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Global nutritional challenges and opportunities: Buckwheat, a potential bridge between nutrient deficiency and food security

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ABSTRACT

Background: The ability to ensure nutritional and food security is seriously threatened by the ever-growing global population. Overreliance on a few staple food crops such as wheat, rice and maize will no longer be able to satisfy the rising demand for future food. Even with increasing agricultural production, over 820 million people are still facing food insecurity and at least 2 billion are facing nutrition insecurity. Therefore, it is imperative to focus on finding simple and sustainable solution to the present threat of global food insecurity. Besides staple food crops, harnessing nutrient-dense, climate-resilient, and locally available crops for production, marketing and consumption as "*Smart Foods*" for the future is needed. Buckwheat is a potential smart food because of its stress resistance and nutritional properties as well as strong antioxidant activity due to presence of flavonoids.

Scope and approach: This paper comprises a comprehensive review of the scientific literature on the valorization of buckwheat crops in terms of germplasm resources, breeding and genetic improvements for yield, bioactive compounds, biological activities and its potential application in food and pharmaceutical industries.

Key findings and conclusions: Identification of elite cultivars and exploitation of buckwheat derived gluten-free bakery and non-bakery food stuffs and beverages such as tea, beer and wine should be explored for human consumption. Abundance of bioactive compounds results in high anti-oxidant, anti-microbial, anti-glycemic, anti-cancer properties and other health-promoting activities highlighting buckwheat's potential application as nutraceuticals and pharmaceuticals.

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1. Introduction

Buckwheat belongs to the Polygonaceae family and *Fagopyrum* genus that harbouring 22 species. The most widely cultivated species include common buckwheat (*Fagopyrum esculentum* Moench) and Tartary buckwheat (*Fagopyrum tataricum* (L.) Gaertn.), which are grown on worldwide due to wide adaptability (Zhang et al., 2021a). Buckwheat is rich in various essential bioactive compounds along with balanced nutritive components (Huda et al., 2021; Joshi et al., 2020). Among all the species, common buckwheat and Tartary buckwheat are used in human nutrition while *F. cymosum* (*F. dibotrys,* golden buckwheat) is employed as traditional Chinese medicine. To meet the world's rising food demand, non-staple crops must receive more attention than staple ones for food security and nutrition (Kumari & Chaudhary, 2020). Further, diversifying food resources through the incorporation of crops with nutritional and medicinal properties, could be used as a potential strategy in modern cropping systems to combat the hidden hunger (Boukid et al., 2018). Buckwheat is one such crop that is known for its abundance of nutrients and bioactive compounds (Table 1). The food industry is playing a crucial role in processing of raw materials derived from agricultural crops to supply foods and add value to economy (Giménez-Bastida et al., 2015*)*. Buckwheat seeds are typically consumed as a cereal after removing the husk and processed into flour. Generally, buckwheat flour is used as raw material to make buckwheat-enriched food products such as bread, noodles, pasta, cakes, biscuits, and some valuable fermented products like wine, beer and vinegar (Suzuki et al., 2020). The leaves can also be used as a fresh vegetable and tea. Buckwheat flowers provides an excellent source of honey production due to its attractive colour and texture.

Consuming buckwheat can help to prevent various chronic illnesses, such as hypertension, obesity, cardiovascular disease, and gallstone formation (Wieslander, 2020). *In vivo* and *vitro* pharmacological studies have confirmed that buckwheat holds anti-diabetic, anti-tumour, anti-inflammatory, antioxidant and hepatoprotective effects (Huda et al., 2021; Zhu, 2016). The flavonoids and phenolics of buckwheat are typically used for the treatment of several diseases such as glycemic disease, diabetes, hypertension, microbial diseases, cancer and others (Huda et al., 2021). According to Traditional Chinese Medicine (TCM) theory, common buckwheat seeds possess the ability to invigorate the spleen, eliminating food stagnating and descending qi-flowing. It has also been listed as an anti-haemorrhagic and hypotensive drug in the British Herbal Pharmacopoeia and used therapeutically for reducing fever, detoxification, and inflammation in Korean folk medicine (Kim et al., 2003). Moreover, Tartary buckwheat roots (called "Qiao ye qi") is rich in cytotoxic phenylpropanoid glycosides, and were historically used to control qi-flowing for reducing pain, energizing spleen, and draining moisture, and frequently employed to cure chronic and incurable diseases, such as malignancies, rheumatic disorders and general debility (Guo et al., 2010; Guo & Yao, 2007; Zheng et al., 2012). In addition, golden buckwheat rhizome (FDR), a significant component of TCM with high medicinal value, is frequently used to treat with a variety of medical conditions, including cancer, inflammation, dysmenorrhea,

Table 1
Nutritional compositions of buckwheat and its satisfactory amount made it one of the most important alternative nutritional source like major staple cereals and some other minor crops. (Data has been adopted and compiled from the following references: Joshi et al., 2019; Chettry & Chrungoo, 2021; Rodríguez et al., 2020; Peng et al., 2015; Zhu, 2019; Kalinova et al., 2019; Stojilkovski et al., 2013; de Sousa et al., 2021; DE Bock et al., 2021; Rodríguez et al., 2020; Chandra et al., 2018; Lydia Pramitha et al., 2023; Chen et al., 2021; Rasane et al., 2013).

Nutrient Composition	Buckwheat	Rice	Wheat	Maize	Amaranth	Quinoa	Finger millet	Oat
Carbohydrate (g/100g)	67.8–81.4	78.2	71.2–83.17	63.6	57.3–65.5	53.7–57.2	66.82–72.60	66.2
Protein (g/100g)	5.7–16.4	6.8	9.0–18.0	9.4	13.0–18.0	13.1–14.1	7.2–7.70	17.3
Fat (g/100g)	3.4–7.4	3.6	1.4–3.3	4.7	2.5–8.0	4.7–5.5	1.50–7.16	7.03
Fibre(g/100g)	10.0–21.5	4.1	2.1–12.2	7.3	6.5–12.5	7–14.7	3.60–11.2	15.4
Essential amino acids (g/100 g protein)								
Lysine(Lys)	5.9–6.1	3.9	2.3	2.7	5.2–5.5	5.4–5.6	2.8	0.379 ± 0.068
Methionine(Met)	2.5–3.7	1.7	1.2	1.9	1.86–2.17	2.2	2.7	0.173 ± 0.020
Tryptophan(Trp)	1.4–2.0	1.3	2.4	0.5	1.1–1.3	1.2–1.3	0.9	–
Leucine(Leu)	6.4–6.7	8.1	6.3	12.4	4.8–5.2	5.9–6.1	8.9	0.917 ± 0.011
Vitamins(mg/100g)								
Thiamine(Vit.B1)	0.4–3.3	0.4	0.5	0.3	0.1–0.5	0.5–0.8	0.4	1.17
Riboflavin(Vit.B2)	0.2–10.6	0.1	0.1	0.1	0.1–0.2	0.2–0.3	0.2	–
Niacin(Vit.B3)	6.2–18.0	1.9	3.7	1.9	0.5–5.5	1.6–1.7	1.3	–
Pantothenic acid(Vit.B5)	0.4	–	–	–	0.2	0.6	0.3	1.5
Pyridoxine(Vit.B6)	0.6	–	–	–	0.5	0.2	0.1	0.1
Folate(Vit.B9)	0.054–0.1	0.02	~0.05	~0.003	0.022–0.027	0.001–0.054	0.034	0.052
α-Tocopherol(Vit.E)	0.3	–	–	–	1.9	2.1	0.2	0.45–1.23
Phylloquinones(Vit.K1)	0.007	–	–	–	–	0.002	0.003	–
Carotenoids (μg/100 g)								
Lutein	220.0	–	1.2–23.9	0.1	3.6–4.4	53	–	–
Minerals (mg/100g)								
Calcium(Ca)	110	10	30	48.3	162	54	344.0	58
Iron(Fe)	2.2–4	0.7	3.5	4.8	9.3–10.0	5.3–7.5	4.6–6.30	5.41
Magnesium(Mg)	231.0–390.0	64.0	138.0	107.9	138.0–325.0	119.0–227.0	130.0–146.0	235
Phosphorus(P)	330.0–347.0	160.0	298.0	210.0	374.0–455.0	212.0–527.0	210.0–250.0	734
Manganese(Mn)	1.3–3.4	0.5	2.3	1.0	2.3–5.3	1.8	3.2	5.63
Zinc(Zn)	0.8–2.4	1.3	2.7	2.2	2.7	3.3–3.6	2.30–2.50	3.11
Potassium(K)	450.0–460.0	–	376.0	324.8	284.0–433.0	474.0–649.0	443.0	566
Sodium(Na)	1.0–11.0	–	17.1	35.0	2.7–6.0	4.5–7.0	4.8	–
Copper(Cu)	0.5–1.1	–	0.5	1.3	0.1–0.8	0.2–0.5	0.7	0.403
Flavonoids								
Rutin (mg/100g)	8100	–	–	–	–	0.0061	–	0–3.20
Quercetin (mg/100g)	857.62	–	–	–	0.0060	0.0068	–	8.90
Emodin(mg/kg)	1.72–2.71	–	–	–	–	–	–	–
Catechin(mg/kg)	6–66	–	–	–	–	–	–	–
Epicatechin mg/kg)	23–110	–	–	–	–	–	–	–
Procyanidin B2(mg/kg)	118.6	–	–	–	–	–	–	–
Procyanidin B5(mg/kg)	4–11	–	–	–	–	–	–	–
Fagopyrin (mg/100g)	19–32	–	–	–	–	–	–	–

lumbago, lung diseases and snakebite (Zhang, Jiang, et al., 2022). A commercial medicine "Wei-Mai-Ning" capsule, has been developed from golden buckwheat and exploited for cancer treatments (Gao et al., 2013). Thus, the abundance of such valuable bioactive compounds makes buckwheat species as source of "super food" and can meet the global nutritional and health challenges in future.

2. Global nutritional and health issues: hidden hunger and malnutrition

Malnutrition is a persistent global issue that contributes significantly to physical, mental and cognitive decline, especially so of children amongst low-income populations. According to UNICEF, 21 million children under the age of 5 suffer from stunting and 6 million suffer from wasting in East Asia and the Pacific (Southeast Asia Regional Report on Maternal Nutrition and Complementary Feeding UNICEF East Asia and Pacific Region, October 2021). The same report highlighted the fact that 46% of children under the age of 5 are micro-nutrient deficient and 27% of women of the reproductive age were anemic. These data underscored the need for good nutrition for proper cognitive and physical development of people in early stages of their life. While there has been a substantial economic growth in the region over the last few decades, the burden of malnutrition continues to hinder the development and equitable economic growth in various nationalities of the region. In addition, deficiency of vitamins and minerals causes some common nutritional disorder such as beriberi (vitamin B1), pellagra (vitamin B3), scurvy (vitamin C) and osteoporosis, rickets, tetany (Calcium) and kwashiorkor (protein energy malnutrition; Younis et al., 2015).

