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Unlocking the Potential of Buckwheat Hulls, Sprouts, and Extracts: Innovative Food Product Development, Bioactive Compounds, and Health Benefits – a Review

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This comprehensive review explores the underutilized buckwheat hulls, sprouts, and grain and sprout extracts, concentrating on their nutritional characteristics, health advantages, and possible uses in developing functional food products. Buckwheat, a pseudocereal, is emphasized for its impressive nutritional content, including high levels of dietary fiber, essential minerals, and vitamins, as well as bioactive compound content, such as phenolic acids and flavonoids mainly rutin. The paper discusses the significant antioxidant and antimicrobial properties of buckwheat hulls, sprouts, and extracts, which contribute to their utility in creating healthier, functional food products. Buckwheat sprouts are noted for their enhanced levels of antioxidants and nutrients compared to mature grains. Meanwhile, buckwheat hulls, traditionally seen as by-products, are identified as sources of dietary fiber and flavonoids, suitable for use in dietary supplements and functional foods. The extracts from these parts are rich in bioactive compounds that offer health-promoting effects. The possible effects of addition of buckwheat hulls, sprouts, and extracts to food products in terms of nutritional, textural, and sensory properties are also discussed. The review underscores the need for further research to optimize the use of buckwheat less-utilized parts and to better understand their health impacts. By highlighting the novel uses and health benefits of buckwheat hulls, sprouts, and extracts, the review contributes to the growing field of sustainable food practices and the development of functional foods.

Keywords: buckwheat derivatives, buckwheat by-products, health benefits, zero-waste food industry

INTRODUCTION

Buckwheat, a pseudocereal distinguished by its impressive nutritional profile and adaptability, has been gaining attention not only for its grains but also for its underutilized parts such as sprouts and hulls, and extracts from these parts and grains. Unlike true cereals, buckwheat is related to sorrel and rhubarb, making it a valuable crop for both human consumption and sustainable agriculture practices, abundant in compounds with antioxidant, antimicrobial, and anti-inflammatory properties like phenolic acids and flavonoids (mainly rutin) [Dębski *et al*., 2021; Mazahir *et al*., 2022]. Buckwheat, replete with substantial amounts of dietary fiber, crucial minerals, and vitamins, functions as an indispensable ingredient across various culinary contexts. Furthermore, it acts as a vital link in addressing nutrient deficiencies and enhancing food security [Jha *et al*., 2024]. The presence of slowly digestible proteins and starches in buckwheat underscores the nutrition value of its derived products [Džafić & Oručević Žuljević, 2022; Kreft *et al*., 2022]. Its sprouts are rich in bioactive compounds [Atambayeva

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et al., 2023; Zhang *et al*., 2015], while the hulls, often discarded as waste, have potential uses in food technology and other industries [Kan *et al*., 2023; Zhang *et al*., 2023]. Buckwheat extracts have also been studied for their antioxidant and functional properties [Hęś *et al*., 2017]. The exploration of these buckwheat parts and extracts aligns with the global trend towards utilizing whole plants to minimize waste and maximize health benefits, marking an innovative shift in food product development.

The potential of buckwheat sprouts, hulls, and extracts in creating new, health-oriented food products is vast, yet underexplored. While the grains of buckwheat have been extensively studied, there remains a significant knowledge gap concerning the optimal use of its other derivatives. Sprouts, which emerge during the germination process, are known for their enhanced levels of antioxidants and nutrients compared to mature grains [Molska *et al*., 2022a; Shreeja *et al*., 2021]. Hulls, traditionally seen as by-products, contain valuable fibers and flavonoids, offering opportunities for use in dietary supplements and as functional food ingredients [Gutiérrez *et al*., 2023; Zhang *et al*., 2023]. Meanwhile, the bioactive compounds in buckwheat extracts, including rutin and quercetin, have demonstrated health-promoting effects, yet their integration into everyday food products is still in its infancy. Moreover, our literature search revealed that information on green buckwheat (thermally untreated) grain, as well as its sprouts and hulls, is notably limited. Investigating green buckwheat and its derivatives could prove economically beneficial since they require no treatment, thus lowering production costs. Also, the abundant bioactive compounds present in green buckwheat offer extensive research opportunities, potentially leading to innovative applications in nutrition and health sciences. This underexplored area promises substantial economic and scientific value, urging further exploration.

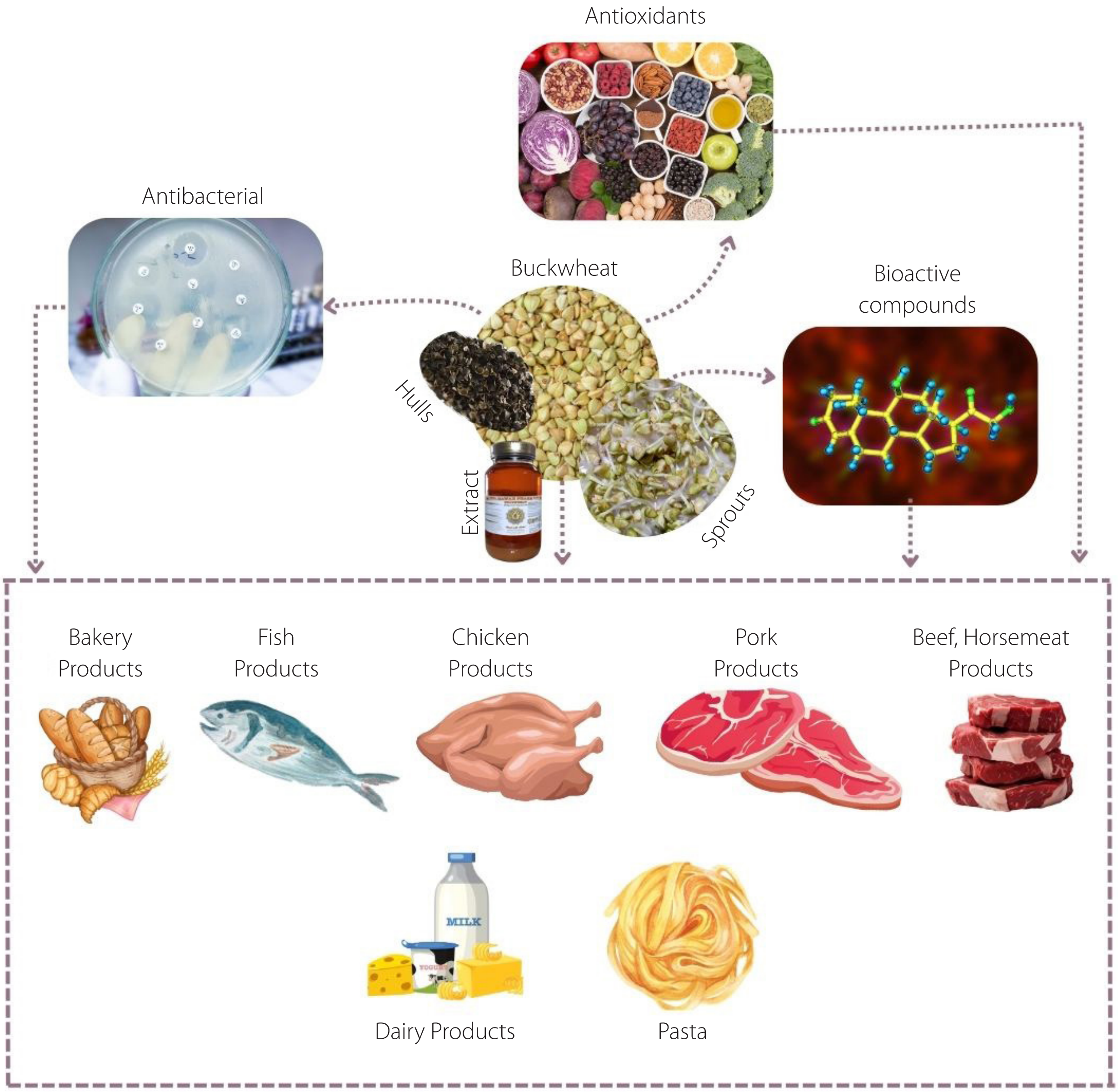

Figure 1. Integration of buckwheat hulls, sprouts, and extracts into diverse food categories for enhanced health benefits.

