruded products, pasta, weaning food, cookies, cakes, muffins, puddings, bread, etc. (Barretto et al., 2021). In Ethiopia, the grain flour of teff is used to make Injera which is a flatbread exhibiting pancake-like softness and texture. The protein in teff does not contain gluten (of the type found in wheat). Due to the presence of prolamins of particularly smaller sizes, these flatbreads prepared from teff flour are easily digestible (Neela and Fanta, 2020). Ready-to-eat Injera from white and red teff via fermentation and determined their nutritional properties (Yisak et al., 2024). It was reported to have superior lipid quality in comparison to other cereals with a high content of α-linolenic acid. The well balanced $\omega-6/\omega-3$ ratio of fatty acids highlights the potential of teff Injera to be used as functional food. In order to cater the demands of celiac consumers, gluten-free breads were prepared using teff (10 % and 20 %) with cereal sourdough (rice/buckwheat). Upon addition of teff to cereal-based sourdoughs, the aroma profiles of the breads were modified and enhanced fruity, toasty, and cereal notes were detected.

Teff grains are also subjected to fermentation for the production of traditional alcoholic beverages in Ethiopia such as Arake, Tella, and Shamita (Fentie et al., 2020; Gebremariam et al., 2014). Arake is prepared by combining the teff derived unleavened bread, referred as kita, and germinated wheat/barley. This mixture is supplemented with water and ground gesho leaves and left for fermentation and finally distilled for consumption (Barretto et al., 2021). Fermented teff malt wort using *Lactobacillus amylolyticus* to produce a drink with pH 3.5 and lactic acid concentration of 9.5 g/L with well-balanced sweetness and sourness of the drink produced (Gebremariam et al., 2015). Teff-based probiotic functional non-alcoholic beverage that was fermented using mixed strain of L. *rhamnosus* (LGG) and L. *plantarum* (LA6) (Alemneh et al., 2021). With a growth of 8.24 and 8.41 log cfu/mL for LGG and LA6, respectively, the whole grain teff flour was effectively used a substrate to produce a functional probiotic beverage without using any other supplement.

3.5. Fonio

In countries, like the United States, fonio is beings actively and commercially being promoted as a healthy grain (Zhu, 2020). Fonio starch are being utilized for various food applications including the production of sprouts, malts, gluten free drinks, infant weaning and children's foods, breakfast cereals, non-wheat pasta, porridge, noodles, cookies, cakes, puddings, crackers, biscuits, sourdough breads and cakes (Zhu, 2020). Since fonio grain and flour do not have gluten in them, they do not exhibit the kind of rheology needed for a range of bakery products. However, due to their balanced nutritional and bioactive composition, fonio grain and flour are incorporated into various ingredients to develop a range of food formulations (Lerner et al., 2019). The techno-functional, rheological, pasting and gelling properties of fonio flour demonstrated good performance suggesting its use as a promising source of starch in preparation such as porridge (Deriu et al., 2022).

Ready-to-use Therapeutic Food (RUTF) for children with severe acute malnutrition was developed by using fonio flour and mixing it with ingredients (cashew nut paste, soya bean flour, crayfish powder, milk powder, sugar, vegetable oil, and mineral/vitamin mix). The developed food constituted of required nutritional content and had the acceptable eating quality (Eloho et al., 2017). Another study suggesting when white fonio flour and/or pigeon pea flours (both up to 20 %) were added to wheat flour for making breads (Olagunju et al., 2020). This resultant composite flour showed improved amino acid profile and increased protein content, while increasing the time of dough development and its pasting viscosity. When sourdough prepared using fonio and bambara groundnut flour mixture (in 1:1 ratio) and added 30 % wheat flour to make sourdough bread (Chinma et al., 2016). The pasting viscosity of the bread decreased with an increased sourdough content. Moreover, an improvement in the protein digestibility, dietary fiber content, antioxidants, minerals, and amino acids was observed with an increase in the proportion of fonio flour containing sourdough mixture. Currently, several studies are being carried out to modify fonio starch and include it in value-added processing for various food applications. In comparison to the conventional and commercially utilized starches such as potato, maize and cassava starches, fonio starch is relatively unconventional and underutilized (Zhu, 2020). A blend of fonio starch and defatted moringa seed flour was prepared by Raji (2018) to make a thick porridge. Fonio starch and moringa seed flour in the ratio 88 % to 12 % resulted in the highest sensory acceptance.

3.6. Millets (Finger millet, pearl millet, foxtail millet, and sorghum)

Due to promising nutritional profiles presented by different types of millets, millet-based goods and their high value uses have expanded in industrial sectors. Different foxtail millet-based food products namely *papad*, vegetable *dalia, sattu, kheer*, rusk, cookies, and bar were formulated and nutritionally evaluated (Arora et al., 2023). These products presented superior nutrient profile, low GI, high resistant starch and high acceptability as compared to the traditional products, suggesting their inclusion in every-day human diets to prevent malnutrition and type 2 diabetes. Various studies indicated that due to low cost and impressionable functional properties of foxtail millet flour and extracted protein concentrates, these products can be used to develop relatively low-cost and protein rich functional food formulations that help in managing various lifestyle related chronic diseases (Sachdev et al., 2021). Optimized the ingredient composition for preparation of foxtail millet (FTM) khichdi that constituted of instantized FTM, instantized green gram dal and oat flakes (Negi et al., 2021). The developed product showed good reconstitution/rehydration properties and a calorific value of 525.11 kcal/100 g. Nutrient-rich foxtail millet (FTM) based instant noodles were developed (Meherunnahar et al., 2023) using a mix of FTM flour and wheat flour. The research findings revealed that the noodles prepared from this composite had significantly enhanced levels of fiber, protein, ash, calcium and phosphorus. These FTM enriched noodles presented higher essential amino acid index, biological value, chemical score and protein efficiency ratio in comparison to that of the commercial noodles.