As a complex issue, which has nutritional, economic, social and administrative components, ensuring "food security" for all has always remained a challenging proposition. United Nations (UN) has defined food security as a state "when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life" (https://www.ifpri.org/topic/food-security). While the original concept of food security focus on averting hunger, inclusion of the term "nutritious" in its definition signals the emphasis on "quality and acceptance" as important contributors towards food security. As a multidimensional issue, the concept of nutritional security has acquired more complexity with economic growth changing environment, consumption patterns, demography, and dynamics of international trade. Attempts to achieve the status of "Zero hunger" by 2030 face a number of complex and interlinked challenges. While the need to feed a population of 8.5 billion people by 2030 will require intensification of farming systems, local issues, such as nutritional and dietary diversity as well as loss of traditional diets, will increasingly demand attention if any long-term form of food security is to be achieved. Simply producing enough food is not sufficient. Processing and distribution of the harvested produce and ensuring the poor are in a position to access the food are equally important challenges. According to the Action Against Hunger (2019), nearly 660 million people could still be hungry in 2030, underscoring the immense challenges in achieving the Sustainable Development Goals (SDGs) of "Zero Hunger" by 2030 (Otekunrin, 2021).

While eradication of world hunger and malnutrition by the year 2030 has been identified by the UN as one of the 17 SDGs yet at the halfway stage, the major challenge lies in translating abstract concepts into tangible changes by identifying appropriate strategies for achieving the SDGs. Two major approaches being pursued in this context, (i) yield enhancements through conventional breeding and improved agronomic practices (Parry & Hawkesford, 2010) and (ii) accelerating the domestication of nutrient-dense and climate-resilient underutilized crops (Mabhaudhi et al., 2019). While the first approach has yielded rich dividends, it has also led to agricultural portfolio reduction for meeting mankind nutritional requirements and increased human population dependency on limited number of crops for their nutritional requirements. Even though the domestication of underutilized crops is a time-consuming process, it facilitates dietary diversification and paves the way for nutritional sufficiency. This approach can also brings degraded soils into agricultural use if the chosen underutilized crops can be successfully grown on poor soils. Given the vast repository of neglected or underutilized crop species, how can those with enough potential to justify investing the very limited resources available for their improvement best be identified? One possible strategy is to look for crops with trait that currently exceed major crops, especially where these are evident in extreme environments such as poor soil, low water availability, extreme temperatures. While this is not a new idea, it becomes challenging under the twin problems of cultivating crops in uncertain future climates and the need to increase food production with fewer inputs. From a breeding perspective, the genetic potential of a crop is determined by the combination of genes it contains, their mutual interactions and interactions with the environment to produce the phenotype, whether that is yield or disease resistance or drought tolerance. Agronomy and management are important tools to favor the crop by generating as optimal an environment as possible. The current agricultural portfolio, which is majorly an outcome of selection breeding with a focus on higher yields, has created contemporary cropping systems in a few staple crops. The current agricultural system also follows a "High input-High output" model which increases the vulnerability of the agriculture to environmental perils. Against the background of uncertainties of climate, dependence on a few staple crops for nutritional requirements in itself poses a threat to food security. Since the yields of major crops, such as rice, wheat and maize, appear to be near 80% of their predicted potential, it is unlikely that dependence on these crops alone would be sufficient to meet either the production gap or nutritional gaps in achieving the status of Zero hunger by 2030. This calls for a paradigm shift towards greater sustainable and diversified food system. However, a refocus away from the extensive cultivation of few species and attention towards the exploitation of nutrient-dense and climate resilient underutilized crop species for food security must be encouraged.

3. Buckwheat: an underutilized "future smart" crop species, potentially can help to achieve the global nutraceutical and food security

3.1. Buckwheat as a climate resilient "future smart" crop species

Buckwheat is well-known for its high degree of environmental adaptability, which make it more resilient to climate changes and environmental stresses including high temperatures/heat, drought, cold, UV-radiation, salt, heavy-metals and diseases (Zargar et al., 2023). Furthermore, the buckwheat root system allows it to access water from deeper soil layers, which can be beneficial during dry periods. Tartary buckwheat tolerance of extreme temperatures is regulated by epigenetic changes (Song et al., 2020; Zargar et al., 2023). In addition, it was noted that several heat-shock protein family members exhibit increased expression during heat stress, which has a critical impact on the degree of embryosac degeneration (Zargar et al., 2023). Two popular common buckwheat accessions, Panda and PA15, have also been found to contain these proteins and was discovered that PA15 is more heat-tolerant than Panda (Zargar et al., 2023). Likewise, study revealed that Tartary buckwheat exhibits greater drought resistance than common buckwheat and is known to be resistant to the effects of cold stress because of its epigenetic regulation. While common buckwheat has drought avoidance mechanism, Tartary buckwheat showed drought tolerance characteristics (Luthar et al., 2021). Additionally the synthesis of metabolite, Cyclitols or D-chiro-inositols which served as a cryoprotectants, have also been reported for Tartary buckwheat and is triggered by abiotic stressors like salt and drought stress (Luthar et al., 2021). In light of metal toxicity, oxalic acid, a significant chelator of aluminum (AL), is secreted by buckwheat roots, demonstrated the plant's resistance to elevated

AL-accumulation (Zargar et al., 2023). In general, buckwheat is tolerant to diseases and not often attacked by pests, but several studies have been published about appearance of diseases or pests (He et al., 2023; Subedi et al., 2020). The molecular breeding for disease resistant varieties is crucial.

3.2. Nutritional aspects of buckwheat as a solution for the global nutritional challenges

In general, common and Tartary buckwheat have been used as food. Buckwheat seeds showed a high percentage of carbohydrates, primarily starch (Bonafaccia et al., 2003). Buckwheat is recognized as highly valuable crop due to its nutritional superiority over major staple crops (rice, wheat and maize) when compared in terms of balanced amino acid profile of seed protein and bioactive compounds of various pharmaceutical uses (Chettry & Chrungoo, 2021; de Sousa et al., 2021; Joshi et al., 2019; Kalinova et al., 2019; Peng et al., 2015; Rodríguez et al., 2020; Stojilkovski et al., 2013; Zhu, 2019). While compared with some important minor crops, nutritional profile of buckwheat was also found to be a potential nutritional source like amaranth and quinoa (Chandra et al., 2018; Chettry & Chrungoo, 2021; DE Bock et al., 2021; Rodríguez et al., 2020), finger millet (Lydia Pramitha et al., 2023), and oats (Chen et al., 2021; Rasane, Jha, Sabikhi, Kumar, & Unnikrishnan, 2013, Table 1).

3.2.1. Carbohydrate (starch)

Starch is regarded as one of the major component of buckwheat groats that contributed up to 75% of the dry weight and are made up of two glucan polymers, amylose and amylopectin (Giménez-Bastida et al., 2015). Starch in buckwheat flour varies in different variety and milling processes and ranged 70%–91% (Zhu, 2016). Amylose content of starch in Tartary buckwheat and common buckwheat is approximately 39% and 43%, respectively (Bonafaccia et al., 2003). It was reported that polyphenols and lipids present in buckwheat flour can give rise to a non-covalent complex with starch and it inhibit the alpha-amylase activity of starch and could provide significant beneficial effect on hyperglycemic patients (Kawa et al., 2003).

3.2.2. Protein and dietary fiber

The gluten free nature of buckwheat protein is due to the absence of α-gliadin protein component and lower content of prolamines, differentiating buckwheats from other gluten containing crops such as wheat, barley and oats (Giménez-Bastida et al., 2015). Protein content in buckwheat ranges from 10 to 15%, which comparable to major cereals like rice, wheat and maize (Joshi et al., 2019). Buckwheat seed proteins are mainly comprised of salt-soluble globulins (Suzuki et al., 2020). Buckwheat contains of 12 amino acids including lysine, arginine, cysteine, and methionine. It also contains a substantial amount of lysine (5.9 g/100 g of protein), which highly limited in cereals (Joshi et al., 2020). Buckwheat seeds are also rich in sulphur, containing amino acids methionine and cysteine (Bonafaccia et al., 2003). In comparison to common buckwheat, Tartary buckwheat showed slightly more protein and fibre, in common buckwheat it was 10.3 % and 2.3%, respectively and in Tartary buckwheat it was 10.5% and 2.6%, respectively (Zhu et al., 2016). However, several factors can influence the nutritional composition of seeds including growing culture, environmental condition and genotype. For example, groats of tetraploid Tartary buckwheat (cv. Shinano kurotsubu) contained significantly higher protein (14.14%) than those of common and Tartary buckwheat cultivars (13.27 and 12.81%, respectively; Tien et al., 2018). The abundance of certain essential amino acids and its gluten free nature render buckwheat protein advantageous over other crops and could therefore contribute to solve the global protein-limiting health challenges.

3.2.3. Fatty acids

The fatty acids composition of seeds play a crucial role in determining food quality. The fatty acids present in Tartary buckwheat including palmitic, stearic, oleic, linoleic, linolenic, and eicosanoid acids (Ge & Wang, 2020). Common buckwheat and Tartary buckwheat showed same fatty acid content (about 3.8%; Li et al., 2019). Tartary buckwheat bran and flour contains unsaturated fatty acids of 84% and 83%, respectively (Ge & Wang, 2020). Buckwheat oil contains 16–25% of saturated and 74.79% of unsaturated fatty acids. Further investigation determined palmitic acid (15–20%), oleic acid (30–45%), and linoleic acid (31–41%) are the major fatty acids (Ge & Wang, 2020).

3.2.4. Vitamins and minerals

Buckwheat is enriched in vitamins, including vitamins B (B1, B2, and B6), C, and E (Zhu, 2016). The availability of such important vitamins can provide protection against beriberi, pellagra, scurvy and other diseases. Buckwheat also contains several minerals including Fe, Zn, Mg, Ca, P, Mn and others at satisfactory amount and are comparable to some staple cereals (Table 1). The mineral content in Tartary buckwheat grain is high (Rodríguez et al., 2020). Since buckwheat accumulates significant amount of selenium (Se), it is recognized to be ideal for biofortification with selenium. As a result, it may serve as a source of Se in the diet of humans (Golob et al., 2018). However, the bio-availability of these minerals, depend on the type of milling used and presence of anti-nutritional factors such as tannins, phytates and protease inhibitors (Liu et al., 2001). The presence of such micronutrients could provide substantial source for combatting "hidden hunger" and can also reduce the chance of anemia, osteoporosis, rickets, tetany like health problems.

3.2.5. Phenolics

Phenolic compounds, exhibit a wide range of physiological activities including antioxidant, antitumor and antibacterial activities (Balasundram et al., 2006). Phenylpropanoids, hydroxybenzoic acid derivatives, and hydroxycinnamic acid derivatives are the main phenolic components present in the buckwheat (Jing et al., 2016). Seven phenolic compounds of tatariside (A-G) were isolated from root of Tartary buckwheat (Zheng et al., 2012). Buckwheat also contains abundant phenolic compounds like rutin, quercetin, *trans*-resveratrol and their contents varied according to growing origin (Yu et al., 2019). Several types of bioactive phenols including flavonoids, condensed tannins, phenylpropanoids and phenol derivatives were isolated from buckwheat species and can exhibited remarkable antioxidant and cardio-cerebral vascular protective effects (Wang, Zhang, & Yang, 2005). In addition, other important phenolics such as D-chiro inositol, fagopyritols etc. and their biological significance has been illustrated in Table 3 and Fig. 2.