This review aims to consolidate existing research on the nutritional and bioactive profiles of buckwheat sprouts, hulls, and extracts, highlighting innovative approaches in food product development (**Figure 1**). By examining how these components have been used in various food matrices, the review will shed light on their functional benefits and potential health impacts. Moreover, it will discuss the technological challenges and opportunities in harnessing these parts of buckwheat and commercial application in food industries. This comprehensive synthesis will not only fill the existing knowledge gaps but also stimulate further research and development in this promising area.

The contribution of this review to the current scientific knowledge is twofold. Firstly, it provides a systematic overview of the potential applications and health benefits of buckwheat lesser-utilized parts and extracts, thus broadening the scope of uses for this versatile plant. Secondly, it encourages the adoption of sustainable practices in the food industry by promoting the use of agricultural by-products. This aligns with the global objectives of reducing food waste and enhancing nutritional quality in food production. Through this review, investors in the food industry, researchers, and consumers will gain a deeper understanding of the innovative potential that buckwheat sprouts, hulls, and extracts hold, steering the future direction of food product development towards more sustainable and health--conscious choices.

LITERATURE SEARCH AND STUDY SELECTION CRITERIA

This review adhered to the PRISMA guidelines [Moher *et al.*, 2009; Rethlefsen *et al.*, 2021] and aimed to conduct a thorough and systematic literature search using several databases, such as PubMed, Scopus, Web of Science SCIE, and Google Scholar. Keywords such as "buckwheat sprouts", "buckwheat hulls", "buckwheat extracts", "bioactive compounds", "health benefits", "flavonoids", "nutritional value", "anti-inflammatory effects", "anti-cancer potential", "functional foods", "dietary fiber", "protein content", "cardiovascular health", "mineral content", and "antimicrobial activity" were employed to locate relevant studies published in peer-reviewed journals. Both original research articles and review papers were included to ensure thorough coverage of the topic. Furthermore, references cited in the chosen articles were examined to uncover additional relevant research. The criteria for inclusion were specifically targeted at studies published in English, which investigated the nutritional makeup, bioactive compounds, and health-related outcomes associated with buckwheat sprouts, hulls, and extracts.

Studies were considered if they met the following criteria: (i) involved samples of buckwheat hulls, sprouts, or extracts; and (ii) analyzed nutrient and bioactive compounds for the development of functional foods and their health benefits.

After searching the following electronic databases PubMed, Scopus, Web of Science SCIE, and Google Scholar, 870 potentially relevant citations were identified, and after removing 51 duplicates and 557 citations for other reasons, 262 abstracts and titles were evaluated according to inclusion and exclusion criteria. Full texts and reference lists of 186 studies were evaluated, among which 120 studies met the criteria and were selected for inclusion in this review. In these studies, buckwheat hulls, sprouts, and some of their extracts and grain extracts have been used as additional ingredients in functional foods development, while their health benefits were studied in animals, and their bioactive compounds were identified in hulls, sprouts, and extracts, which we discuss in detail in the later sections.

NUTRITIONAL AND FUNCTIONAL INSIGHTS OF BUCKWHEAT HULLS, SPROUTS, AND EXTRACTS

■ Macronutrients (protein, fiber, carbohydrate, fat)

While buckwheat may not offer as much protein as other pseudocereals, like amaranth (139 mg/g dry weight, dw) and quinoa (165 mg/g dw) [Ahmed *et al.*, 2014], it typically contains more protein than rice (6.8 g/100g grain), wheat (11.8 g/100g), and maize (9.4 g/100g) [Pirzadah & Malik, 2020]. Guo *et al.* [2007] reported that the average protein content in buckwheat is 12.94 g/100 g. The slower buckwheat protein digestibility, possibly due to polyphenol binding, is balanced by a highly beneficial amino acid composition that effectively meets essential biological needs [Luthar *et al.*, 2021; Zhu, 2021]. Although buckwheat grains contain relatively low protein levels (~12 g/100 g), with these levels being higher than in most cereals, yet significantly lesser than in leguminous plants such as soybean meal (~51 g/100 g), it distinguishes itself through an abundant presence of lysine and arginine, two amino acids indispensable to human health [Ahmed *et al.*, 2014; Dziadek *et al.*, 2016; Jin *et al.*, 2022; Luthar *et al.*, 2021].

■ Buckwheat hulls

Buckwheat hulls, often considered a by-product in the production of buckwheat dehulled grains, have a modest nutritional profile, particularly in terms of crude protein and crude fat content (**Table 1**, **Figure 2**). Significant variability was observed among different varieties of buckwheat in terms of their hull protein content, ranging from 3.0 g/100 g to 6.5 g/100 g among 10 cultivars, with the average of 4.7 g/100 g [Lu *et al.*, 2013]. Despite this low level, buckwheat proteins still offer all the essential amino acids, contributing 1.04 g/100 g dw for essential amino acids and 1.53 g/100 g dw for non-essential amino acids [Zhang *et al.*, 2023]. However, these amounts are not sufficient to fulfil dietary requirements on their own.

In terms of crude fat, buckwheat hulls contain even smaller quantities (<1 g/100 g), compared to dehulled seed (~2.5 g/100 g), which varies depending on the cultivar [Ahmed *et al.*, 2014; Dziadek *et al.*, 2016; Matseychik *et al.*, 2021; Zhang *et al.*, 2023]. This minimal fat content comprises primarily of unsaturated fatty acids [Dziadek *et al.*, 2016; Zhang *et al.*, 2023]. The low-fat content is consistent with the composition of most plant hulls, which are primarily designed to protect the seed rather than store nutrients.

Buckwheat hulls were identified as a particularly rich source of total carbohydrates, with an average content of 92.02 g/100 g across six different cultivars/strains, as reported in a study by Dziadek *et al.* [2016]. The carbohydrates of buckwheat hulls are mostly

Table 1. Proximate composition of buckwheat hulls and sprouts.

Index	Hulls	Sprouts	Reference
Crude protein	on average 5.42 g/100 g	-	Dziadek *et al.* [2016]
	on average 4.7 g/100 g		Lu *et al.* [2013]
	4.05 g/100g		Zhang *et al.* [2023]
	4.83 g/100g		Matseychik *et al.* [2021]
		18.75 g/100 g fw	Sturza *et al.* [2020]
		24.3 g/100 g db	Kim *et al.* [2001]
		21.82 g/100 g dw	Lee & Kim [2008]
		20.8 g/100 g db	Kim *et al.* [2005]
		16.3 g/100 g dw	Peng *et al.* [2009]
		14.4 g/100 g dw	Molska *et al.* [2022b]
	on average 57.5 g/kg dm		Biel & Maciorowski [2013]
Crude fat	on average 0.59 g/100 g		Dziadek *et al.* [2016]
	trace		Matseychik *et al.* 2021
	0.4-0.9 g/100 g		Ahmed *et al.* [2014]
	0.13 g/100 g		Zhang *et al.* [2023]
		2.98 g/100 g dw	Lee & Kim [2008]
		25.26 mg/g	Zhang *et al.* [2015]
		1.3 g/100 g db	Kim *et al.* [2005]
		2.5 g/100 g dw	Peng *et al.* [2009]
		5.54 g/100 g fw	Sturza *et al.* [2020]
Total carbohydrates	on average 92.02 g/100 g		Dziadek *et al.* [2016]
	41.31 g/100 g		Matseychik *et al.* [2021]
		71.42 g/100 g dw	Lee & Kim [2008]
Ash	on average 1.97 g/100 g		Dziadek *et al.* [2016]
	on average 1.94 g/100 g		Lu *et al.* [2013]
	1.7 g/100 g		Zhang *et al.* [2023]
	1.49 g/100 g		Matseychik *et al.* [2021]
	on average 21 g/kg		Biel & Maciorowski [2013]
		2.53 g/100 g fw	Sturza *et al.* [2020]
	6.82 g/100 g		Matseychik *et al.* [2021]
		3.21 g/100 g db	Kim *et al.* [2001]
		3.78 g/100 g dw	Lee & Kim [2008]
		2.6 g/100 g db	Kim *et al.* [2005]
Starch	on average 1.20 g/100 g		Dziadek *et al.* [2016]
	2.55 g/100 g		Zhang *et al.* [2023]
		61.3 g/100 g dw	Peng *et al.* [2009]
Dietary fibre	on average 79.11 g/100 g		Dziadek *et al.* [2016]
	on average 80.6 g/100 g		Lu *et al.* [2013]
	31.31 g/100 g		Zhang *et al.* [2023]