Finger millet is another staple millet that is well known for its nutritional quality that includes high amounts of dietary fiber, starch and protein. In a study conducted (Meena et al., 2023), white finger millet (WFM) was used for the production of probiotic beverages using ultrasound treatment. It was observed that the total flavonoids, phenols, antioxidant activities and reducing sugar content was significantly high. It was proposed that the millet as a substrate for the production of probiotic beverage could overcome certain health concerns such as high cholesterol and lactose intolerance. With high proliferation kinetics of L. *rhamnosus*, the fermented WFM beverage poses to be a healthy probiotic rich functional food product. Researcher prepared yoghurt-like beverage from finger millet using a co-culture of *Weisella confusa* and *Lactiplantibacillus plantarum* (Vila-Real et al., 2022). The beverage showed improved physicochemical and nutritional profiles as compared to the unfermented control. This developed functional prototype proved to be of high quality and organoleptically acceptable for targeting the population in diverse demographic subgroups in the international market. Due to the rising prevalence of celiac disease, gluten-free flours for the preparation of flat breads are encouraged, Maize flour is a widely consumed flour that is used to make unleavened flatbreads. However, due to lack of gluten, its viscoelasticity is limited that causes problems in rolling, sheeting and puffing of the bread dough. Therefore, Kumar et al. (Kumar et al., 2023) supplemented maize flour with finger millet flour. After evaluating the properties of composite flour, it was observed that the finger millet flour had a promising potential to improve the rheology, nutritional quality and techno-functionality of maize based flatbreads.

3.7. Bambara groundnut

Bambara groundnut is commonly used to produce snacks after roasting or boiling. The green pods, dry nuts as well as grains from bambara groundnut are very nutritious and are processed to make a variety of food products (Khan et al., 2021). The fresh green nuts are either grilled or steamed, and served as snackable titbits, while the seeds and flour are used to make porridge, breads, and flat cakes. In African subcontinent, its seeds and flour have been used to produce a myriad of traditional food such as *okpa* (steamed pudding prepared from bambara groundnut flour and red palm oil), *koose* (savoury fried bean paste), *gablee* (boiled bean paste), *tubani* (bean paste steamed in leaves), etc. (Tan et al., 2020b). Value-added snacks were prepared from bambara groundnut paste and flour (Oyeyinka et al., 2018). The snacks prepared from the flour exhibited higher protein content (23.41 g/100*g*) as compared to the sample prepared from the paste (19.35 g/100 g). A developed extruded snacks using orange-fleshed sweet potato and bambara groundnut to nutritionally enrich them and enhance consumer acceptability (Honi et al., 2018).

Germinated bambara groundnut flour (GBF) was used as an ingredient at different proportions (5 %, 10 %, 15 %, 20 %, 25 % and 30 %) in preparing wheat bread (Chinma et al., 2023). The composite breads so prepared exhibited significantly improved the dietary fiber content, resistant starch, total flavonoid content, protein digestibility, antioxidant activities and corrected amino acid scores. The supplementation of GBF in wheat flour influenced the texture and color properties of bread, where 20 % GBF presented higher scores in aroma, taste and overall acceptability. This study provided a suitable possibility of partial substitution of wheat flour with bambara groundnut flour to improve the functionality and functionality of bread. Research was carried out for aqueous extraction of milk from bambara groundnut flour after dehulling the seeds followed by parboiling (Pahane et al., 2017). The milk was then fermented into yogurt which was reported to have a high protein content (1.8 g/100 g) and protein digestibility (91.5–96 %), while the phytate content decreased significantly (0.29 g/100 g). These results indicated that the quality of bambara groundnut protein enhances through its processing into high value yogurt.

3.8. Winged bean

Winged bean has been reported as a multi-purpose crop where its different parts including the flower, tubers, tender pods, leaves and dried seeds are used to make different food products. The raw winged bean flowers are tossed in salads, used as a coloring agent in gravies, and also fried in oil for developing mushroom-like taste. The leaves give a spinach like flavour and are consumed in a similar way, while seeds are eaten in soups (in immature form) or dried and roasted, and then ground into flour (Bepary et al., 2023). On a commercial scale, preparation of winged bean tempeh, miso, milk, fermented milk (tairu) and curd, as well as formulation of weaning foods is being carried out in Ghana, Indonesia and Thailand. Furthermore, a coffee substitute was prepared from the roasted seeds of winged bean and a tobacco substitute from its dried leaves (Mohanty et al., 2020b).