3.3. Buckwheat's acceptance as a future food on a global scale

3.3.1. Is buckwheat cultivation and processing sustainable?

Buckwheat cultivation is sustainable in environmental and economic terms because it can reduce the use of agricultural inputs such as chemicals, synthetic fertilizers, and fossil energy. This not only benefits global habitats and ecosystems but due to the low irrigation demands of buckwheat, also addresses freshwater scarcity and mitigating the environmental footprint associated with agricultural practices (Small, 2017; Wen et al., 2021). Buckwheat growth significantly improves the soil characteristics, such as texture, porosity, aeration, water retention, and nutrient content (Hudek et al., 2022). These soil enhancements support the soil biodiversity and contribute to the implementation of sustainable soil management practices (Small, 2017).

In optimal agricultural circumstances, buckwheat has less yield than staple cereal crops, however it proves economically competitive in less fertile soils and cooler climates with shorter growing seasons. According to Small (2017), this comparison may not be entirely equitable, because significant advancements in breeding have been achieved of major cereals over the past century, whereas buckwheat breeding has been relatively limited. Crop rotation with buckwheat offers alternate crops within a single season, which reduced diseases and pests build up and also provides cover crop, green manure crop, or nurse crop (Small, 2017). Nevertheless, there is a growing awareness and interest in the public regarding the agricultural products that are produced sustainably and because of all beneficial characters, buckwheat unequivocally merits increased production (Small, 2017).

Post-harvest processing of buckwheat includes cleaning, dehulling, milling and fractionation methods to produce diverse fractions like groats, flour, etc. All these processes can be optimized to align with sustainability goals. Buckwheat hulls are firm, and the kernels fit tightly inside the hull (Zhang, Yang, et al., 2023). Dehulling in Tartary buckwheat is difficult process as compared to common buckwheat. However, Tartary buckwheat cultivar rice-Tartary buckwheat Mikuqiao18 (Wang et al., 2022) and Miqiao 1 (Song et al., 2019) were reported to exhibit a notable dehulling efficiency among the other varieties. Dehulling methods includes mechanical, chemical and physical (microwave and hydrothermal treatment) have been used for hulled grains. In which the traditional mechanical hulling method involves damage to the kernel, chemical process entails issues like food safety and environmental pollution while physical dehulling improves the dehulling properties of the hulled grain, but heat-based method can cause the decomposition of nutrients and flavonoids present in buckwheat grain (Zhang et al., 2010, 2023c).

The dehulling procedure also ought to reduce grain breakage and increased rate of recovery of the entire kernel. However, a significant differences were found between heat treatment and cold plasma-treated dehulled buckwheat in terms of solubility and quality parameters of seed grain in which cold plasma-treated dehulling process found as an adjunctive technique to dehull buckwheat in order to produce high-quality flour (Zhang, Yang, et al., 2023). The hull's critical damage force was reduced by 58.3% as a result of the etching and dehydration caused by cold plasma treatment (Zhang, Yang, et al., 2023). In recent years, cold plasma technique has been extensively applied in food processing industries.

The buckwheat seeds with or without hull were used for the wet-milling process (Wronkowska & Haros, 2014). When comparing the resulting starchy materials to the raw material, the wet-milling process did not significantly alter their qualities (Wronkowska & Haros, 2014). The two main processes in this procedure are soaking in alkali or acidic water solutions at a specific temperature and then mechanically separating the starch, protein, germ, fiber, and hull fractions based on differences in their densities and particle sizes (Wronkowska & Haros, 2014). When preparing common or Tartary buckwheat food products, steaming and boiling treatments are also advised as they can reduce thermal degradation or maximize the amounts of phenolic components and antioxidant capabilities (Liu, Cai, et al., 2019). To get high-quality roasted groats, the dehulling process is preceded by increasing the moisture level of the raw whole seeds followed by simultaneous steaming and heating was also recommended (Giménez-Bastida et al., 2015). However, more suitable dehulling technology and development of high dehulling efficiency cultivars will be recommended for future study to reduce the negetive impact of the dehulling process on the grain quality and nutritional composition of buckwheat grain. Further, processing industries aim to establish energy-efficient manufacturing systems in the future, to reduce the environmental impacts by enhancing the environmental performance of manufacturing processes (Pawar et al., 2023). During the processing of buckwheat in the food industry, a very large amount of by-product is generated as solid waste, which must be managed sustainably (Pocienė & Šlinkšienė, 2022). The recycling of the by-products derived from milling of buckwheat grains is a significant step for sustainable organic economy. Innovative efforts to utilize the waste generated during production appear in numerous industries (food industry, chemical industry, textile industry, pharmaceutical production, etc.).

3.3.2. Global extension of buckwheat cultivated area with respect to traditional cereals

The extension of buckwheat growing area increased from 1.8 to 2.9 million hectares worldwide from 2010 to 2017 (faostat.org). After 2017, a 38.5% decrease was observed in the growing area, which entailed a decrease in production but there has been a slow rise in recent years. The main producers of buckwheat are the Russian Federation, China, Ukraine, and the United States. However, the sown area of the main cereals, such as wheat and rice were steady and constant, while the growing area of maize increased. In many European countries, crops are primarily cultivated for economic motivations rather than ecological considerations (Small, 2017). However, the variability of recent years, both in terms of extreme weather conditions and fluctuation of seed prices, will make long-term planning more and more prominent.

Due to wider adaptability nature of buckwheat, both temperate and subtropical climates are suitable for its cultivation, as long as there is sufficient rainfall during the growing season. At higher altitudes, it can also be grown in the tropics (Jansen, 2006). Buckwheat is an undemanding plant; its cultivation is also economical in areas where the dominant cereals do not give good results. The occurrence of pathogens and pests in arable land is only rarely to be expected. This fact, as well as the short growing season and the cost-effective, extensive cultivation method, making buckwheat cultivation attractive for both organic and traditional farming. Farmers may have low motivation to cultivate buckwheat due to its lower productivity and profitability. Urgent actions are required, with policy makers and scientists are of a great importance to increase buckwheat cultivation (Babu et al., 2018), which is crucial due to the growing population, requirement of special diet, sustainability and global climate change.

3.3.3. How can buckwheat compensate eventual loss of staple cereals in terms of cultivation and production?

By increasing biodiversity in plant production, using sustainable technologies, considering food safety, it is possible to manage and compensate for losses in the cultivation of cereals, for which buckwheat - as an underutilized crop - provides a great opportunity. Buckwheat is a crop suitable for meeting the nutritional needs of the growing population living in high altitude areas. It is considered a sustainable option for the livelihood of millions of mountain people, it is the only crop grown in the higher Himalayan region, where buckwheat is grown on 90% of the cultivated area (Babu et al., 2018; Singh et al., 2014), and cultivation of other cereals is difficult. Buckwheat can grow in a wide range of soils and fertility levels and is more tolerant to soil acidity than any other cereal crop (Rangappa et al., 2023). It can be also grown in conditions where soil moisture is not suitable for any other crop cultivation (Rana et al., 2012). Buckwheat has a short growth period and can cope with unfavorable conditions (Zamaratskaia et al., 2023), so its cultivation is possible those regions where the growing season is limited. Moreover, it has weed suppressant ability, so chemical weed control can be avoided.

3.3.4. Production of flour and other post-harvest processing derivatives of buckwheat

The seeds of pseudo-cereals, such as buckwheat, can be processed first into flour and then into pastry, similarly to cereals, but the differences are not only present in their classification system groups (Poaceae or Polygonaceae), but also in their content values of grain. Buckwheat flour is a good raw material to produce gluten-free food products. Buckwheat grain has a very valuable amino acid content and due to its high proportion of resistant starch (up to 30% of total starch) it has a low glycaemic index value. Structure of starch and the presence of the substance that inhibits α-amylase activity also may slow down the starch degradation process. Gelatinization temperature for buckwheat starch is higher than for cereals, and its rheological properties are different from those of cereals. Comparing to the wheat grain, the pericarp of buckwheat is loosely attached to the testa, germ can be found inside the endosperm. Production of buckwheat flour is different from those of wheat flour: several flour types may be produced by using different milling technology, while milling technology for wheat and other cereals are highly standardized (Skřivan et al., 2023).

Buckwheat hull (after dehulling) and bran (after milling) are the large amount processing wastes (Gonçalves et al., 2023). Nowadays hulls are commonly used as pillow fillers. According to laboratory tests, buckwheat hulls (based on its purity, rheological, chemical and flammability properties) proved to be an excellent raw material for filling mattresses, pillows and seats, especially for therapic purpose. In addition, its therapeutic effect was also confirmed during the inclusion of skeletal system problems and inpatients in the test (Nawirska-Olszańska et al., 2021). The utilization of buckwheat hulls has proven also to be useful, as an additive in the production of polyurethane foams. Added together with perlite, it changed the physical and mechanical properties of polyurethane foams, improving e.g. the burning properties of foams (Anna et al., 2023). In the process of creating polymer composites by injection molding, buckwheat hull can be used as a natural filler in place of wood fiber, which is becoming less and less accessible as a result of deforestation (Andrzejewski et al., 2019). During testing of the buckwheat hull and its ash, it was established that the hull can be used with good results in the production of ceramic products (especially porous ceramics) as a substitute for sawdust (Siauciunas & Valanciene, 2020).

Buckwheat hull extract, for example, proved to be a very good dye in experiments where environmentally friendly materials and methods were tested in the production of wool fabrics (Zhang et al., 2020).

However, the buckwheat hull (about 22% of the grain) is a very valuable and cheap source of many biologically active substances and food technology raw materials (antioxidants, cellulose, brown melinin pigment). By utilization the powder and melanin produced from the buckwheat hull by-product in desserts, their antioxidant activity and dietary fiber content can be increased (Sujka et al., 2022).

Different methods were tested for biorefining the large amount of by-product (hull) produced during the dehulling of the grain. With the appropriate extraction methods applied to the hull, a product containing high antioxidant and other functional substances can be produced, which can be added to food and nutritional supplements (Mackėla et al., 2017).

Buckwheat husk ash and uncleaned buckwheat husk contain significant amounts of nutrients (phosphorus, potassium, calcium, magnesium and microelements), so they can be very suitable for biofertilizer production. Returned to the soil, this type of nutrient replacement may significantly contribute to sustainability (Pocienė & Šlinkšienė, 2022).

Bran is the main by-product of milling, and it is mainly used as feed in animal husbandry or for production of biofuel (due to its high carbon and hidrogen content) or bioactive compounds (Pocienė & Šlinkšienė, 2022; Solanki et al., 2023). The composition of buckwheat bran is significantly influenced by whether or not the grain was hulled before milling. If milling takes place without hulling, then the bran contains a large amount of diatery fiber (20–26%) (Heuzé et al., 2019; Zamaratskaia et al., 2023).