Table 1 continued. Proximate composition of buckwheat hulls and sprouts.

Index	Hulls	Sprouts	Reference
	40.01 g/100 g		Matseychik *et al.* [2021]
	91.18 g/100 g		Dziedzic *et al.* [2012]
Crude fibre	average of 511.13 g/kg		Biel & Maciorowski [2013]
		4.67 g/100 g fw	Sturza *et al.* [2020]
		8.59 g/100 g db	Kim *et al.* [2001]
		16.11 g/100 g dw	Molska *et al.* [2022b]
		4.2 g/100 g dw	Peng *et al.* [2009]
Soluble dietary fibre		41.2–43.3 mg/g	Wu *et al.* [2023]

db, dry basis; dw, dry weight; fw, fresh weight.

in the form of insoluble non-starch polysaccharides (31.1 g/100 g), which contribute to their high fiber content [Zhang *et al.*, 2023]. The fiber content in buckwheat hulls is primarily insoluble and comprises significant amounts of xylose (15.78%), glucose (9.67%), and uronic acid (3.68%) relative to the total content in the hull [Zhang *et al.*, 2023]. This composition indicates a rich presence of hemicellulose-based fractions like xylan, xyloglucan, arabinoxylan, or galactoxyloglucan, alongside pectin-type polysaccharides, which are essential for digestive health [Matseychik *et al.*, 2021; Zhang *et al.*, 2023]. As well, the soluble fibre in the buckwheat hulls was also mainly composed of 0.06% xylose, 0.09% glucose, and 0.09% uronic acid [Zhang *et al.*, 2023].

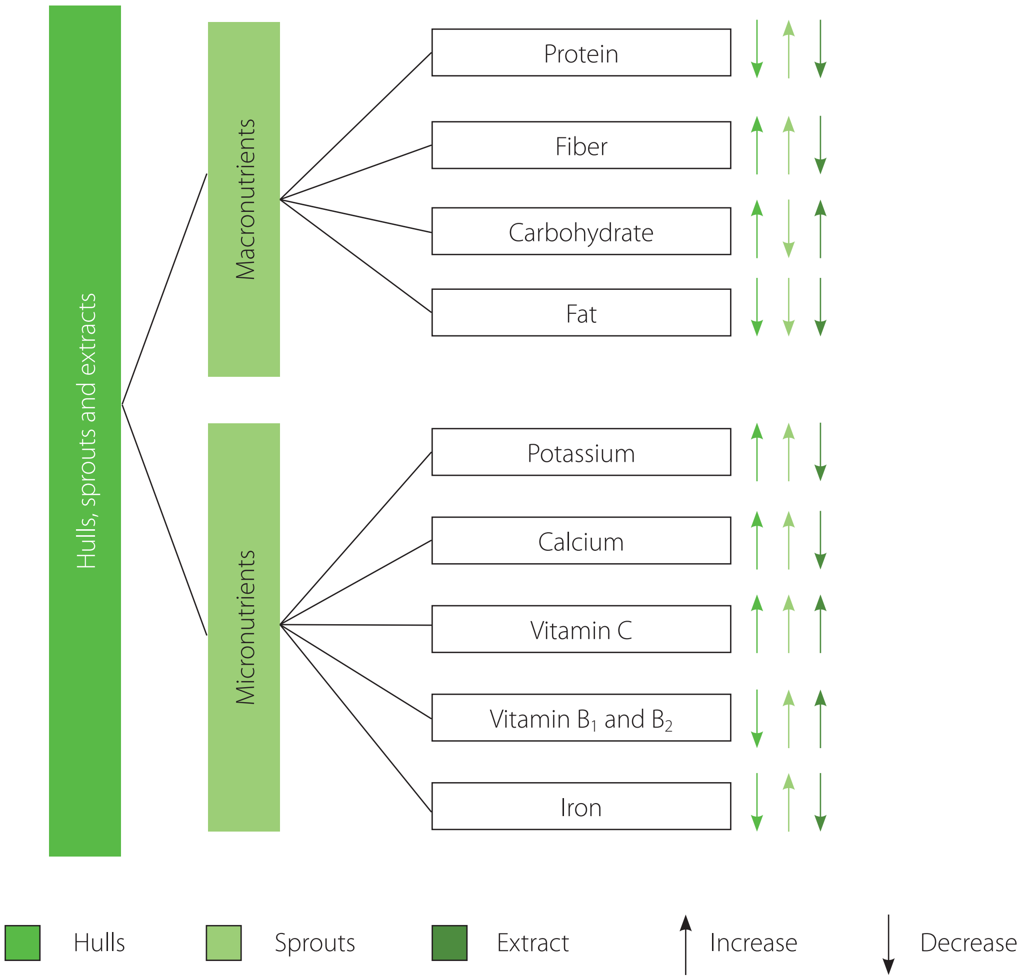

Figure 2. Nutritional compounds of buckwheat hulls, sprouts, and extracts.

Buckwheat sprouts

The buckwheat sprouts as a new vegetable were introduced for the first time by Kim *et al.* [2001, 2004] and since then, these sprouts have gained popularity in many countries, primarily consumed as they are, cherished for their soft yet slightly crispy texture and appealing fragrance. Buckwheat sprouts are noted for their elevated levels of protein, minerals, and crude fiber, exceeding those found in grains and hulls. Protein content varies under different sprouting conditions, as evidenced by various studies: Sturza *et al.* [2020] recorded 18.75 g/100 g fresh weight (fw), Kim *et al.* [2001] found 24.3 g/100 g dw (on the 8th day of germination), Lee & Kim [2008] determined 21.82 g/100 g dw (on the 7th day of germination), Kim *et al.* [2005] noted 20.8 g/100 g, and Peng *et al.* [2009] reported 16.3 g/100 g dw. Additionally, buckwheat sprouts modified with a probiotic yeast strain demonstrated a total protein content increase of approximately 22%, rising from 11.6 to 14.4 g/100 g [Molska *et al.*, 2022b]. This augmentation is largely attributable to an increase in glutelins, which, along with globulins, form the major protein fractions in buckwheat [Molska *et al.*, 2022b]. The protein found in these sprouts is of a notably high quality, featuring a comprehensive spectrum of essential amino acids such as valine, tyrosine, and lysine [Kim *et al.*, 2001, 2004; Woo *et al.*, 2013]. Also, modifications using yeast have led to an increase in methionine content, according to Molska *et al.* [2022b]. The protein content in sprouts can be higher than in unsprouted buckwheat seeds due to changes in seed chemistry that occur during germination and the breakdown by proteases of insoluble storage proteins into soluble peptides and then by hydrolases to generate amino acids, basic sugars, and unsaturated fatty acids, thereby enhancing the digestibility of nutrients in grains [Ali & Elozeiri, 2017; Guzmán-Ortiz *et al.*, 2019; Zhou *et al.*, 2016]. The different innovative technologies such as microwave, magnetic, electromagnetic, ultrasonic, and light (visible and ultraviolet) applied for seed germinating enhance the bioavailability of proteins and increase the levels of not only essential amino acids, such as glutamic acid and aspartic acid, but also accumulation of active compounds such as flavonoids [Wang *et al.*, 2019]. This makes buckwheat sprouts a highly nutritious option for inclusion in healthy foods, offering a rich source of plant-based protein that supports muscle growth, repair, and overall health. Their high protein content, coupled with other nutritional benefits, positions buckwheat sprouts as a superior ingredient in the development of functional and fortified food products [Kim *et al.*, 2001, 2004; Sturza *et al.*, 2020].