Research was carried out to prepare tempeh using only soybean (control) and winged bean seeds combined with soybean in equal amounts (Maitresya and Surya, 2023). It was elucidated that the tempeh formulated using winged bean with soybean constituted of an observably major amount of protein and antioxidant activity in comparison to the control sample. Protein rich cookies were prepared using corn flour combined with winged bean seed and tuber flour (Gajanayaka et al., 2021). Among all the different formulations of the cookies prepared, the highest sensory score of 7.25 was obtained by the cookies containing 40 %-winged bean seed flour, 20 %-winged bean tuber flour and 20 % corn flour. This formulation exhibited an impressionable protein content of 16.39 % and fiber content of 23.70 %. In another study, zero-trans-fatty acid margarine blends were formulated using 50 % winged bean oil, 48.5 % palm stearin and 1.5 % palm olein (Makeri et al., 2019). The margarine so prepared from underutilized winged bean oil, having high solid fat content, exhibited low atherogenic and thrombogenic indexes, thereby reducing the risk of coronary heart disease and associated ailments. The seed-oil extracted from white, light-brown and dark-brown seeds of winged bean was deemed suitable and comparable with soybean seed-oil (Mohanty et al., 2021).

3.9. Lablab bean

The lablab beans or the hyacinth beans are an excellent source of protein, essential amino acids, fatty acids, carotenoids, tocopherols and bioactive compounds (Habib et al., 2017b). Various ancient records revealed that lablabs have been used in China for various culinary used such as in steamed dishes, porridge, ground powder, cakes, boiled preparations, stew, fried snacks, etc. (Yao et al., 2024). In the state of Maharashtra, India, special curries are prepared using lablabs during the vegetarian fasting time of Shraavana festival. *Pitakapappu hanupa/anapa* or the pressed lablab and a curry called *pitikina anapaginjala caaru/ pitaka pappu* is another preparation made from deskinned lablab beans that is eaten with bajra bread in Andhra Pradesh and Telangana states of India. These hyacinth beans are also added in Burmese curry called *hnat*, and also served in Burmese pickled tea leaf salad after frying (Yao et al., 2024).

A researcher characterized the usage of lablab bean as a protein supplement in biscuits (Rana et al., 2021). The biscuits prepared with combined wheat/ lablab bean seed powder proved to be nutritionally rich as compared to control wheat biscuits. Additionally, the reasonable sensory properties (color, flavor, taste, texture and acceptability) may allow the use of lablab bean seed in the processing of other baked items. In a recent study, nutrionally rich lablab bean seed powder was used to develop protein-rich biscuits. Upon adding the bean seed powder, the biscuits exhibited a protein content of 9.92 %, crude fiber content of 1.84 % and ash content of 1.39 % (Akter et al., 2024). The organoleptic studies revealed that the control biscuits and those with 5 % lablab bean seed powder ranked similarly. Protein hydrolysates were extracted from lablab by enzymatic hydrolysis followed by isoelectric precipitation and were later added into apple juice. A major reduction in the oxidant compound profile in the juice was exhibited, demonstrating that the lablab or hyacinth hydrolysates offer a considerable potential for their use as natural antioxidants in the food industry (Roy et al., 2022).

3.10. Moringa

Supplementation of food products with moringa resulted in their enrichment with minerals, vitamins, essential amino acids and oil, thereby, improving their nutritional value (Milla et al., 2021). M. *oleifera* leaves have been included in various food items such as cereal porridge, yoghurts, cookies, bread, cheese, cake, etc. and have been reported to boost consumers' endogenous antioxidant ability to scavenge free radicals while extending the product shelf life and overall sensory acceptability (Falowo et al., 2018). Utilization of moringa based products to develop natural and healthy functional foods is a sought-after research and commercialization area. M. *oleifera* Lam. leaves were added to the Fuzhuan Brick Tea (FBT) for co-fermentation (Li et al., 2022) that resulted in enhanced contents of organic acid, lipids, amino acids, alkaloids and quinate in the final product. This was a promising strategy to enhance the nutritional and functional components in FBT. Since moringa leaves have been recommended as rich source of vitamins including vitamin A, C and B6) as well as different minerals and protein, they are used as complementary nutritional foods in different baby diet formulations. An instant porridge was prepared using three formulas comprising of moringa leaf flour (5, 6 and 7 g, respectively) and mixed with oatmeal powder (30 g), powdered formula (40 g), refined sugar (10 g) and banana flour (5 g) (Katmawanti et al., 2021). The formula with 5 g of leaf flour exhibited the best results with desirable color, taste, and texture results with an energy content of 196 kcal/serving. The nutritional value of this baby porridge was in accordance with SNI 01–7111.1 having protein content twice as compared to the commercial counterpart.

The seeds of moringa plant are rich in protein (~52 %), constituting of all essential amino acids. Therefore, it is an important source to be tapped for the production of protein isolates for various food applications (Kumar et al., 2022). A study was conducted (Cardines et al., 2018), to see the impact of addition of moringa seed extract (obtained via ultrafiltration) into yoghurt. The results revealed that the moringa extract containing yoghurt presented higher consistency index value, protein content, and cohesive casein content, whereas the syneresis value was reported to be lower than the control. These findings endorsed moringa seed extract as a natural thickening agent in food systems. Protein-polyphenol hydrogen bonding and hydrophobic interactions between moringa seed residue protein (MSRP) and tannic acid (TA) were explored which were utilized as Pickering stabilizers (Huang et al., 2022). The MSRP:TA ratio of 1:0.5 improved the emulsion stability at lower ionic strengths (<0.2 M) and higher pH values (pH 7–9), indicating the potential of this complex to be used as an emulsifier in foods.