A rutin enriched substance from Tartary buckwheat bran was prepared, which was used efficiently to enrich wheat-containing foods (Cho et al., 2014). Due to the effective absorption properties of buckwheat straw and hull, it can be a tool for removing the different materials (e.g. heavy metal ions and oil) from the aqueous medium, which can assist the treatment processes of natural and wastewater (Shaikhiev et al., 2020). Utilizing by-products of milling for feed, bioenergy, and biomaterials can minimize waste generation and enhance the overall sustainability of the process. Developing innovative products from milled buckwheat fractions, such as gluten-free foods and functional ingredients, can contribute to market diversification and sustainability in the food industry. The impact of traditional and modern processing techniques on the nutritional profile and functionality of the final products has been carefully evaluated. Each stage in the processing stage has significant impact on the nutritional content, flavour, and functional properties of the end products (Solanki et al., 2023).

3.3.5. Buckwheat's chances of being globally accepted as wheat and rice

Wheat and rice are basic food, it is unlikely that any other food will replace them. However, the world's population is constantly increasing, and the food supply may be threatened by global dependence on a small number of staple crops (Zargar et al., 2023), for example, in the early 1840s, ca. 1 million people starved to death in Ireland due to massive crop losses caused by the rapidly spreading of potato late blight (*Phytophtora infestans* (Mont.) de Bary) (Schumann & D'Arcy, 2000). Thus, cultivation of under-utilized crops can help to ensure food security (Zargar et al., 2023). Nevertheless, as a valuable source of nutrients, buckwheat may play an increasingly important role in healthy nutrition in the future, especially in gluten-free diet. Moreover, as a source of cheap protein, it could play a significant role in reducing the harmful effects of hunger in developing countries (Sofi et al., 2022). However, the climate changes, leading to global warming may result in new challenges for buckwheat breeding including targeted development of new varieties with early maturity and with higher abiotic and biotic stress tolerance (Breslauer et al., 2023).

3.3.6. Buckwheat germplasm diversity and germplasm resources for future use

The global distribution of buckwheat genetic resources largely follows the crop's migration and domestication pathways from the region of origin in southern China. While Tartary buckwheat and golden buckwheat are primarily restricted to the highlands of southwest China and the Himalayas, common buckwheat is widely grown in all continents of the world (Suvorova & Zhou, 2018). Genetic resources for buckwheat include landraces, advanced breeding lines, wild species and subspecies. Only a few districts in the Chinese provinces of Yunnan and Sichuan are home to wild *Fagopyrum* species. According to Suvorova and Zhou, native landraces have been spread to several highland regions in China, Nepal, India, and Bhutan that are less economically developed. There is a great diversity in buckwheat and its wild relatives and significant efforts have been made to preserve genetic resources ex-situ. Currently, more than 10,000 different buckwheat accessions are being kept worldwide, with which East and South Asian gene banks holding the majority of them (Zhou et al., 2018, p. 382). According to Joshi et al. (2019), China has the greatest buckwheat germplasm resource, surpassing 2804 germplasms whereas 2116 in Russia, 1600 in Ukraine, 1050 in India, 511 in Nepal, 378 in Slovenia, 226 in Japan, and 170 in Prague. Genetic variation for agro-morphological features are well characterized and documented in China, India, Korea, Japan and Nepal (Joshi et al., 2019). A significant example of the efficient use of buckwheat germplasm in the breeding program was the release of the cultivars Himpriya, Himgiri, VL7, PRB1, and Sangla B1 in India, which are selected from indigenous and foreign germplasm lines (Joshi et al., 2019).

However, in recent decades, several wild species like *F. longistylum, F. homotropicum,* (high self-compatibility, Zhang et al., 2021c; Zhang, He, et al., 2023), *F. megaspartanium, F. pilus, F. cymosum* (high flavonoids content) and some other wild species (Chen et al., 2018) have been successfully employed for wide-hybridization to increase germplasm resources. The domestication and improvement of staple crops has yielded significant insights into the evolution of staple crops (Wang et al., 2023) which could be used as reference for broadening the buckwheat germplasm resources.

4. Application of existing buckwheat-derived foodstuffs in food industries as a nutritional source and their health beneficiary effects

Buckwheat fractions has been employed to make several healthy food items bakery as well as non-bakery foods (Table 2 and Fig. 1).

Table 2
Buckwheat fractions, as a source of "super food" basket and its application in food industries for human nutrition.

Buckwheat-derived food items	Major ingredients	Biological function/ Nutritional importance	References
Bread			
	Buckwheat flour (~40%) mixed with wheat flour, Chia flour and rye flour	Reduces the intestinal chronic disease, regulates the inflammatory bowel diseases, reduces type-2 diabetic disease, increases nutritional status with omega-3 alpha-linolenic acid and anti-oxidant activity, reduces the problems of celiac disease and mineral deficiencies	Costantini et a. (2014); Giménez-Bastida et al. (2018); Su-Que et al. (2013);
Biscuits			
	Buckwheat flour (~20%) and rye flour	Increases nutritional status, high rutin content and anti-oxidant activity, exhibits ACE inhibitory activity	Zieliński et al. (2020); Breslauer et al. (2023)
Snacks			
	Corn flour and buckwheat flour (~30%)	Attractive item for appetizers with high nutritional characteristics and anti-oxidant properties	Giménez-Bastida et al. (2015); Wójtowicz et al. (2013)
Cake			
	Buckwheat flour (~30%) and pea flour	Low-fat or fat-free food item	Min et al. (2010); Kour et al. (2022); Breslauer et al. (2023)
Buckwheat noodles			
	Buckwheat flour (~20 %–60%) and wheat flour	Rich in carbohydrates, Lipase, Peroxidase and Suitable diet for diabetic patients	Giménez-Bastida et al. (2015); Suzuki et al. (2020); Kreft et al. (2002); Breslauer et al. (2023)
Pasta			
	Buckwheat flour (~30%), the mixture of buckwheat flour and rice flour	Rich in dietary fibre, reduces hypertension, chance of type 1 diabetes and celiac disease	Mercier et al. (2016); Bouasla and Wójtowicz (2019); Vetrani et al. (2019); Breslauer et al. (2023)
Groats/ Cereal grain			
	Dehulled buckwheat seeds ('Kasha')	Excellent source of total dietary fibre (TDF), and carbohydrate; an alternative to rice and potato, reduced Glycemic index(GI = 34.7), it does not create unhealthy spikes in blood sugar levels	Giménez-Bastida et al. (2015); Suzuki et al. (2020)
Sprouts			
	Fermented buckwheat seeds	Rich in some essential flavonoids like; rutin, isoorientin, vitexin, isovitexin and anthocyanins such as cyanidin 3- O-glucoside and cyanidin 3-O-rutinoside, it reduces blood pressure	Rauf et al. (2019); Molska et al. (2022, 2023)
Buckwheat honey			
	Buckwheat flowers	Exhibiting the activities such as; anti-bacterial, anti-oxidation, ACE-inhibitory, anti-inflammatory, hepatoprotective, inhibits DNA damage, bactericidal action against anti-biotic resistant bacteria, treatment of nosocomial-associated infections and reduces reactive oxygen species (ROS)	Boukid et al. (2018); Giménez-Bastida et al. (2015); Bonafaccia & Fabjan (2003); Noda et al. (2021)
Tea			
	Buckwheat flowers, hulls and dried leaves	It contains several nutrient as well as bioactive compounds like; protein, amino acids, starch, fat, fatty acids, flavonoids and most predominant aromatic compound 3-ethyl-2,5-dimethyl-pyrazine.Exhibits antioxidative and antiglycation properties, inhibitory activity against formation of advanced glycation end products (AGEs), α-glucosidase inhibitory activities	Zielińska et al. (2009); Zielinska et al. (2013); Niu et al. (2022); Guo et al. (2017)
Beer			
	Buckwheat malt prepared from groats	Reduces the chance of celiac disease, dementia and cardiovascular diseases	Dežlak et al. (2014); Ren et al. (2019)
Wine			
	Chinese rice wine (CRW): mixture of rice grain malt and Tataricum buckwheat malt	Enhances nutritional status with high anti-oxidant activity	Ren et al. (2019)
Tarhana			
	Mixing and fermenting wheat products, yoghurt, some vegetables and spices with buckwheat	Supplies nutrients; fat, ash, protein and minerals like K, Mg, and P and lysine content	Giménez-Bastida et al. (2015)
Viniger			
	Boiled or steamed raw buckwheat seed grain mixed with koji	Buckwheat vinegar contains volatile compounds like aldehyde and ketones, high concentrations of anti-oxidative products compared to other vinegars made	Suzuki et a. (2020)

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Table 2 (*continued*)

Buckwheat-derived food items	Major ingredients	Biological function/ Nutritional importance	References
		from oats or rice flavour components	
Tofu	Fermented buckwheat seeds	Retains high protein content and calories	Suzuki et a.l (2020)

4.1. Bakery food products

In recent years, the demand for gluten-free bakery products has increased (Gómez, 2022), such as breads, cakes, noodles, and pastas (Giménez-Bastida et al., 2015). Because of its nutritional value and role in promoting health, buckwheat has increasing interest (Pirzadah & Malik, 2020). For the food industry, buckwheat seeds are a valuable raw material that can be the basis to produce functional foods.

However, it is important to use the suitable proportion of gluten-free buckwheat flour used in making bakery products such as bread, biscuits, cakes, and snacks. In this context, it was reported that the level of total proteins, total mineral components, and resistant starch were increased when buckwheat flour was used in the range of 30–50% in gluten-free bakery products; while the sensory quality improvement was observed in breads containing 30% of buckwheat flour (Wronkowska & Soral-Śmietana, 2008.). In Slovenia, mixture of 70% wheat flour and 30% buckwheat flour is applied most often for making breads and blend of 50-50% is used in households (Kreft & Germ, 2008).

4.1.1. Bread

Bread is one of the most important nutritious diets in our daily life. Bread is generally prepared from wheat flour, but gluten component of wheat is not suitable for some people who have celiac disease. To reduce the gluten in bread, ~30% buckwheat flour had been used to made buckwheat-enriched wheat bread (Giménez-Bastida et al., 2015). Gluten-free bread, with high anti-oxidation properties and beneficial omega-3 alpha-linolenic acid, can be prepared from a mixture of Tartary buckwheat flour and chia flour (Costantini et al., 2014). However, study reported that in vitro digestion of buckwheat bread reduces the inflammatory bowel diseases (Giménez-Bastida et al., 2018) and type-2 diabetes (Su-Que et al., 2013).