The fat content in buckwheat is relatively low, typically ranging from 1 to 3 g/100 g of dw [Ahmed *et al.*, 2014]. During the germination process, fats and carbohydrates are broken down to supply energy for seed growth, resulting in decreased levels of these macronutrients. According to a study by Zhang *et al.* [2015], the crude fat content in buckwheat was observed to decline from 30.68 mg/g in ungerminated seeds to 25.26 mg/g after germinating for 72 h. Despite the low quantity, the fat in buckwheat sprouts is rich in essential fatty acids, particularly linoleic acid, and α-linolenic acid, with unsaturated fatty acids comprising over 83% of the total lipid content, which are important for maintaining heart health and supporting immune function [Kim *et al.*, 2004; Molska *et al.*, 2020; Shahidi & Ambigaipalan, 2018; Zhou *et al.*, 2015].

Buckwheat sprouts offer a higher crude fiber content at 8.59 g/100 g (on the 8th day of germination), surpassing that of unsprouted seeds which contain 3.82 g/100 g, according to Kim *et al.* [2001]. Furthermore, Sturza *et al.* [2020] highlighted that sprouted buckwheat flour had the richest fiber composition at 4.67 g/100 g when compared to regular buckwheat at 4.08 g/100 g and wheat flour at only 1.14 g/100 g. The crude fiber in these products includes a variety of fibrous materials such as cellulose, lignin, and hemicellulose, and its composition can vary depending on the buckwheat cultivar [Witkowicz *et al.*, 2019]. Dietary fiber is categorized into two types: insoluble dietary fiber (IDF) and soluble dietary fiber (SDF). IDF mainly includes cellulose, hemicellulose, and lignin, substances that do not dissolve in water. Conversely, SDF consists of water-soluble components like pectin and gums [Guan *et al.*, 2021]. Molska *et al.* [2022a] found that probiotic-rich buckwheat sprouts had the highest content of total dietary fiber (16.11 g/100 g), while the lowest content was found in seeds (11.37 g/100 g) and the dominant dietary fiber fraction in probiotic-rich sprouts was soluble dietary fiber. Kim *et al.* [2009a] found that the thermomechanical extrusion process altered the balance between soluble and insoluble dietary fibers, favoring an increase in SDF. Consequently, SDF content in sprouts rose from 9.0 g/100 g to 12.4 g/100 g, while IDF content decreased from 15.3 g/100 g to 10.5 g/100 g. SDF yields from common and tartary buckwheat sprouts were comparably measured at 43.3 mg/g and 41.2 mg/g, respectively, indicating that germination enhances the SDF content in buckwheat seeds [Wu *et al.*, 2023]. The high fiber content helps in promoting satiety, reducing cholesterol levels, and supporting overall gut health, making buckwheat sprouts an ideal ingredient for functional foods aimed at improving digestive wellness [Kim *et al.*, 2004].

Buckwheat extracts

Buckwheat extracts, typically obtained from the seeds, sprouts, or hulls of buckwheat, are concentrated sources of bioactive compounds, therefore they are relatively low in macronutrients such as crude protein and crude fat (**Figure 2**). Unlike many common plant protein sources where globulin is the most abundant protein (60–80%), albumin (20.99%), globulin (12.80%), and glutelin (13.31%) are the predominant fractions in buckwheat protein [Hua *et al.*, 2024]. The proteins tend to aggregate and precipitate out of solution, making their extraction less efficient [Yang *et al.*, 2021]. This aggregation and precipitation of the large protein molecules is the primary reason for the low protein content observed in buckwheat extracts.

As mentioned in the previous section, buckwheat seeds and sprouts, particularly those of the species such as *Fagopyrum esculentum* and *Fagopyrum tataricum*, are recognized for their low crude fat content. Therefore, the fat present in buckwheat grain, hull and seed extracts is in trace amounts unless specifically targeted for extraction.

Lack of proteins and lipids in extracts makes them ideal for use in supplements and functional foods where high-intensity natural bioactives are desired without additional calories from macronutrients. The main bulk substances of buckwheat extracts are carbohydrates, primarily in the form of starch and various soluble carbohydrates like fagopyritols [Ahmed *et al*., 2014; Zhang *et al*., 2023; Zieliński *et al*., 2019]. Fagopyritols, which are galactosyl derivatives of D-chiro-inositol, play a crucial role in the maturation of buckwheat seeds [Zieliński *et al*., 2019]. The carbohydrate content in buckwheat extracts can vary depending on the extraction and processing methods used.

■ Micronutrients (mineral and vitamin composition)

Buckwheat hulls and sprouts each offer distinct profiles of minerals and vitamins [Dziadek *et al*., 2016; Witkowicz & Biel, 2022]. The content of individual minerals in both hulls and sprouts, as well as extracts can vary depending on the plant cultivar, grain processing, and extraction methods (**Table 2**). While buckwheat extracts are rich in bioactive compounds and they do not serve as significant sources of traditional nutrients such as vitamins and minerals.

■ Buckwheat hulls

Buckwheat hulls contain trace amounts of magnesium, calcium, and phosphorus [Dziadek *et al*., 2016; Ikeda *et al*., 1999; Kim *et al*., 2005; Matseychik *et al*., 2021; Sytar *et al*., 2016; Witkowicz & Biel, 2022]. Although the contents of these minerals in the hulls are relatively low, they still contribute to the overall mineral intake when included in the diet. Studies have shown that the hulls are particularly high in calcium, making them beneficial for bone health [Ikeda *et al*., 1999]. In addition, they contain minerals such as iron, zinc, and manganese, which are crucial for various metabolic processes and maintaining overall health [Yilmaz *et al*., 2020]. The presence of these minerals has led buckwheat hulls to be considered as a valuable ingredient for developing fortified foods such as noodles, yogurt, or tea [Ikeda *et al*., 1999; Liu *et al*., 2022; Zielińska *et al*., 2013; Znamirowska *et al*., 2020]. Buckwheat hulls, while primarily valued for their high fiber content, also contain important vitamins, albeit in smaller quantities compared to other parts of the buckwheat plant. Thus, Kuznetsova *et al*. [2020] documented the mineral and vitamin content in buckwheat hull across various cultivars, revealing a range of contents. Iron was determined between 38.32 and 77.85 mg/kg, zinc from 10.36 to 18.54 mg/kg, copper from 1.18 to 4.66 mg/kg, and manganese from 2.95 to 4.96 mg/kg. The hulls also contained significant levels of vitamins, with vitamin B_1 (thiamine) at 4.6 mg/g, B_3 (niacin and niacinamide) at 17.6 mg/g, B_5 (pantothenic acid) at 10.2 mg/g, and vitamin C (ascorbic acid) at 42.5 mg/g. The presence of these vitamins contributes to the overall nutritional profile of buckwheat hulls, supporting metabolic processes and antioxidant defences. Nandan *et al*. [2024] found that the mineral distribution in buckwheat hull was 3.40–4.20 g/100 g.