3.11. Jackfruit

Jackfruit can be eaten fresh as well as utilized for the development of various products such as jackfruit-based curries, salads, smoothies, *biryani*, etc. (Khan et al., 2023). The consumption of jackfruit in the fresh form or as canned slices, dried chips and fruit juice, primarily depends on its stage of maturity. Young jackfruit (*gori*) is a popular raw material for cooking a variety of Indonesian dishes such as jackfruit curry, *sayur lodeh* (soup with vegetables and coconut milk), *oseng-oseng gori* (cooked quickly using very little oil), *sayur megana* (chopped and cooked with grated coconut and spices), *rujak* (salad), etc. (Yudhistira, 2022). The functional properties of different Chinese cultivars of jackfruit were investigated for their potential to be used as food thickening and gelling agents (Zhang et al., 2018). Significant differences in their functional attributes led to their classification into three groups where the cultivars in the first group (M8, ZZ) were suitable as food thickening/gelling agents; the ones in second group (M2, M3, M4) were recommended for application in glutinous foods, and the third group cultivars (X2, X3, X4, X11) could be used for fillings in confectionery or weaning foods. The relatively lower breakdown and setback values of native jackfruit seed starch in high acid foods like chilli sauce at optimized concentrations, resulted in its use as a thickener and stabilizer to prevent serum separation during storage (Rengsutthi and Charoenrein, 2011).

The seeds of jackfruit plant, often dismissed as by-products, exhibit of a promising nutritional and bioactive profile constituting of flavonoids, phenolics and saponins. This knowledge encouraged the researchers to incorporate jackfruit seed flour into bakery products to

Table 2
Summarised food-based products and their description from potential underutilized crops.

Crop	Category	Description	References
Quiona	Gluten free bakery food	• Low glycemic index • Greater amounts of dietary fibres and phytochemicals • Balanced amino acid profile	(Mu et al., 2023)
	Meat analogues	• Useful for vegan meat alternatives • Prevent water loss during cooking • Improve oxidative stability of meat product	(Park et al., 2021)
	Plant Milk and yoghurt Fermented Beverages	• Lower glycemic index compared to rice milk (52 vs. 79) • Lower soluble nitrogen content • High levels of soluble proteins • Effective agents in reducing red wine turbidity	(Pineli et al., 2015) (Kordialik-Bogacka et al., 2018)
	Quinoa dessert	• Quinoa used as a milk substitute • Quinoa flour used as a gelling agent	(Yarabbi et al., 2023)
Amaranthus	Amaranth-wheat based bakery product	• Significant improvement in nutritional content • Enhancements in sensory attributes such as hue, gustatory perception, aroma, and visual presentation	(Sindhuja et al., 2005)
	Amaranth oil	• High antioxidant content in squalene derived from amaranth • Protecting the skin from oxidative damage induced from free radicals	(Huang et al., 2009)
	Weaning foods formulations	• Improved flour quality and reduce anti-nutritional factors	(Soriano-García and Saraid Aguirre-Díaz, 2020)
	Functional beverages	• Considerable fat, protein, and ash content • Potential in preventing and treating chronic-degenerative diseases	(Sarker et al., 2024)
Buckwheat	Gluten free bakery products	• Improved antioxidant and sensory properties • Enhanced hardness, bulkiness, and adhesiveness when incorporated in durum semolina spaghetti	(Chlopicka et al., 2012) (Chillo et al., 2008)
	Sprouts Beer	• Rich in flavonoids and anthocyanins, potent antioxidants • Cost effective gluten-free beverage • Enhanced bitterness in beer attributed to buckwheat's high polyphenol and amino acid content	(Nakamura et al., 2013) (Deželak et al., 2014)
	Honey	• Improved antioxidant properties • High anti-inflammatory properties • Unique taste and aroma	(Gheldof et al., 2003)
Teff	Gluten-free fermented flatbread (Injera)	• $\omega-6/\omega-3$ ratio of fatty acids in balanced proportions • Desirable palatability and nutritional composition	(Yisak et al., 2024)
	Sourdough bread	• Improved aroma scores and enhanced fruity and toasty levels • Bread with teff flour (20 %) exhibited reduced loaf volume and high score in visual appearance	(Campo et al., 2016)
	Functional probiotic beverage	• L. *rhamnosus* (LGG) and L. *plantarum* (LA6) growth (8.24 and 8.41 log cfu/mL, respectively) on teff flour without any supplement; <5 % ethanol detected	(Alemneh et al., 2021)
	Malt for lactic-acid fermented drink	• At optimum conditions (temperature: 42°C, initial pH: 5.4, initial cell concentration: 1.86×10^5 cells/mL, fermentation time: 52 h) • L. *amylolyticus* mediated fermentation produced teff based beverage with lactic acid concentration of 9.5 g/L, pH of 3.5 and lactic acid: sugar ratio of 0.26	(Gebremariam et al., 2015)
Fonio	Flour	• Pasting, gelling, techno-functional, and rheological properties of fonio flour demonstrated good performance suggesting its use as a promising ingredient in gel-like food formulations	(Deriu et al., 2022)
	Bread	• Fonio flour (10 %) was added to wheat flour to make bread • Fonio addition of 2.5 % increased the bread volume whereas 5–10 % addition showed no effect on the volume	(Olagunju et al., 2020)
	Starch noodles from white fonio	• Fonio starch (88 %) mixed with defatted moringa seed flour (12 %) and cooked to make a thick porridge with good sensory attributes	Raji, 2018
	White fonio based ready-to-eat therapeutic children's food	• Combination of white fonio flour, soy bean flour, cashew nut paste, vegetable oil, milk powder, crayfish powder, and a mineral-vitamin mix • Resulting product exhibited recommended nutritional requirements and displayed acceptable eating quality	(Eloho et al., 2017)
	Sourdough bread	• White fonio and bambara nut flour mixed in the ratio of 1:1 and fermented to sourdough which was further mixed with wheat flour to bake bread. • Addition of the sourdough increased the nutritional content (dietary fiber, minerals, antioxidants, amino acids), improved sensory quality and decreased antinutrients (tannins and phytate).	(Chinma et al., 2016)
Foxtail millet	*papad*, vegetable *dalia, sattu, kheer*, rusk, cookies, and bar	• Foxtail-millet based food products displayed high protein content (10.98–16.10 g/100*g*). • Foxtail kheer was reported to contain the maximum protein (16.01 g/100 g); resistant starch and predicted glycemic content ranged between 13.67–22.61 and 46.12–57.55 g/100 g, respectively.	(Arora et al., 2023)
	Nutrient rich instant noodles	• Higher protein efficiency ratio, biological value, essential amino acid index and chemical score than that of commercial noodles	(Meherunnahar et al., 2023)
	Khichdi	• Khichdi prepared using instantized foxtail millet, oat flakes, and instantized green gram dal • The khichdi presented good reconstitution/rehydration properties and a calorific value: 525.11 kcal/100g	
Finger millet	Probiotic beverage	• White finger millet based probiotic beverage prepared using ultrasound treatment exhibited high nutrient content and viable counts of good bacteria (L. *rhamnosus*) • The fermented finger millet-based beverage proved to be a healthy and enriched probiotic-rich functional food.	(Meena et al., 2023)