4.1.2. Biscuits and snacks

The bakery products from buckwheat flour, biscuits and snacks are the most palatable items to consumers. The acceptance of buckwheat products creates an increasing demand in the food market. These two items are the least studied so far. According to Giménez-Bastida et al. (2015) buckwheat flour-enriched biscuits and snacks both are new bakery products. Buckwheat flour contributes a significant effect on physicochemical and sensory properties of biscuits. During baking, there is a chance of reduction of several valuable phytochemicals, nutrients and bioactive compounds. A recent study reported that the rutin content remained unchanged during baking of rye-buckwheat enriched biscuits and also there was an increment in total phenolics and anti-oxidant capacity when buckwheat-rye biscuits supplemented with rutin (Starowicz et al., 2019). Buckwheat biscuits digestion might partially explain the bio -accessible ACE inhibitory activity (Zieliński et al., 2020). Buckwheat flour is used as valuable raw material and added in the mixture of corn flour that ranged from 10 to 50% of corn grits mass in extrusion-cooking to obtain buckwheat-corn enriched snacks (Wójtowicz et al., 2013). Corn-buckwheat snacks served as an attractive type of appetizer with high nutritional characteristics (Giménez-Bastida et al., 2015). From the mixture of buckwheat (80%) and almond (20%) flour, gluten-free biscuits with better nutritional parameters and good sensory traits also can be made (Masoodi et al., 2023). According to

Table 3
Buckwheat as a source of 'herbal garden' for bioactive compounds and their significant role in the treatments of several disease.

Disease	Source of treatment	Effects	References
Cancer/Malignant tumour formation			
Human cancer cell lines A549, HL-60, HCT116, and ZR-75, HepG2 and the human breast cancer cell line Bcap37	Tartary Buckwheat Soluble Protein 31 and Tatariside C derived from *F. tataricum*	Apoptosis of malignant cells included the human cancer cell lines A549, HL-60, HCT116, and ZR-75, as well as the human hepatoma cell line HepG2 and the human breast cancer cell line Bcap37	Guo et al. (2010)
Lung cancer, liver cancer, colon cancer	*Fagopyrum dibotrys* extract (FDE), Mixture of FDE + Daunomycin (in a dose of 25–40 g/mL)	Inhibit the growth of cancer cells of lung (H460), liver (HepG2) and colon (HCT116)	Jing et al. (2016)
Lewis lung tumour	*F. dibotrys* rhizome (FDR) fraction Fr4(a dose of 400 mg/kg)	Reduce the growth of tumour C57BL/6 in mice	Jing et al. (2016)
Human gastric cancer, lung cancer and oesophageal cancer	Extracts from *Rosa roxburghii* Tratt and *F. dibotrys*	Inhibits the growth of cancer cells of gastric (SGC-7901), lung (A549) and oesophageal (CaEs-17)	Jing et al. (2016)
LPS (lipopolysaccharide) -induced ALI (Acute lung injury)	Isorhamnetin of FDR extract	Decreases the COX-2 activation and reduce the oxidative stress	Zhang, Zhang, et al. (2023)
Inflammatory disease	Ethanol extract of *F. esculentum* sprouts	Reduced the levels of IL-6 and TNF- in mice triggered by LPS	Ishii et al. (2008)
Diabetes			
Type I and type II diabetes	D-chiro-inositol, derived from *F. tataricum*	Significantly reduced diabetic symptoms in patients, also lowering fasting blood glucose (FBG), glycosylated haemoglobin (GHb), and glycosylated serum protein (GSP), and raising fasting serum insulin levels	Jing et al. (2016); Cao et al. (2008)
	Ethanol extracts of Isoquercetin and D-chiro-inositol *from F. esculentum* and *F. tataricum* seeds	Both showed hypoglycaemic effects by lowering blood glucose levels and reduces the Type I and type II diabetes	Jing et al. (2016)
Viral diseases			
Corona virus disease-2019 (COVID-19), ALI, SARS-COV-2	FDR Extract	Reduces viral growth	Zhang, Zhang, et al. (2023)
African swine fever virus (ASFV)	FD extract rich in genkwanin flavonoids	Inhibiting the ASFV Ba71V strain in Vero cells	Zhang et al. (2021b)
Rotavirus	FD extract rich in ursolic acid	Restricts early virus replication	Zhang et al. (2021b)

(continued on next page)

Table 3 (*continued*)

Disease	Source of treatment	Effects	References
Influenza virus	FD extract rich in tricin flavonoids	Exhibits the inhibitory effect against influenza virus by reducing expression of hemagglutinin and matrix protein in influenza virus-infected cells	Zhang et al. (2021b)
Non-alcoholic fatty liver disease (NAFLD)	FD extract	FD extracts supplementation significantly alleviates hepatic steatosis, insulin resistance, and glucose tolerance in NAFLD	Zhang et al. (2022)
Alzheimer's disease (AD)	FDR extract, vitexin and ferulic acid component of FDR extract	Have therapeutic effects by anti-oxidant activity	Liang et al. (2017)
Bacterial diseases			
Staphylococcus epidermidis and *Staphylococcus aureus*	Quercetin, Isoquercetin and rutin extracts from *F.tataricum* bran	Effective antibacterial action	Wang et al. (2013)
Streptococcus haemolyticus B and *pneumococcus*	Ethyl acetate extract of FD	Exhibit anti-bacterial effects	Wang, Zhang, and Yang (2005)
Allergenic disease			
Cutaneous anaphylaxis induced by anti-dinitrophenyl IgE	Oral administration of Buckwheat (*F. esculentum*) grain extract (BGE)	Anti-allergic activity by preventing mast cell histamine release and cytokine gene expression	Kim et al. (2003)

sensory evaluations report, cookies made up with up to 20% buckwheat flour were most acceptable to the consumers (Breslauer et al., 2023). In addition, polyphenols component of buckwheat plays a significant role in the formation of volatile compounds that leads to the future application in the development of healthy bakery products with high antioxidant capacity (Starowicz et al., 2019).

4.1.3. Cake

Nowadays, the food industry is facing challenges to mitigate consumer's demand to create and supply low-fat or fat-free foods with palatable taste and texture. Buckwheat flour was successfully included into low fat-cake compositions for shortening up to 20% by weight after being thermomechanical changed by steam jet-cooking (Min et al., 2010). Recently, Zhang, Geng, et al. (2022) documented the manufacturing of buckwheat cakes and their antioxidant potential. In other gluten-free pancake products, the buckwheat flour was added in 30% to the premix containing 15% amaranth and 10% makhana flour to ensure the high-quality protein content, as well as the appropriate amount of fiber and mineral content (Kour et al., 2022). In this context, cakes made up with 30% buckwheat flour had revealed highest score for sensory attributes (Breslauer et al., 2023). Thus, more advanced studies on processing techniques could play an important role in producing low-fat cake with good flavour in bakery industries.

4.2. Non-bakery foodstuffs

4.2.1. Noodles & pasta

Buckwheat noodles (BWN) and pasta, both are most commonly used fast food items and could serve as a good source of carbohydrate. BWN is consumed popularly in Japan and some traditional areas of China, Bhutan and in the regions of southern slopes of the European Alps, namely, Slovenia, Italy, Switzerland, and France. A mixture of wheat flour and buckwheat flour are used to make BWN (Giménez-Bastida et al., 2015). The Japanese Food Agency recommended that a minimum of 35% buckwheat flour must be present in soba noodles (Giménez-Bastida et al., 2015). In addition, "Hele", a kind of Chinese noodle, is made entirely of common buckwheat flour (Breslauer et al., 2023). BWN with 20% common buckwheat flour was found to be most preferable noodles in terms of eating quality (Breslauer et al., 2023). BWN is also recommended as a suitable diet for diabetic patients (Kreft et al., 2002). Although more recent investigations suggested that noodles made from flour of Tartary buckwheat variety "Manten-Kirari", retained high rutin concentration, with better in taste (Suzuki et al., 2015). On the other hand, pasta is gained its wide acceptability due to its high nutrient enrichment, easy making, easy handling, palatability, long shelf-life and bearable cost (Mercier et al., 2016). In recent years, a new type of gluten free pasta was made by using rice grain and buckwheat flour as raw materials (Bouasla & Wójtowicz, 2019). Recent studies showed several health benefits of pasta. Buckwheat sprouts enriched pasta is found to be most effective against hypertension (Meschini et al., 2015) and type 1 diabetes and celiac disease (Vetrani et al., 2019).

4.2.2. Buckwheat groats/cereal grains

Dehulled buckwheat seeds are consumed as cereal grains or 'Kasha'in Russia, Ukraine and some regions in Japan (Giménez-Bastida et al., 2015). Buckwheat grains are a major part of buckwheat plant that we are consuming either in the form of raw groats (dehulled seed) or as roasted groat. Buckwheat groats are used as the major carbohydrate source in the diet. In Central and Eastern Europe roasted buckwheat groats or "kasha" are ready to use in cooking and usually served as an alternative to potatoes and rice (Boukid et al., 2018). In order to assess nutrient and other health benefits of buckwheat groats, the total dietary fiber (TDF) content of buckwheat groats ranged from 5 to 10% and the indigestive dietary fiber content (IDF) of whole buckwheat groats accounts for 31.4% of TDF (Giménez-Bastida et al., 2015). Glycemic index (GI) of buckwheat groats is showed a lower value (GI = 34.7) that indicates it does not create unhealthy spikes in blood sugar levels (Różańska et al., 2020). Buckwheat groats supplies 2.7 g dietary fiber per 100 g basis, making food transport easier in the digestive tract to regulate bowel movement (Joshi et al., 2020).

4.2.3. Sprouts

Another item that is now popular and has pro-health qualities is buckwheat sprouts, which is a delicious, crunchy food with a pleasant aroma and texture (Rauf et al., 2019). In addition to the nutritional content of food, the digestibility of the nutrients in it is also very important. Sprouting may improve the digestibility of starch and proteins (Molska et al., 2022) and the amount of biologically useful compounds (e.g., polyphenols, rutin, quercetin, ascorbic acid, reducing sugars, total lipid, essential amino acids) can increase significantly (Hung et al., 2020). Increased level of vitamin C, total flavonoid and rutin were proven to be involved in increased antioxidant activity of sprouted buckwheat seeds (Zhou et al., 2016). Production of probiotic-enriched sprouts by addition of *Saccharomyces cerevisiae* var. *boulardii* yeast may improve further the nutritional value of the sprouts such as increased methionine content and antioxidant activity (Molska et al., 2022). Moreover, these probiotic-rich sprouts involved in diet also may decrease the risk of cardiovascular diseases due to its favorable fatty acid and its beneficial effect may also be manifested in the case of a high-fat (atherogenic) diet (Molska et al., 2023).