■ Buckwheat sprouts

Buckwheat sprouts are highly nutritious, with a mineral profile that surpasses that of the grains [Ikeda *et al*., 1999; Pongrac *et al*., 2016]. The sprouts are particularly rich in magnesium, phosphorus, potassium, calcium, and molybdenum [Kim *et al*., 2001, 2005; Witkowicz & Biel, 2022]. Kim *et al*. [2005] reported that buckwheat sprouts contained significant levels of calcium at 152.0 mg/100 g, zinc at 9.9 mg/100 g, magnesium at 485.0 mg/100 g, and iron at 5.4 mg/100 g on a dry basis. Also, the vitamin content was determined, revealing vitamin A at 1,180 IU/100 g, vitamin C at 203 mg/100 g, and vitamin E at 32.1 mg/100 g on a dry basis. Mentioned minerals play crucial roles in numerous physiological processes, such as muscle and nerve activity, maintaining bone health, and generating energy. Sprouts evolve from grains through imbibition, germination, and various seedling development stages. During this process, they lose dry matter (primarily nonfibrous carbohydrates) due to respiration, while water content and mineral uptake from newly developed roots increase. These changes enhance the content of minerals in sprouts, leading to higher mineral contents in both tartary and common buckwheat sprouts compared to their grain forms [Pongrac *et al*., 2016]. Lee *et al*. [2006] reported higher contents of magnesium, phosphorus, potassium, and iron, but lower contents of calcium and zinc in tartary buckwheat sprouts. The contents of these minerals make buckwheat sprouts a nutrient-dense food. Buckwheat sprouts are also rich in vitamins. They are particularly high in vitamin C, with levels increasing significantly during the germination process, reaching up to 171.5 mg/100 g at the end of sprouting [Kim *et al*., 2004]. Furthermore, buckwheat sprouts have abundant vitamins B_1 and B_6 [Kim *et al*., 2004]. The high vitamin content, especially of vitamin C, makes buckwheat sprouts an excellent choice for boosting the nutritional value of various food products such as sprouts as a functional food [Kim *et al*., 2001, 2007b], spices [Serikbaeva *et al*., 2021], or bread [Xu *et al*., 2014].

ANTIOXIDATIVE AND ANTIMICROBIAL CAPACITIES OF BUCKWHEAT HULLS, SPROUTS, AND EXTRACTS

Buckwheat contains various bioactive compounds, such as flavonoids (vitexin, isovitexin, isoorientin, orientin, rutin, isoquercetin, and quercetin), phenolic acids (ferulic, vanillic, protocatechuic, and gallic acids), and carotenoids [Cui *et al*., 2020; Lim *et al*., 2012; Park *et al*., 2019]. These compounds contribute to numerous health benefits through their antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and cardiovascular support properties, as well as promote gastrointestinal health, bone health, and antiaging effects (**Figure 3**). Among the bioactivities caused by phenolic compounds, the antioxidant and antimicrobial potential of buckwheat sprouts and hulls, as well as extracts from these parts of the plant and from grains, is often highlighted in terms of the use of various forms of buckwheat as a valuable ingredient in the development of functional foods.

■ Antioxidant potential of buckwheat hulls, sprouts, and extracts

■ Buckwheat hulls

Buckwheat hulls are recognized for their potent antioxidant effects, attributed to abundance of phenolic compounds such as quercetin, rutin, and protocatechuic acid. According to Dziadek *et*

Table 2. Mineral content of buckwheat hulls and sprouts.

Mineral	Hulls	Sprouts	Reference
Calcium	-	1,118 mg/100g db	Kim *et al.* [2001]
	-	3.9 g/kg dm	Witkowicz & Biel [2022]
	-	152.0 mg/100 g	Kim *et al.* [2005]
	-	8,410 mg/kg dw	Pongrac *et al.* [2016]
	260.0 mg/100 g	-	Matseychik *et al.* [2021]
	97.4 mg/100 g dw	-	Ikeda *et al.* [1999]
Magnesium	-	804.0 mg/100 g	Kim *et al.* [2001]
	-	5.5 g/kg dm	Witkowicz & Biel [2022]
	-	5,470 mg/kg dw	Pongrac *et al.* [2016]
	-	485.0 mg/100 g	Kim *et al.* [2005]
	112 mg/100 g dw	-	Ikeda *et al.* [1999]
Phosphorous	-	12.1 g/kg dm	Witkowicz & Biel [2022]
	-	7,930 mg/kg dw	Pongrac *et al.* [2016]
	127 mg/100 g dw		Ikeda *et al.* [1999]
Potassium	-	1,798 mg/100 g db	Kim *et al.* [2001]
	-	11.7 g/kg dm	Witkowicz & Biel [2022]
	-	7,290 mg/kg dw	Pongrac *et al.* [2016]
	840.0 mg/100 g	-	Matseychik *et al.* [2021]
	1,267 mg/kg dw	-	Ikeda *et al.* [1999]
Sodium	-	134.9 mg/100 g db	Kim *et al.* [2001]
	-	0.7 g/kg dm	Witkowicz & Biel [2022]
	1,000.0 mg/100 g	-	Matseychik *et al.* [2021]
Zinc	-	10.5 mg/100 g db	Kim *et al.* [2001]
	-	9.9 mg/100 g	Kim *et al.* [2005]
	-	130 mg/kg dw	Pongrac *et al.* [2016]
	-	48.5 mg/kg dm	Witkowicz & Biel [2022]
	varied from 10.36 to 18.54 mg/kg	-	Kuznetsova *et al.* [2020]
	1.24 mg/kg dw	-	Ikeda *et al.* [1999]
Copper	-	5.8 mg/100 g db	Kim *et al.* [2001]
	-	9.0 mg/kg dm	Witkowicz & Biel [2022]
		10.8 mg/kg dw	Pongrac *et al.* [2016]
	varied from 1.18 to 4.66 mg/kg	-	Kuznetsova *et al.* [2020]
	0.63 mg/kg dw	-	Ikeda *et al.* [1999]
Manganese	-	2.7 mg/100 g db	Kim *et al.* [2001]
	-	22.4 mg/kg dm	Witkowicz & Biel [2022]
	-	21.1 mg/kg dw	Pongrac *et al.* [2016]
	varied from 2.95 to 4.96 mg/kg	-	Kuznetsova *et al.* [2020]
	9.16 mg/kg dw	-	Ikeda *et al.* [1999]

Table 2 continued. Mineral content of buckwheat hulls and sprouts.

Mineral	Hulls	Sprouts	Reference
Iron	-	20.6 mg/100 g db	Kim *et al.* [2001]
	-	50.3 mg/kg dm	Witkowicz & Biel [2022]
	-	5.4 mg/100 g	Kim *et al.* [2005]
	-	70.7 mg/kg dw	Pongrac *et al.* [2016]
	48.0 mg/100g	-	Matseychik *et al.* [2021]
	varied from 38.32 to 77.85 mg/kg	-	Kuznetsova *et al.* [2020]
Molybdenum	-	45.7 mg/kg dm	Witkowicz & Biel [2022]
	-	1.89 mg/kg dw	Pongrac *et al.* [2016]

dm, dry matter; db, dry basis; dw, dry weight.