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Table 2 (*continued*)

Crop	Category	Description	References
	Flatbread	• Gluten free maize flatbreads were prepared using extruded finger millet • Enhanced textural and elastic character displayed by the composite maize dough	(Kumar et al., 2023)
	Probiotic yoghurt	• L. *plantarum* and W. *confusa* -promising starter co-culture for fermentation of cereal matrix • Fermented yoghurt like beverage displayed improved physicochemical and nutritional profiles, compared to the unfermented control	(Vila-Real et al., 2022)
Bambara groundnut	Biscuits from wheat and bambara groundnut blends	• The bambara flour (BF) and bambara protein isolates (BPI) used for the production of biscuits • Essential amino acid content, biological value, and protein efficiency ratio in the composite flour as well as the biscuits adequately fall in the requisite range to support the growth and development of infants, children, and adults	Adegbanke et al., 2024
	Bread	• Bambara groundnut flour (GBF) added into wheat flour • Dough showed higher water absorption capacity, gelatinization temperatures, higher dietary fiber, protein digestibility, resistant starch, phenolics, antioxidant capacity; addition of 15 % GBF did not significantly impact the bread volume	(Chinma et al., 2023)
	Extruded snacks	• Recipe incorporating bambara groundnut flour and orange-fleshed sweet potatoes was prepared • The extruded snacks were acceptable, shelf life stable and vitamin A enriched	(Honi et al., 2018)
	Protein rich snacks from paste and flour	• Value added snacks were prepared from Bambara groundnut paste and flour • Snacks formulated using flour exhibited a protein content of 23.41 g/100 g which was higher than that of snacks prepared from the paste, having protein content of 19.35 g/100 g	(Oyeyinka et al., 2018)
	Milk and yogurt	• Aqueous extraction of milk from bambara groundnut flour and fermentation into yogurt • Yogurt constituted of a high protein content (1.8 g/100 g) and protein digestibility (91.5–96 %), while the phytate content decreased significantly (0.29 g/100 g)	(Pahane et al., 2017)
Winged bean	Tempeh	• Bean tempeh formulated using winged bean seeds (50 %) • Significant high antioxidant activity and protein content was detected	(Maitresya and Surya, 2023)
	Protein enriched cookies	• Cookies prepared using winged bean seed flour (40 %), winged bean tuber flour (20 %) and corn flour (20 %) • Exhibited a protein content of 16.39 % and the highest sensory score (7.25) among all the formulations	(Gajanayaka et al., 2021)
	Refined seed oil	• The refined oil extracted from winged bean seeds proved to be comparable with soybean seed oil, exhibiting a considerable thermal stability.	(Mohanty et al., 2021)
	Margarine blend	• Winged bean oil used as a base to produce zero-trans-fatty acid margarine blend; the blend constituted of 50 %-winged bean oil, 48.5 % palm stearin and 1.5 % palm olein; the margarine displayed low thrombogenic indexes.	(Makeri et al., 2019)
Lablab bean	Biscuits enriched with protein	• Protein enriched biscuits formulated with lablab bean seed powder • Protein content, crude fiber and ash content of biscuits increased to 9.92 %, 1.84 % and 1.39 %, respectively after supplementation of bean seed powder • The control and 5 % bean seed powder ranked similarly in the organoleptic analysis	(Akter et al., 2024)
	Apple juice additive	• Hyacinth bean protein hydrolysates displaying strong antioxidant activities were incorporated in apple juice (at a rate of 3 g/L) • These hydrolysates delayed the development of oxidising products for a period of 6 days during storage at ambient temperature	(Roy et al., 2022)
	Semi-dried noodles	• Crude peptide extract from lablab bean at a concentration of 200 mg/mL was added in rice noodles • it improved the color of the noodles and reduced the cooking time.	(Bai-Ngew et al., 2021)
	Biscuits from seed flour	• Lablab bean powder blended with wheat flour; the resultant biscuits showed higher protein content, dietary fiber, ash content and lower carbohydrate and fat content; reasonable sensory properties of the biscuits were also reported.	(Rana et al., 2021)