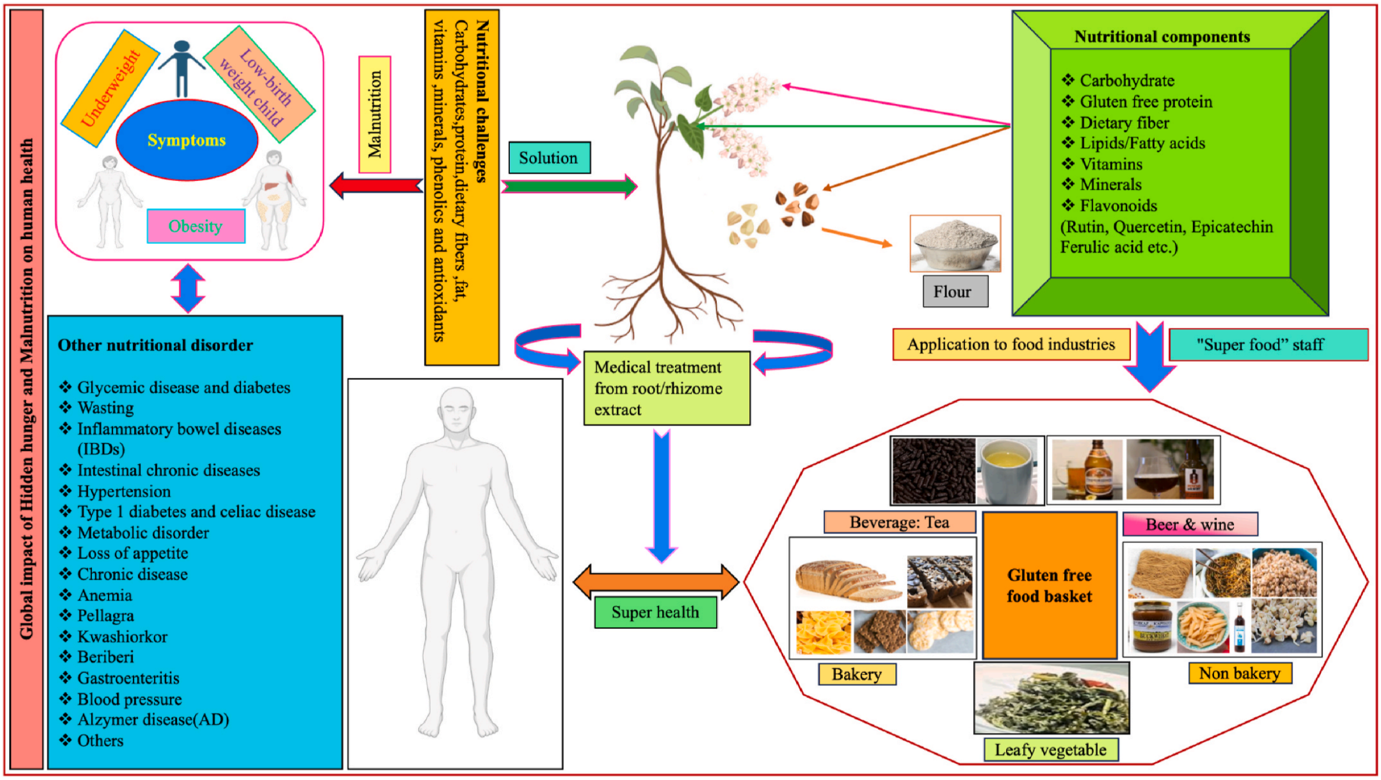

Fig. 1. Demonstrates the global nutritional challenges and their impact on human health along with buckwheat as an opportunity which provide an excellent nutraceutical source and application of its by products to the food industries and human nutrition.

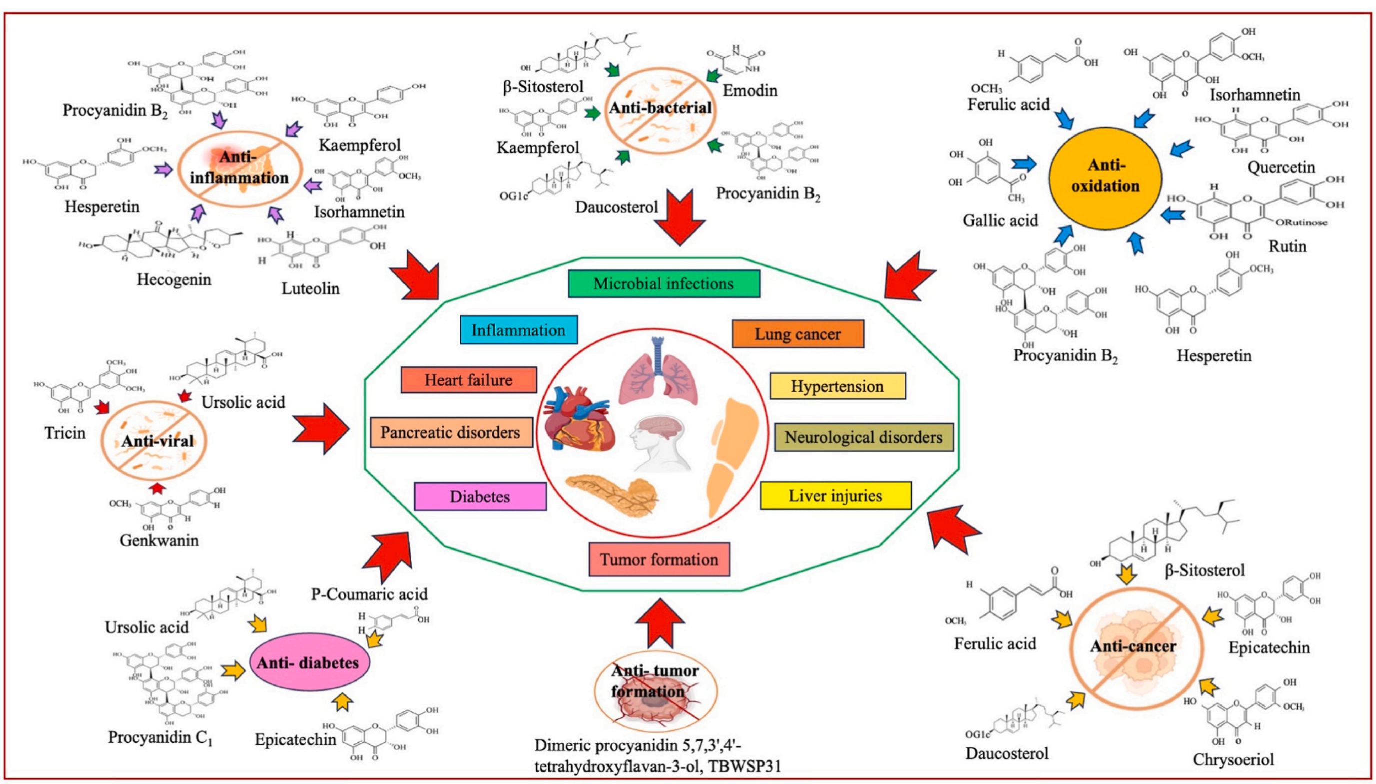

Fig. 2. Buckwheat derived bioactive compounds and their significant role in several diseases' treatment. The chemical structures have been adopted from Zhang et al. (2021b).

4.2.4. Buckwheat honey

Buckwheat honey is most widely used in Russia, Poland, Germany, and the Netherlands, and buckwheat monofloral honey is mostly produced in North America (Canada and California) and China (Panseri et al., 2013). Buckwheat flower is the source of buckwheat honey production (Deng et al., 2018). According to the studies the quality of honey depends on the colour of the flower (pink, white and red) and red coloured buckwheat flower showed higher antioxidant capacity than white coloured flower (Giménez-Bastida et al., 2015). Giménez-Bastida et al., reported that colour of buckwheat honey is a reddish brown and having a strong animal aroma and sustained several quality advantages over other honey such as higher antioxidant capacity, higher flavonoid and total phenolic content. There is little research on the evaluation of buckwheat honey's sensory character. Several studies have been made on buckwheat honey suggested its plenty of medical advantages that made it popular food item. Although the sugars are regarded as major components of buckwheat honey, the other components such as proteins, minerals, phenolic compounds and some minor components also take part into various biological activities like antibacterial and antioxidant, anti-browning, ACE-inhibitory and anti-inflammatory activities (Deng et al., 2018). Several other potential medical properties of buckwheat honey are listed in Table 2.

4.3. Beverages

4.3.1. tea

Buckwheat tea, a very popular tea beverage (called as Soba-cha in Japan) can be made from its roasted groats (Zielińska et al., 2009). Due to its antioxidative and antiglycation properties, buckwheat tea is one of the most popular beverages (Zielinska et al., 2013). It is the most widely consumed buckwheat product in China, Japan, South Korea, and Europe (Masoodi et al., 2023). Most often, the Tartary buckwheat is used to make a beverage, tea, or tea soup (the tea material is brewed for 10 min, then filtered, is repeated several times and the filtrates are poured together) (Guo et al., 2017; Niu et al., 2022), because it has more favorable nutritional contents compared to common buckwheat (Bonafaccia & Fabjan, 2003). High rutin, polyphenol, total vitamin B (especially B6) and trace element content makes it more suitable for disease prevention (Bonafaccia & Fabjan, 2003).

The main types of Tartary buckwheat tea are usually made from roasted grains, young (roasted) leaves or a mixture containing stem, leaf, flower, and grain (extruded pellets) (Noda et al., 2021). Nutrient composition of buckwheat tea includes protein, amino acids, starch, fat, fatty acids, and flavonoids although their presence and quantity may depend on the plant part used, the method of processing and preparation of the drinks (Guo et al., 2017; Noda et al., 2021). It also holds antioxidant and α-glucosidase inhibitory activities and 14 aromatic compounds from Tartary buckwheat has been reported in which 3-ethyl-2, 5-dimethyl-pyrazine identified as the predominant compound (Guo et al., 2017). In addition, the rutin content in the tea made from the roasted bran of Tartary buckwheat ('Manten-Kirari') was 389 mg/l, whereas the tea made from the roasted grains by the same way contained 68 mg/l of rutin (Noda et al., 2021). This cultivar was developed to have rutinosidase (when water is added to flour, it hydrolyses the rutin to quercetin and rutinose within a short time) at a low quantity, which makes production of food with high rutin content possible after processing its yield (Noda et al., 2021).

4.3.2. beer & wine

Beer is one of the most common and oldest alcoholic beverages in the world (Hager et al., 2014). According to epidemiological studies, regular and moderate beer intake has health benefits such as it decreases cardiovascular disease and mortality (Yang & Gao, 2022; de Gaetano et al., 2016), lower chance of dementia, cognitive impairment, and osteoporosis (Yang & Gao, 2022). Generally, beer is made from the grain of barley or wheat (Hager et al., 2014), the standard brewing ingredients contain immunoreactive parts of hordein and gliadin proteins, which can cause allergic reactions and intolerance to beer in people with celiac disease (Hager et al., 2014) an autoimmune disease affecting primarily the small intestine, which cannot be cured, but can be treated well with diet (Caio et al., 2019). Providing a special drink for this consumer group is debatable, but from a sociocultural point of view, it seems that the possibility of consuming gluten-free beer is an advantage in terms of public life and health (Yang & Gao, 2022; de Gaetano et al., 2016). The brewing industry – with the growing demand for gluten-free beers (Wijngaard et al., 2005) is continuously interested in new developments and processing in new raw materials such as rice, oat, quinoa, sorghum, millet or buckwheat (Hager et al., 2014). Buckwheat seeds contain a high concentration of phytonutrients that provide effective help in the treatment of insulin resistance and affect the glycemic index, such as flavonoids, D-chiro and myo-inositol (Duliński et al., 2019).