al. [2016], the total phenolic content in these hulls varies between 434.06 and 525 mg/100 g, dependent on the cultivar or strain. Zhang *et al.* [2023] identified protocatechuic acid (390.71 mg/kg) as the most prevalent metabolite in buckwheat hulls, present in both free (184.81 mg/kg) and bound (205.91 mg/kg) forms. Further, an analysis by Zhang *et al.* [2017] identified seven distinct flavonoids in buckwheat hulls — orientin, isoorientin, vitexin, isovitexin, hyperin, rutin, and quercetin. The levels of vitexin/isovitexin, hyperin, and rutin in buckwheat hulls showed considerable variation across the eight cultivars tested [Zhang *et al.*, 2017]. The content of vitexin and isovitexin ranged from 101.65 to 188.78 mg/100 g, hyperin content varied from 53.55 to 274.10 mg/100 g, while rutin content ranged from 62.43 to 173.57 mg/100 g [Zhang *et al.*, 2017]. According to results given by Cui *et al.* [2020], rutin, isoorientin, vitexin, and hyperoside showed varied efficacy in scavenging different free radicals ($^{\bullet}$OH, $O_2^{\bullet-}$, DPPH$^{\bullet}$) and only rutin showed excellent total antioxidant capacity (T-AOC). Rutin was particularly notable as a predominant flavonoid in buckwheat hulls, a finding supported by several studies [Cui *et al.*, 2020; Park *et al.*, 2019; Sedej *et al.*, 2012; Zhang *et al.*, 2017]. These bioactive compounds through their antioxidant activity offered numerous health advantages such as lowering cholesterol levels [Lin *et al.*, 2008], reducing blood pressure, diminishing inflammatory responses [Al-Khayri *et al.*, 2022; Qing *et al.*, 2023; Tsai *et al.*, 2012], and aiding in the management of diabetes and obesity [Cai *et al.*, 2023; Zhao *et al.*, 2018]. Phenolic antioxidants found in buckwheat hulls have been shown to decrease the formation of reactive oxygen species (ROS) and malondialdehyde (MDA) or increase catalase (CAT) activity on cellular-based assays [Cui *et al.*, 2020]. Although the existing evidence is promising, further investigations are required to clarify the full scope of buckwheat hull effects.

Buckwheat sprouts

Buckwheat sprouts are particularly rich in antioxidants, including rutin, quercetin, and various phenolic acids such as chlorogenic, caffeic, ferulic, and gallic acids [Ji *et al.*, 2016; Mansur *et al.*, 2022; Molska *et al.*, 2022a]. The total phenolic content of buckwheat sprouts is higher than that of seeds [Aloo *et al.*, 2021; Molska *et al.*, 2022a]. Three phenolic acids (caffeoyl-glucoside,

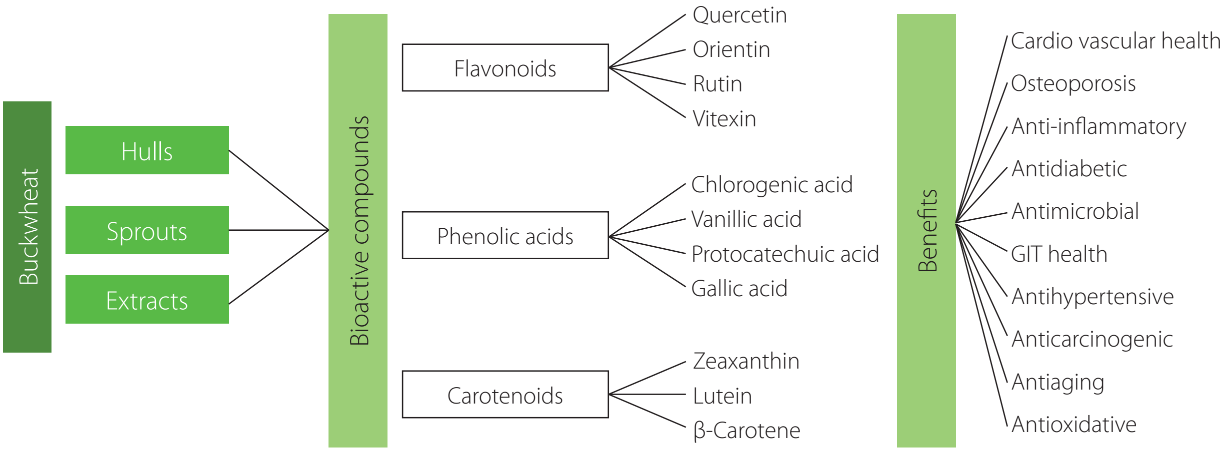

Figure 3. Bioactive compounds of buckwheat hulls, sprouts, and extracts and their potential health benefits.

caffeoyl-rhamnopyranosyl-glucopyranosyl-glucopyranoside, and caffeoyl-rhamnopyranosyl-glucopyranosyl) were identified in the sprouts [Molska *et al*., 2022a]. Caffeoyl-rhamnopyranosyl-glucopyranosyl was the dominant phenolic acid; its content in control sprouts was 92.04 µg/g dw and in probiotic-rich sprouts it was 118.23 µg/g dw. The caffeoyl content was 53.23 µg/g dw in control sprouts, and 55.48 µg/g dw in probiotic-rich sprouts. It is also important to note that the specific contributions of flavonoid content, specifically rutin, orientin, and epicatechin uniquely contribute to the overall antioxidant activity, illustrating a complex relationship between specific flavonoid levels and the antioxidant capacity in both common and tartary buckwheat sprouts [Rauf *et al*., 2019; Wiczkowski *et al*. 2014; Zych-Wężyk & Krzepiłko, 2012]. Significant increases in specific flavonoids have been documented during the sprouting process; for example, Borgonovi *et al*. [2023] observed that rutin content soared from 9.91 µg/g dw in buckwheat grain to 23.01 µg/g dw in grains sprouting for 72 days. Similarly, quercetin content increased from 3.39 µg/g dw in the unsprouting grain to 28.12 µg/g dw in grains sprouting over the same period. As the germination continued, the levels of rutin and quercetin progressively increased, enhancing the sprouts' capacity to reduce oxidation and scavenge free radicals [Borgonovi *et al*., 2023].

During sprouting, the phenolic content in buckwheat increases, leading to enhanced antioxidant capacity. The ferric reducing antioxidant power (FRAP) of grains was shown to increase significantly from 9.91 µmol Trolox eq/g dw in unsprouting grains to 17.98 µmol Trolox eq/g dw in the grains germinating for 72 h [Borgonovi *et al*., 2023]. Meanwhile, the total antioxidant capacity (TAC) showed a notable increase only after 72 h of sprouting, from 26.21 to 46.99 µmol Trolox eq/g dw. Also, the antioxidant potential measured by ABTS assay was at 12.63 mg Trolox eq/g (control sprouts) and 19.78 mg Trolox eq/g (probiotic-rich sprouts) before digestion (*in vitro*), and at 9.13 mg Trolox eq/g (control sprouts) and 11.05 mg Trolox eq/g (probiotic-rich sprouts) after digestion, with genetically-modified sprouts showing the highest activity [Molska *et al*., 2022a]. In terms of reduction power, the modified sprouts exhibited the highest value at 31.15 mg Trolox eq/g, significantly surpassing that of the seeds [Molska *et al*., 2022a]. Liu *et al*. [2008] analyzed the reducing power of ethanol extracts from both common and tartary buckwheat sprouts and found that the reducing power, measured in absorbance at 700 nm, was greater in the tartary buckwheat sprouts extracts, with a peak value of approximately 0.35, compared to common buckwheat sprouts, which showed a maximum of about 0.25. This suggests a superior antioxidant capability of the tartary buckwheat sprout extract at the concentration of 5 mg/mL.

In the investigation conducted by Aloo *et al*. [2021], the focus was on evaluating the impact of sprouting on alfalfa and buckwheat seeds in terms of their antioxidant, antidiabetic, and antiobesity capabilities, as well as alterations in their metabolite compositions. The findings demonstrated that buckwheat sprouts outperformed the rest, showcasing the strongest ability to scavenge DPPH$^{\bullet}$ and ABTS$^{\bullet +}$, followed in effectiveness by alfalfa sprouts, buckwheat seeds, and finally alfalfa seeds.