Moringa	M. *oleifera* Lam. leaf tea	• Fuzhuan Brick Tea (FBT) mixed with moringa leaves for co-fermentation • the metabolomic analysis of the final product exhibited significant increase in alkaloids, amino acids, organic acids, lipids and quinate	(Li et al., 2022)
	Emulsifier in foods	• Moringa seed residue protein (MSRP) combined with tannic acid (TA) to develop pickering stabilizers • Exhibited an improved emulsion stability at optimized MSRP: TA ratio which was 1:0.5	(Huang et al., 2022)
	Baby porridge	• Moringa leaf powder, oatmeal powder, banana flour, powdered formula and refined sugar combined in the ratio 5:30:5:40:10:10 • Instant porridge with high nutritional content and overall sensory analysis acceptance	(Katmawanti et al., 2021)
	Flavouring agent	• Moringa leaf powder (1 %) supplemented into mango flavored yogurt • Aroma, texture, color and overall acceptability reported to be the highest amongst different formulations • Exhibited storage time of 15 days and lower pH and moisture content relative to the control sample	(Saeed et al., 2021)
	Yoghurt thickener	• M. *oleifera* seed extracts were used as promising thickening agents in yoghurt production; exhibited lower values of syneresis and improved yoghurt viscosity using ultrafiltered moringa additives	(Cardines et al., 2018)
Jackfruit	Thickening agent in soups	• Jackfruit by-products (peel, core and tandem) subjected to pectin extraction at w/v; temperature of extraction: 80℃; pH: 2.0; time of extraction: 105 min and solid-liquid ratio: 1.29 % • Jackfruit-pectin combined with low quantity of starch exhibit promising thickening quality in vegetable soups, securing high scores in sensory properties	(Islam et al., 2023)

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Table 2 (*continued*)

Crop	Category	Description	References
	Meat analogue formulation	• By-products of jackfruit constituting of rinds, rags, and seeds: 58 %, combined with wheat gluten (20 %) for the development meat analogues that exhibited promising sensory attributes	(Hamid et al., 2020)
	Thickener and gelling agent (for weaning/confectionary items)	• Jackfruit cultivars (ZZ, M8) suitable as gelling/thickening agents. For pastries, cakes • Cultivars: X3, X4 and X11 suitable as fillings in food items (confectionary/weaning)	(Zhang et al., 2018)
	Fried Chips	• Jackfruit bulb slices were pre-partially dried and pre-frozen; the pre-frozen chips prepared showed high sensory acceptability	(Maity et al., 2018)
	Chilli sauce additive	• Native jackfruit starch on adding in high acid foods like chilli sauce at 1 % level maintain the titration acidity, pH, and total soluble solids of the sauce • Further, jackfruit starch presents low setback and breakdown value, thus, showing no serum separation during storage.	(Rengsutthi and Charoenrein, 2011)

improve their nutritional profiles and enhance their functional properties such water and oil absorption capacity (López-Martínez et al., 2024). The potential of jack-fruit by-products (outer layer of skin, rinds, rags and seeds) combined with wheat gluten were investigated for the production of meat analogue formulations (Hamid et al., 2020). The prepared meat analogue consisting of jackfruit by-products (58 %) and vital wheat gluten (20 %) exhibited the most promising sensory qualities (appearance, taste, aroma, juiciness, color, and hardness) and therefore overall acceptability. In another study was conducted by using the by-products of jackfruit (peel, core and tandem) for acid extraction of pectin (pectin yield: 35.13 %) under optimized conditions (solid-liquid ratio: 1.29 %, w/v; temperature of extraction: 80°C; pH: 2.0; time of extraction: 105 min) (Islam et al., 2023). The pectin after extraction was then used as a thickener in vegetable soups in optimized concentrations. The jackfruit-pectin combined with a low amount of starch exhibited good quality and overall sensory acceptability, thereby highlighting its application as a thickening agent in soups.

Table 2.