Wine is also one of the most demanding and popular fermented beverages across the world. Among the various ingredients of wine, gluten is one of the major component and it comes from malt of barley, quinoa crops. Buckwheat and quinoa crops were found to be better than barley for wine making sources (Deželak et al., 2014). Chinese rice wine (CRW), a unique wine item and possess a long history in China. The production of CRW wine with Tartary buckwheat grain was determined to be beneficial to the development of new rice wine products (Ren et al., 2019).

4.3.3. Other food and drink products

Some other drink such as soba shochu is also most popular alcoholic drink which is made by the fermentation of buckwheat seed grain with *Aspergillus oryzae* (Giménez-Bastida et al., 2015). Consumption of soup prepared from instant mix containing gelatinized buckwheat flour in 30% also may play role in health preservation due to its favor functional parameters (7.71% protein, 5.61% fiber, high level of phenolics and flavonoids) (Gomathi & Parameshwari, 2023). To obtain more valuable nutritional profile of the food product, rice flour can be substituted in 40% by buckwheat flour when "papad" (a traditional Indian dough) is prepared (Srikari et al., 2023). In Southern Asia, the very popular "sesame laddu" also can contain buckwheat flour in 20% to be healthier, although this food product can be more expensive than those made only from sesame seed and jaggery (Yasodhadevi et al., 2022). Other food items made from buckwheat are listed in (Table 2).

4.3.4. Buckwheat as a suitable source of foods for infants and children

For all infants, mostly breastfeeding is recommended feeding method (Vandenplas, De Mulder, et al., 2021). Recent research has been focused on plant-based nutritionally balanced liquid feeding for infants and childrens, despite the growing demand from consumers for plant-based liquid feedings for toddlers as an alternative to dairy. However, not all plant-based beverages are nutritionally suitable for young children and infants. There are some nutritionally adapted formulas are available, for example, almond and buckwheat-based liquid feeding for toddlers; almond, buckwheat and tapioca-based young child formulas (Vandenplas, De Mulder, et al., 2021). Recently, some vegan toddler formulas with a mild, pleasant flavor that fully meets nutritional requirements have been made using ingredients from pea, rice, buckwheat, and almond (Vandenplas, Brough, et al., 2021). More recently, in a controlled-neonatal piglet trial, it was reported that the effects of plant-based infant formula (which uses buckwheat and almonds as the main source of protein) on gut microbiota growth and health outcomes had similar effects as commercially available dairy-based formula (Gurung et al., 2023).

Additionally, some baby foods made with buckwheat can be found online (https://www.vitaminglobal.com/and https://www.amazon.com/) under various names, including Bebi Buckwheat Cereal for Babies from 4 months, Arrowhead Mills Maple Organic Cereal, Buckwheat Flakes, Le Pain Des Fleurs Organic Buckwheat Crispbread, Fleur Alpine Beby Buckwheat Hypoallergenic for Babies from 4 months, Buckwheat

Cereal for Babies Enriched with Vitamins and Minerals 200 g - Better & Different etc. Therefore, developing plant-based liquid meals that are suitable for young children and offer a balanced nutritional composition are an important avenue by which buckwheat could also be used. Additional research on the precise nutritional composition and flavors levels in most of these is also welcomed.

5. Pharmacological importance of bioactive compounds and its application in disease treatment

The presence of versatile bioactive compounds in buckwheat and their potential application in various medical treatment has been reported so far. For example, anti-cancer effects of Tartary buckwheat soluble protein have been found to be effective against breast cancer causing malignant cell Bcap37 (Guo et al., 2010). A significant anti-inflammatory response after treatment with ethanol extract of common buckwheat sprouts, have also been reported (Ishii et al., 2008). Extracts of both common buckwheat and Tartary buckwheat have shown anti-diabetic effects (type I and type II diabetes) (Jing et al., 2016) and significantly reduced the non-site-specific and site-specific DNA strand breaks (Cao et al., 2008). A naturally occurring substance present in buckwheat seeds, 2-hydroxybenzylamine (2-HOBA) inhibits the formation of adducts with proteins and DNA by reacting with all isolevuglandin adducts which prevents inflammatory-prone diseases (Rathmacher et al., 2023). Quercetin and isoquercetin components of Tartary buckwheat have showed anti-bacterial activity against *Propionibacterium acnes*, *Staphylococcus epidermidis*, and *Staphylococcus aureus* (Wang et al., 2013). Several anti-viral activities of golden buckwheat extracts have been reported including corona virus disease-2019 (COVID-19) treatment (Zhang et al., 2021b, 2023b). Oral administration of buckwheat grain extract found to be effective against some anti-allergic response (Kim et al., 2003) (also see Table 3 & Fig. 2). Non-alcoholic fatty liver disease (Zhang, Jiang, et al., 2022) and Alzheimer's disease (Liang et al., 2017) can also be regulated by golden buckwheat extracts disease (Liang et al., 2017) (Table 3 & Fig. 2).

6. Genomics driven investigation of buckwheat for food and nutritional security in the 21st century

Understanding the genetic basis of agro-morphological traits is a key goal for all crops. The floral structure plays a crucial role in determining the seed yield, which is one of the most important trait for increasing yield (Luo et al., 2023). In buckwheat, low yields due to seed shattering because of pedicel breaking and heterozygosity due to self-incompatibility (SI) as a consequence of dimorphic heterostylism have always remained major problems in achieving large scale incorporation of common buckwheat (*F. esculentum*) in the agricultural portfolio. To understand SI in common buckwheat, and the genetics underpinning the presence of two floral architectures - thrum, or short style, and pin, or long style needs to be discerned (reviewed by Zargar et al., 2023) and it is known that this is determined by a single genetic locus (S). In this context, recently, genetic analysis of *F. homotropicum* has revealed that the *FhS-ELF3* gene contributes to the homomorphic self-compatibility of common buckwheat and involved in increased fertility (Zhang, He, et al., 2023).

Seed shattering in buckwheat is due to the presence of brittle pedicle whose formation is controlled by two complementary dominant genes viz. *Sht*1 and *Sht*2 (Matsui et al., 2004; Wang, Scarth, & Campbell, 2005). While the non shattering populations of common buckwheat carried only a single recessive gene, the shattering populations carried recessive alleles at two to three loci Wang, Scarth, and Campbell (2005). Their results suggested a two gene model with three alleles at the S locus and two alleles at the S_c locus. Although conventional breeding has been used to address seed shattering issues in buckwheat, efforts to produce non-shattering cultivars have been hindered by the lack of robust germplasm resources and inefficiency in conventional breeding strategies. Therefore, it is imperative to introduce approaches that combine bulked segregant analysis with whole-genome sequencing which would dramatically accelerate the process of identifying candidate genes involved in shattering.

Numerous attempts have been made to hybridize buckwheat species in order to increase the compatibility rate and enhanced yield. However, most of these interspecific crosses have not been successful in producing interspecific hybrid progenies as of yet with the exception of some following successful crosses: tetraploid *F. tataricum* × tetraploid *F. cymosum*; and among successful crosses, an annual man-made new species of buckwheat *F. giganteum* with white hetero-style flower has been developed (Chen et al., 2018). Moreover with the help of wide-hybridization and genomic selection, some high seed yield and high flavonoids yield has been developed.

Although buckwheat grains are highly nutritious, the digestibility of its proteins is low because of the presence of anti-nutritional factors such as tannins, phytates and protease inhibitors (Liu et al., 2001). Further, quercetin, the hydrolysis product of rutin, imparts a bitter taste to the dough prepared from buckwheat flour. Development of a genome-based pipeline and a road map for addressing the issues that hinder acceptability of buckwheat in the mainstream agriculture to help bridge the "*Food-nutrition gap*" would therefore be essential steps in accelerating the improvement of buckwheat. The road map would have three aapproaches: i) genome driven identification of important QTLs; ii) breeding for yield stability and iii) genetic engineering for loose hull and low allergenicity. Sampling a 'core collections' which represents the bulk of the genomic variation in buckwheat, could be the first key step and a useful strategy for identifcation of novel variants and genome-wide association studies (GWAS) to characterize QTLs/candidate genes responsible for economically important traits. In the past few decades, genomic selection (GS) (Yabe et al., 2018), QTL mapping (Li et al., 2023) and GWAS (Hou et al., 2022) have been effectively used for genome assisted breeding in buckwheat. The availability of draft buckwheat genome of common and Tartary buckwheat (1.2 Gbp and 0.48 Gbp, respectively) (Yasui et al., 2016; Zargar et al., 2023; Zhang et al., 2017) has laid the basis for the establishment of breeding pipelines that can integrate phenotype with genotype for desired traits.

Previously, transcriptome-based gene expression profiling has identified several candidate genes that regulate various agronomic traits, such as seed size, yield, heterostyly, flavonoid biosynthesis, nutritional quality, biotic and abiotic stress tolerance in buckwheat (Hu et al., 2016; Logacheva et al., 2011; Yasui et al., 2016). Zhang et al. (2017) have reported a whole-genome duplication event after divergence of buckwheat from sugar beet, which led to the expansion of many protein families that render adaptability of this crop to harsh environments. However, Mizuno and Yasui (2019) have ascribed the low nucleotide diversity in the European genome, and the low level of divergence between Asian and European populations, to the presence of genetic bottlenecks associated with the dispersion of common buckwheat from Asia to Europe, and/or intensification of agriculture and selection of common buckwheat in Europe. The availability of chloroplast genome sequences for common (Cho et al., 2015) and Tartary (Zhang et al., 2017) buckwheat have also paved a way to understand genetic diversity in buckwheat. Proteome mapping, protein-protein interactions, and comparative proteomics have also provided valuable information regarding functional characterization of proteins for a variety of biological processes and many essential proteins associated with seed maturation, endosperm growth, and glucose metabolism have been identified (Altelaar et al., 2013). Lee et al. (2016) have identified 166 distinct cytosolic proteins involved in cellular metabolism during light stress. Out of these 79 proteins were specific to golden buckwheat, 81 proteins were specific to Tartary buckwheat, and 6 proteins were common to both species. Song et al. (2019) demonstrated the link between dehulling efficiency and lignin to cellulose ratio in the hulls with varieties with loosely adhering hulls having high lignin and low cellulose levels. These findings point the way for a breeding programme to discover variants with improved agronomic traits. While the main focus of common and Tartary buckwheat breeding efforts has been on yield stability and development of self-compatible lines of common buckwheat, nutritional quality optimization and development of loose hulled cultivars of Tartary buckwheat have gained more attention in recent years (Kreft et al., 2020). However, with a tightly adhering hull and high rutinosidase activity which converts rutin to quercetin, Tartary buckwheat flour is bitter in taste. Development of high yielding variants with low rutinosidase activity and large seeds with a non-adhering hull are major aims of a breeding program in Tartary buckwheat. Suzuki et al. (2014) have developed 'Manten-Kirari,' a new "sweet" cultivar of Tartary buckwheat with low rutinosidase activity.