Utilizing advanced analytical techniques, such as liquid chromatography/electrospray ionization tandem mass spectrometry (LC/ESI-MS/MS), the investigation into anthocyanin profiles spanned various varieties and breeding lines of common and tartary buckwheat sprouts [Kim *et al*., 2007b]. This research uncovered the presence of four distinct anthocyanins in common buckwheat sprouts and two in tartary buckwheat sprouts. Notably, the Hokkai T10 variety emerged with the highest anthocyanin content, positioning it as an exceptional candidate for "Moyashi" type sprouts. Anthocyanins are known for their antioxidant activity; therefore, it seems that this group of phenolic compounds may also contribute to the antioxidant potential of buckwheat sprouts.

Buckwheat extracts

Sun & Ho [2005] found that extracts from buckwheat whole grains, using solvents such as acetone, butanol, ethanol, ethyl acetate, and methanol, exhibited significant antioxidant effects. Notably, the methanolic extract was the most effective, showing a high antioxidant activity coefficient of 627 at 200 mg/L, measured *via* the carotene-bleaching method. In contrast, acetone extracts had the highest total phenolic content at 3.4 g catechin eq/100 g and displayed the strongest scavenging activity, at 78.6%, at a concentration of 0.1 mg/mL, according to the 1,1-diphenyl-2-picryl hydrazyl (DPPH) assay. Li *et al*. [2013] demonstrated that extracts from buckwheat hulls had a higher total phenolic content (TPC) and antioxidant capacity than those derived from buckwheat flour. Common buckwheat (*F. esculentum* Möench) hull extract exhibited the highest reducing power and DPPH radical scavenging activity with the average EC_{50} 84.54 µg/mL and IC_{50} 11.54 µg/mL, respectively compared to flour extract which showed the lowest TPC, reducing power and DPPH radical scavenging activity. Further research by Hęś *et al*. [2012] revealed that extracts from buckwheat hulls, especially those obtained using methanol as a solvent, had significantly high DPPH radical scavenging activity, with methanol extracts displaying double the activity of acetone extract and eight times the activity of water extract. These findings suggest that methanol is an effective solvent for extracting antioxidants from buckwheat and that these extracts show great potential as food additives to replace artificial antioxidants. This is also confirmed by the fact that buckwheat hull extracts were able to significantly reduce the total oxidation rate of bulk oil and oil-in-water and water-in-oil emulsions [Lee *et al*., 2022], *i.e.*, model systems corresponding to food products. The authors concluded that flavonoid glycosides and methylated phenolics were mainly responsible for the reduction in the emulsion oxidation rate.

Antimicrobial properties of buckwheat hulls, sprouts, and extracts

The rising prevalence of bacterial resistance to current antibiotics has become a serious concern, necessitating the search for novel classes of antibacterial agents, particularly from natural sources. Buckwheat hulls, sprouts, and extracts are known not just for their nutritional and antioxidant properties but also for

Table 3. Antimicrobial activity of buckwheat hull and sprout extracts.

Extracted material	Extract concentration	Diameter of inhibition zone (mm)							Reference
		Gram-positive				Gram-negative			
		Staphylococcus aureus	*Bacillus subtilis*	*Bacillus cereus*	*Enterococcus faecalis*	*Salmonella choleraesuis*	*Proteus mirabilis*	*Escherichia coli*	
Hull	100 mg/mL	12.6	-	13.9	13.6	11.3	11.0	10.6	Čabarkapa *et al.* [2008]
	50 mg/mL	11.6	-	13.3	13.3	10.0	10.33	9.6	
	500 µg	9	-	-	-	-	-	-	Cho *et al.* [2006]
Sprouted grain	Not mentioned	3.7	3.6	-	-	-	-	1.5	Zhou *et al.* [2011a]

their antimicrobial capabilities, attributed to their high content of flavonoids like rutin and quercetin, making them valuable in potential therapeutic applications. The crude methanol extract from tartary buckwheat sprouts showed significant inhibitory activity against various bacteria, impacting both Gram-negative strains (*Pseudomonas lachrymans* and *Salmonella typhimurium*) and Gram-positive strains (*Bacillus subtilis*, *Scaphirhynchus albus*, and *Staphylococcus aureus*), with minimum inhibitory concentration (MIC) values varying between 0.8 mg/mL and 3.2 mg/mL [Zhong *et al.*, 2022]. Among the six primary flavonoids analyzed for their antibacterial properties — including isoorientin, vitexin, isovitexin, rutin, quercetin, and kaempferol — quercetin emerged as the most effective, demonstrating robust antibacterial activity against all the tested bacteria except for *E. coli* and *S. epidermidis* [Zhong *et al.*, 2022]. Moreover, buckwheat hull extracts have shown effective antimicrobial activity against a range of pathogens (**Table 3**). Cho *et al.* [2006] identified three antimicrobial compounds in methanol extracts of buckwheat (*F. esculentum*) hulls using mass spectrometry (MS) and nuclear magnetic resonance (NMR) spectroscopic techniques. Their structures were elucidated as 6,7-dihydroxy-3,7-dimethyl-octa-2(*Z*),4(*E*)-dienoic acid, 6,7-dihydroxy-3,7-dimethyl-octa-2(*E*),4(*E*)-dienoic acid, and 4,7-dihydroxy-3,7-dimethyl-octa-2(*E*),5(*E*)-dienoic acid. At a concentration of 500 µg, these compounds exhibited antimicrobial activity against *S. aureus* as assayed by the paper disc method. Research detailed in a study by Čabarkapa *et al.* [2008] demonstrated that buckwheat hull extracts exhibited notable antimicrobial activity against both Gram-positive and Gram-negative bacteria, more so at higher concentrations when determined by the disk diffusion method. At 100 mg/mL, the extracts showed significant inhibition against Gram-positive bacteria like *S. aureus*, *Bacillus cereus*, and *Enterococcus faecalis*, in contrast to weaker effects against Gram-negative bacteria such as *Salmonella choleraesuis*, *Proteus mirabilis*, and *Escherichia coli*. Also, ethanolic extracts from buckwheat hulls have been found to inhibit the growth of *Aspergillus flavus* and reduce aflatoxin production [Nobili *et al.*, 2019]. Currently, there are insufficient studies on the use of controlled delivery systems in real food applications, particularly lacking comparisons with direct additions of similar quantities of antimicrobial plant phenolics or extracts. Such comparisons are crucial to determine the value added by controlled delivery systems, considering the extra costs associated with their formulation and development. This gap in research highlights the need for more comprehensive studies to assess the effectiveness and cost-efficiency of these innovative delivery methods in food technology.

HEALTH-RELATED PROPERTIES OF BUCKWHEAT HULLS, SPROUTS, AND EXTRACTS

The consumption of buckwheat and its sprouts, moreover different food products with buckwheat hull and extracts, can provide health benefits. The antioxidant (discussed above) [Borgonovi *et al.*, 2023; Cui *et al.*, 2020; Mazahir *et al.*, 2022], anti-cancer [Kim *et al.*, 2007a], anti-inflammatory and anti-hypertensive [Karki *et al.*, 2013; Koyama *et al.*, 2013] properties of buckwheat sprouts, hulls and their extracts were reported. Researches have also highlighted the anti-obesity and anti-diabetic effects of buckwheat grain and bran extracts and sprouts [Aloo *et al.*, 2021; Hosaka *et al.*, 2014; Lee *et al.*, 2017]. Including buckwheat hulls, sprouts, and extracts in diets offers extensive health advantages, which are summarized in **Table 4**.