4. Challenges and opportunities in commercializing underutilized crops

Bringing underutilized crops to the mainstream market presents several significant challenges that hinder their widespread adoption and commercialization. One of the primary issues is the yield variability and susceptibility to various biotic and abiotic stresses, which make these crops less predictable and reliable compared to conventional staple crops like wheat, rice, and maize. The lack of well-established agronomic management practices further exacerbates this issue, as there are limited guidelines available for optimizing the cultivation of these crops under diverse environmental conditions (Adelabu and Franke, 2023; Farooq et al., 2023, 2023; Wani et al., 2021). Additionally, maintaining pure line seeds is a challenge, leading to inconsistent crop quality and performance. Apart from that major obstacle is the lack of a robust supply chain infrastructure, many underutilized crops do not have established post-harvest processing units for storage, transportation, and value addition which makes it difficult to ensure product quality and reduce post-harvest losses. The absence of proper storage facilities also leads to spoilage and reduced shelf life, further discouraging farmers from cultivating these crops.

The lack of high-throughput phenotyping facilities along with key challenges during the crossing program further hinder the potential for utilizing the vast genetic diversity present in underutilized crops found in their gene pools. This underutilization limits are the major opportunities to improve crop resilience, productivity, and adaptation to changing environmental conditions. Limited systematic public programs and almost negligible industrial support in underutilization research and improvement at current phase in worldwide. Other major crops such as wheat, rice, maize, soyabean and so on are gaining more scientific attention, funding and support at institutional, academic, industrial as well as at policy levels, which comparatively, has not been quite the case with underutilized crops. In the future, integration of genomic advances into public and private breeding program to develop nutrition rich cultivars from underutilized crops and their broader adoption in target environments will be crucial for maximizing their potential.

Another primary challenge is the limited and fragmented data, which hampers the understanding and promotion of diverse diets and improved nutrition through the use of these crops. The scattered and inaccessible nature of relevant information further restricts its reach to policymakers and practitioners. Additionally, there is a significant gap in consumer awareness and demand for products derived from underutilized crops. Without sufficient consumer interest, there is little incentive for farmers and producers to invest in these crops. Regulatory hurdles also pose challenges, as these crops may not meet the established standards and certifications required for market entry, limiting their access to global markets. Farmers are often reluctant to grow underutilized crops due to the absence of fixed Minimum Support Prices (MSPs) and the ease of selling conventional staples. The competition with these conventional crops, which are easier to sell and come with assured prices, discourages farmers from experimenting with potentially riskier underutilized crops. Furthermore, there is a lack of capacity due to poorly developed infrastructure and markets, which are essential for the promotion and consumption of these crops. The global food system and trade policies tend to prioritize exotic or imported foods, which are often underpriced and externalize health and environmental costs, making them more convenient choices for consumers. Addressing these challenges requires concerted efforts to develop agronomic packages, improve supply chain infrastructure, enhance consumer awareness, and provide policy support to encourage the cultivation and commercialization of underutilized crops.

On the other hand, the integration of underutilized crops into mainstream food systems presents numerous opportunities for innovation in product development, marketing strategies, and sustainability practices. One of the most promising areas is the creation of novel, value-added food products that cater to the growing consumer demand for health-conscious, gluten-free, and plant-based options. By leveraging the unique nutritional and functional properties of these crops, R&D teams and academic institutions can collaboratively develop scientifically validated products including, nutritious snacks, cereals, and functional foods, that appeal to health-focused and eco-conscious consumers, bridging innovation with market demand. In terms of marketing, there is a significant opportunity to position underutilized crops as "superfoods" or key components of sustainable diets. Effective branding and storytelling that emphasize their nutritional benefits, cultural heritage, and role in supporting biodiversity can help raise consumer awareness and drive demand. Collaborations with influencers, health professionals, and sustainability advocates can further enhance the market appeal of these crops. From a sustainability perspective, underutilized crops offer a pathway to more resilient and diversified agricultural systems. Their adaptability to marginal environments and low input requirements makes them ideal candidates for sustainable farming practices, including agroecology and regenerative agriculture. This aligns with global efforts to mitigate climate change and reduce the environmental footprint of food production. Potential areas for further research and development include enhancing the agronomic traits of these crops through biotechnological approaches, optimizing processing techniques to retain nutritional value, and improving supply chain logistics to ensure product quality and accessibility. By investing in these areas, stakeholders can unlock the full potential of underutilized crops and contribute to a more sustainable and nutritious global food system.