In recent years, significant progress has been made in the molecular genetic research of buckwheat, including gene expression (especially stress related), epigenetic and other proteomic/metabolomics studies (He et al., 2022; Zargar et al., 2023; Zhang et al., 2021a). For example; combined GWAS and gene expression studies have identified potential candidate genes such as *FtUFGT3* and *FtAP2YT1* are associated with flavonoid accumulation and grain weight in Tartary buckwheat, respectively (Zhang et al., 2021a); glycosyl hydrolase gene *FtGH1*, hydrolyse rutin to quercetin (Lai et al., 2023); Jasmonic acid-induced *FtBPM3* associated with flavonoids accumulation in Tartary buckwheat (Ding et al., 2022); *FdMYB44* and *FdCRF4* genes are putatively involved in flavonoid accumulation and differentiation of plant architecture respectively in golden buckwheat (He et al., 2022); Zhang, He, et al. (2023) have identified*, Fh05G014970* as a potential major regulator of flowering period, *Fh06G015130 for* flavonoid*s and FhS-ELF3* contributed to the homomorphic self-compatibility of common buckwheat; *FtWRKY46* associated with enhanced salt stress tolerance in Tartary buckwheat (Zargar et al., 2023); He et al. (2023) identified *FtASP, FtADH1, FtPG1, FtCES18, and FtKCS11* genes that were associated with enhanced disease resistance in case of *Rhizoctonia. solani* strain AG4-HGI 3; *FtMADS* (Liu, Fu, et al., 2019) and *FtAG* (Fukuie et al., 2020) genes were linked to high dehulling efficiency.

However, we can now quickly identify new resistance genes, produce disease-resistant crop plants, and accurately modify the genomes of crop species with the help of genome editing based on clustered regularly interspaced short palindromic repeats/CRISPR associated protein9 (CRISPR/Cas9). This opens up new possibilities for breeding and biotechnology (Zhao et al., 2022; Zhou et al., 2023). It is hoped that buckwheat will become more popular as new varieties with better agronomic traits are introduced (Zargar et al., 2023).

7. Concluding remarks

7.1. Aspects of global food, nutrition and health securities

The problems of food crisis and malnutrition are common in developing countries and challenging due to the increasing population globally. An inadequate diet with insufficient nutrients, minerals, and vitamins to grow and sustain a healthy body is one of the main causes of malnutrition. There is a lot of potential to fight poverty, hunger, and malnutrition using neglected and underutilized crop species. Buckwheat is one example of an underutilized crop species, despite having an abundance of nutritional and bioactive components. The functional properties of this crop can support their potential use in structuring food products. The gluten-free nature of buckwheat has attracted attention for its essential role in human health. In food industries, buckwheat is used in making various bakery, non-bakery, and fermented foodstuffs. Besides the high-quality nutritional profile, pharmacological studies have shown that buckwheat possesses potential anti-inflammatory, anticancer, anti-oxidant, anti-bacterial, and anti-diabetic activities which partially support the ethnomedicinal uses of buckwheat. Flavonoids and phenolic compounds are the main active ingredients of buckwheat. Therefore, the presence of vital nutrients and bioactive compounds in buckwheat has the potential to address global nutritional and health challenges, effectively reducing hidden hunger and malnutrition.

7.2. Issues for buckwheat cultivation and genetic improvement

The main problems in the cultivation and breeding of buckwheat are related to the unknown inheritance of agronomic characters and quality, such as the unpredictable crop yield, synthesis of medicinal compounds, low seed production, seed formation on branches, and synthesis of buckwheat metabolites. To address these challenges, the application of OMICS technology is necessary for identifying and characterizing desirable genes or alleles responsible for e.g nutraceutical properties, which can help establish the functional role of buckwheat-based products and foods in promoting human health (Zargar et al., 2023).

Additional problems that must be paid attention to during breeding work - including but not limited to - such as difficulties in cultivation technology. Harvesting can be made difficult by lodging, choosing of the harvest date by indeterminate growth, harvesting loss may be increased by a tendency to break the peduncle (Zargar et al., 2023).

Moreover, buckwheat yield is strongly dependent on the weather, which may be due to direct effects of high temperature on seed setas well as indirectly due to a lack of bee pollination (Breslauer et al., 2023). Other problems may stem from the heterozygous character of cross-pollinated crops such as buckwheat (Zargar et al., 2023).

Considering the food products, further problem may occur related to the presence of allergens (Zargar et al., 2023). There are still problems to be solved during processing (e.g. dehulling) (Breslauer et al., 2023). Likewise, anti-nutritional factors such as tannins, phytates and protease inhibitors (Liu et al., 2001) which decrease bioavailability of micronutrients, is one of the major problems. Therefore, breeding and "omics" strategies to reduce such factors are required.

There are several related species hold alleles/genes, which may be incorporated to improve above mentioned characters (Fig. 3). However, collection, storage, evaluation of these genotypes and establishment a globally accessible database of those results would be necessary to reveal the genetic potential inherent in the species/types (Zargar et al., 2023).

Although, many species can be hybridized with cultivated buckwheat species, incompatibility issues may occur resulting in embryo abortion (Mendler-Drienyovszki et al., 2013). However, self-incompatibility presents similar problems in breeding (Zargar et al., 2023). With this context, some case study has also been reported like, a tetraploid variety "Hongxin Jinqiao" was reported to be developed by crossing among golden buckwheat accessions with low seed shattering rate (Chen et al., 2018), In addition, a hybrid variety 'IP2/IH3' with higher seed yield was also reported (Kasajima et al., 2017).

7.3. Priorities for future studies

Going forward, the following priorities should increase the awareness and popularity of buckwheat. Popularity must be increased in two main areas: cultivation and consumption of the final product. A significant part of the tasks falls indirectly on the breeding work. Development of new varieties with early maturity, with good seed set ability, with more determined growth habit, with resistance to environmental stress, to lodging, with decreased yield loss due to break peduncle etc. These improvements may promote the willingness to grow and economic cultivation of buckwheat. Breeding for abiotic stress resistance especially drought and high temperature is one of the most important tasks. Improving fertility conditions and possibly producing self-fertile varieties would also be a very useful output. Genetic resources are available to identify genes/alleles related to useful characters, and the establishment of a database including information of seed collections accessible to everyone would be of considerable use.

From the point of view of improving attractiveness for the consumer, the examination of crop genotypes for useful bioactive substances and allergens is important. Discerning the metabolic pathways underlying

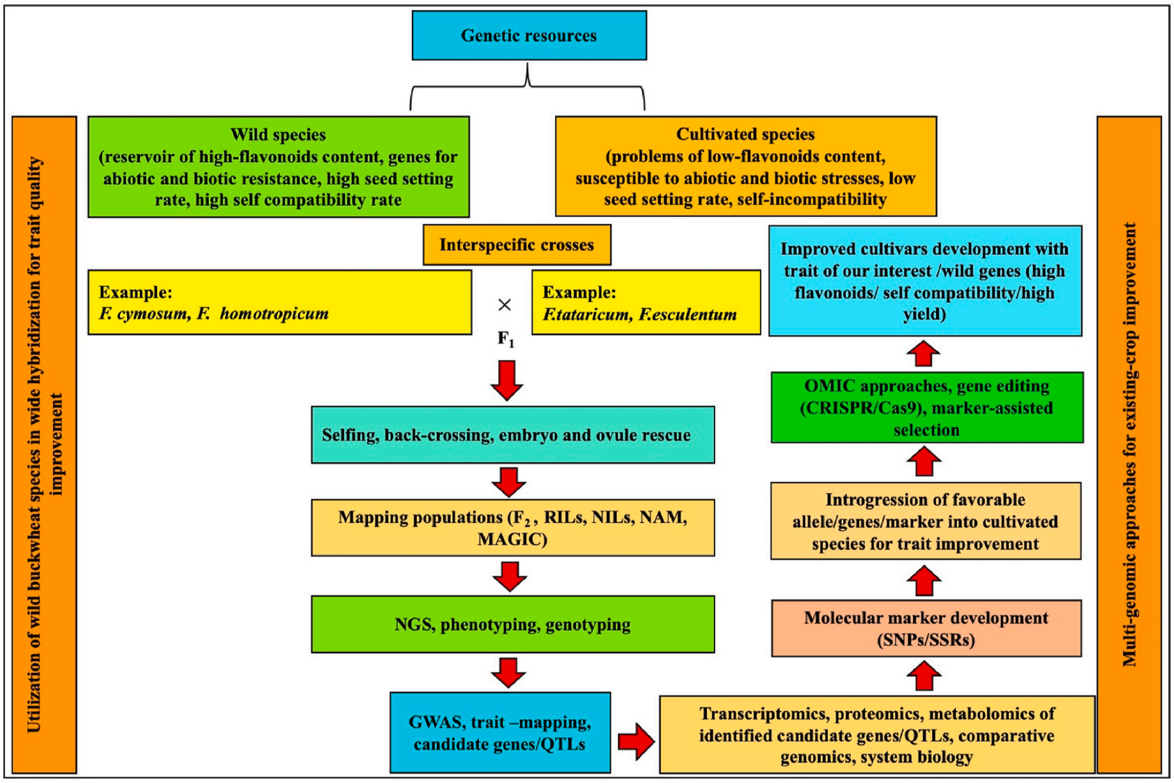

Fig. 3. Illustrates exploitation of wild buckwheat species in inter-specific crossing and overall genomic approaches to improve the existing cultivar and broadening of buckwheat genetic resources. (RILs = Recombinant Inbred Lines; NILs = Near Isogenic Lines; NAM=Nested Association Mapping; MAGIC = Multi-Parent Advanced Generation Inter-Cross; GWAS=Genome Wide Association Studies; QTL = Quantitative Trait Loci; CRISPR/Cas9 = Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR associated protein9).

the biosynthesis of bioactive compounds may help production of new varieties with improved nutrient content. Improving the taste of products intended for consumption should also be considered in parallel.

There is also work to do on the “road” between the field and the consumer. The processing of the buckwheat crop into a final product still requires a lot of work. When the production of gluten-free products is the aim, the mixing ratio of the flours must be tested. Further, the multiple steps of processing (cleaning, dehulling, heat treatment, grinding) affects the quality of the final product, the content of bioactive substances, and the taste of the product. Therefore, these technological processes must be optimized to improve quality and reduce losses. The utilization of by-products has significant potential for buckwheat, for example as a tea ingredient.

Considering medicinal importance of buckwheat, future study also focus on identification of other new bioactive compounds. For example, recently identified natural compound 2-HOBA was found to be present in buckwheat seeds which entails beneficial effects on oxidative stress and inflammatory disease (Rathmacher et al., 2023). Overall, buckwheat has significant but underexplored potential as a future crop for food and nutrition security; and this review highlights some of the key potential aspects which need to be explored.

CRediT authorship contribution statement

RJ and MZ conceived the idea and wrote the manuscript. KZ, YH, NM-D, KM-T, MQ, MG, IK, VM, KI, MAC, DJ, GP, S-HW, SB, MIG, NC and AB have edited the manuscript. All authors have revised and approved the final manuscript.

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Declaration of competing interest

The authors have declared no competing interests.

Data availability

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

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