5. Future directions and concluding remarks

To utilise the potential of underutilized crops in modern food systems, several key areas require further research and development. A key area is the exploration, identification, conservation, and evaluation of local germplasm, particularly from regions with rich biodiversity. The potential of Artificial Intelligence-driven prediction modeling in crop selection is immense, mainly for mainstreaming underutilized crops that possess unique and diverse germplasm. Many of these crops, particularly those from biodiversity hotspots, possess rich genetic diversity and are extensively conserved in national and international gene banks. For example, the National Gene Bank of India, the world's second-largest gene bank, safeguards a wide range of crop germplasm, including potential underutilized crops. However, their commercial adoption remains limited due to the lack of systematic evaluation of their nutritional and agronomic traits. Traditional methods for assessing these crops require destructive sampling, extensive biochemical analysis, and significant time, labor, and financial resources, thus making large-scale screening challenging. To accelerate the characterization and selection process, non-destructive analytical techniques such as Near-Infrared Spectroscopy (NIRS) and Fourier Transform Infrared Spectroscopy (FTIR) have emerged as powerful tools. When coupled with AI-based modeling approaches, particularly deep learning architectures like 1D-CNNs, transformers, and hybrid models, these techniques enable rapid, high-throughput, and accurate screening of underutilized crop germplasm (Singh et al., 2024; Kaur et al., 2024d, 2024e; Padhi et al., 2022; John et al., 2023). AI-driven models can analyze spectral data efficiently and allow the identification of nutritionally superior and chemically diverse chemotypes within a large genetic pool (Kaur et al., 2024b, 2024c). This eliminates the need for costly and time-consuming wet lab experiments which makes the evaluation of nutritional and non-nutritional traits much faster and scalable.

By utilising AI-integrated NIRS profiling, nutritionally rich and agronomically promising accessions can be identified for breeding programs and varietal development for ultimately facilitating their integration into mainstream agriculture. Several studies have already demonstrated the potential of NIRS coupled with AI-driven models in predicting biochemical and functional properties in potential underutilized crops such as Perilla (Kaur et al., 2024e), Cowpea (Padhi et al., 2022), and Lablab Bean (Singh et al., 2024; Kaur et al., 2024d). These approaches enhance selection efficiency, improve breeding precision, and support targeted crop improvement strategies. In addition to screening larger germplasm accessions, genomic selections using biotechnological interventions and targeted breeding strategies are essential for improving the nutritional profiles of underutilized crops. Biotechnological approaches such as genetic engineering, CRISPR-Cas9 genome editing, and marker-assisted breeding can enhance the agronomic traits of underutilized crops by improving stress tolerance, disease resistance, and nutritional quality. Additionally, microbial biofertilizers and metabolic engineering play a crucial role in enhancing soil health, nutrient uptake, and bioactive compound synthesis. These advancements contribute to the development of resilient and nutritionally superior crop varieties. By focusing on these desirable traits, researchers can develop nutrient-rich varieties that are better suited for global markets, thereby increasing the commercial viability of underutilized crops. The sustainability and resilience of underutilized crops help mitigate climate change impacts through drought and heat tolerance, improved soil health, and enhanced carbon sequestration. Their cultivation supports biodiversity conservation, reduces monoculture dependence, and ensures food security in climate-vulnerable regions by maintaining stable production under unpredictable climatic conditions.

Furthermore, the development of functional food products from these crops requires innovative processing methods that preserve and enhance their nutritional properties. Techniques such as extrusion, fermentation, and fortification should be explored to create food products that cater to the growing demand for health-conscious and functional foods. Understanding how different processing methods impact the bioavailability of nutrients is also important for developing products that maximize the health benefits of these crops. To achieve these goals, an interdisciplinary approach is essential. Combining expertise from agricultural science, food technology, nutrition science, food biochemistry, AI, and biotechnology intervention can lead to the development of scientifically validated, nutrient-dense food products. By working together, these fields can address the complex challenges associated with the commercialization of underutilized crops, ultimately contributing to global nutritional security and sustainable agriculture.

This article has highlighted the significant potential of underutilized crops including quinoa, amaranth, buckwheat, teff, minor millets, bambara groundnut, winged bean, lablab bean, moringa, and jackfruit in addressing the global challenges related to food security, nutrition, and sustainability. Through the development of scientifically validated and commercially viable food products, these crops can play a pivotal role in diversifying our food systems, offering a broader range of nutrient-rich options that are often more resilient to environmental stresses. Key findings emphasize that many underutilized crops, such as quinoa, amaranth, teff, millets, and others, possess unique nutritional profiles and functional properties that make them suitable for modern food applications. Moreover, innovative processing techniques have been shown to preserve and enhance the nutritional benefits of these crops, creating functional foods that meet the growing consumer demand for health-oriented products. The importance of integrating underutilized crops into the global food system cannot be overstated. Their inclusion not only enhances dietary diversity but also contributes to the sustainability of agricultural practices by promoting the use of crops that are naturally adapted to a range of environments. This is especially crucial in the face of climate change and the need for more resilient food production systems. For these reasons, it is imperative that stakeholders including researchers, industry leaders, and policymakers invest in the development, promotion, and commercialization of underutilized crops. Such investments will be key to unlocking the full potential of these crops, ultimately contributing to a more secure, nutritious, and sustainable global food supply.

CRediT authorship contribution statement

Simardeep Kaur: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Gurkanwal Kaur:** Writing – review & editing, Writing – original draft, Investigation. **Arti Kumari:** Writing – original draft. **Ayantika Ghosh:** Writing – original draft. **Gurjeet Singh:** Writing – review & editing. **Rakesh Bhardwaj:** Writing – review & editing, Validation, Supervision. **Amit Kumar:** Writing – review & editing, Validation, Project administration, Conceptualization. **Amritbir Riar:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors assert that they have no conflict of interest. They also confirm that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Ethical statement

The authors confirm that no human or animal subjects were utilized in the experiments conducted for this study.

Data availability

No data was used for the research described in the article.

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