Kim *et al.* [2007a] extracted buckwheat hull with 70% ethanol, then fractionated it stepwise. Hexane and ethyl acetate fractions showed significant inhibition against human carcinoma cells including human breast adenocarcinoma (MCF-7), human hepatocellular carcinoma (Hep3B), and human lung adenocarcinoma (A549). All samples, except the aqueous fraction, demonstrated anticancer effects, with inhibition rates above 20% in sarcoma-180 implanted mice, suggesting potent anticancer properties. Similarly, tartary buckwheat sprout extract rich in flavonoids showed strong inhibitory activity for the growth of MCF-7 and human gastric cancer cell line (MGC80-3) using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay [Zhou *et al.*, 2011a, b; 2019]. Flow cytometry confirmed apoptosis and cell cycle arrest. Also, the extracts inhibited angiogenesis in a chick chorioallantoic membrane (CAM) assay, suggesting their potential for antitumor therapy or functional food additives. Moreover, buckwheat hulls have shown promising anticancer properties post-digestion in simulated gastrointestinal conditions, significantly reducing the growth of human colon adenocarcinoma cells (HT-29) [Dziedzic *et al.*, 2018].

Table 4. Health benefits of buckwheat hulls, sprouts, and extracts.

Type of diseases	Buckwheat added way	Model of study	Effect of study	Reference
Obesity and diabetes	Tartary buckwheat sprouts	Rats fed a diet with tartary buckwheat sprout powder	• Lower plasma cholesterol levels • Increased fecal bile acid excretion	Kuwabara *et al.* [2007]
	Buckwheat sprouts	Hamsters	Reduced liver/body weight ratios, serum triglycerides, LDL cholesterol	Lin *et al.* [2008]
	Buckwheat hull extracts rich in flavonoids	Type 2 diabetic rats	• Alleviated insulin resistance • Lowered blood glucose levels and enhanced oxidative stress responses	Wang *et al.* [2021]
Atherosclerosis	Buckwheat sprouts diet	32 Wistar rats	A statistically significant decrease of fat digestibility in the groups fed a high-fat diet	Molska *et al.* [2023]
Alcohol abuse	Rutin-enriched tartary buckwheat flour extracts	Single oral dose in rats	Helped protect the liver from damage caused by repeated ethanol exposure	Jin *et al.* [2020]
Cancer	Buckwheat hull extract	Study *in vitro*, SRB assay	• Hexane and ethyl acetate fractions showed higher inhibition effects against MCF-7 cells and Hep3B cells • The ethyl acetate fraction yielded the highest inhibition rate against A549 cells • Decreases tumor formation in sarcoma-180 implanted mice	Kim *et al.* [2007a]
	Sprout extract rich in flavonoids	Study *in vivo*, CAM assay	Significant inhibitory activity on the growth of MCF-7 cancer cells	Zhou *et al.* [2011b]
	Sprout extract rich in flavonoids	Study *in vitro*	Showed anti-tumor activity against MGC80-3	Zhou *et al.* [2019]
Hypertension, dyslipidemia, hyperglycemia	Germinated buckwheat extracts	Rats	• Lowered systolic blood pressure • Reduced oxidative damage in aortic endothelial cells	Kim *et al.* [2009b]

CAM, Chick chorioallantoic membrane assay; MGC80-3, human gastric cancer cell line; MCF-7, human breast adenocarcinoma; Hep3B, human hepatocellular carcinoma; A549, human lung adenocarcinoma; LDL, low-density lipoprotein; SRB, sulforhodamine B.

Rutin-enriched extracts from tartary buckwheat flour were produced using hydrothermal treatment and their pharmacokinetic characteristics were assessed after a single oral dose in rats [Jin *et al*., 2020]. The findings indicated that these rutin-enriched extracts were absorbed more effectively and remained in the bloodstream longer compared to native tartary buckwheat flour extract or standard rutin formulations. Moreover, their antioxidant properties helped protect the liver from damage caused by repeated ethanol exposure. A study quantifying rutin in raw buckwheat extracts and germinated buckwheat extracts (RBE and GBE) through high-performance liquid chromatography (HPLC) assessed their impacts on body weight, systolic blood pressure (SBP), and nitrotyrosine levels in hypertensive and normotensive rats [Kim *et al*., 2009b]. It was found that GBE, which contained higher levels of rutin, lowered SBP more effectively than RBE. Additionally, both extracts demonstrated a reduction in oxidative damage within aortic endothelial cells, underscoring GBE's potential for antihypertensive effects and vascular protection.

An investigation into the effects of different buckwheat sprouts on cholesterol metabolism in rats revealed that diets enriched with tartary buckwheat sprout powder significantly reduced plasma cholesterol levels and increased fecal bile acid excretion compared to control groups [Kuwabara *et al*., 2007]. These findings suggest that tartary buckwheat sprouts may enhance cholesterol metabolism by promoting the upregulation of hepatic mRNA expression and boosting the excretion of fecal matter.

In another work, Lin *et al*. [2008] discovered that contents of total phenolics, quercetin, and L-ascorbic acid in buckwheat sprouts peaked on day 8, while on day 10, the highest levels of oxalic, malic, tartaric, citric acids, rutin, and γ-aminobutyric acid was found. Ethanolic extract of sprouts after 8 days of germination exhibited potent antioxidant properties and moderate Fe^{2+}-chelating ability. Supplementing Syrian hamsters' diets with these sprouts significantly enhanced their health markers, reducing liver/body weight ratios, serum triglycerides, LDL cholesterol, and improving feed efficiency, thus underscoring their nutritional value.

A study by Molska *et al*. [2023] was conducted to evaluate the effects of incorporating buckwheat sprouts (*F. esculentum* Moench), modified by the probiotic yeast strain *Saccharomyces cerevisiae* var. *boulardii*, into a high-fat (atherogenic) diet on rat morphology and digestibility parameters. The findings indicated a statistically significant reduction in fat digestibility among the groups consuming the diet supplemented with these sprouts, highlighting a novel application for buckwheat sprouts in dietary interventions.

Flavonoids extracted from common buckwheat hulls significantly alleviate insulin resistance, thus lowering blood glucose levels and enhancing oxidative stress responses in type 2 diabetic rats [Wang *et al*., 2021]. Notably, treatment with these buckwheat hull flavonoids also improved symptoms of diabetes-related liver damage. This improvement was evident through the reduction of liver fat and decreased levels of serum alanine aminotransferase (ALT) and aspartate aminotransferase (AST), which are markers of liver health. These findings highlight the potent antioxidant and hepatoprotective capabilities of buckwheat hull flavonoids, suggesting their potential as valuable nutraceuticals and dietary supplements for preventing and/or treating liver disorders.

EFFECT OF BUCKWHEAT HULLS, SPROUTS, AND EXTRACTS ADDITION ON THE NUTRITIONAL, TEXTURAL, AND SENSORY PROPERTIES OF FOOD PRODUCTS

Research has delved into the utilization of buckwheat hulls, sprouts, and their respective extracts as potential functional ingredients in food production [Wronkowska *et al*., 2023; Yang *et al*., 2019; Zhang *et al*., 2023; Znamirowska *et al*., 2020]. Such studies have methodically explored the impact these additions have on the nutritional value, textural characteristics, and organoleptic qualities of food products (**Table 5**).

■ Meat products

In response to growing health concerns associated with meat consumption, there is an increasing interest in enhancing the nutritional profile of meat products. This is being addressed by incorporating various nutritious ingredients into meat products. Such enhancements aim to improve the overall health benefits of meat consumption, making these products more attractive to health-conscious consumers. This approach not only diversifies the nutritional content, potentially reducing the risks linked to high-meat diets but also aligns with consumer trends favoring functional foods that support a healthier lifestyle [Geiker *et al*., 2021]. Adding dietary fiber sources, such as buckwheat and its derivatives, offers a promising approach. Various studies have aimed to examine the effects of adding buckwheat sprouts, hulls, and extracts, to meat products including pork, beef, horsemeat, and poultry products to improve their nutritional value, texture parameters, and taste (**Table 5**).

A study by Salejda *et al*. [2022] showed that adding 3% hulls to frankfurter sausages increased cooking losses, enhanced firmness, enriched the amino acid profile, increased total amino acid content (from 161.8 to 228.0 mg/kg), and elevated essential mineral levels, proving buckwheat hull efficacy as a sustainable, nutritional meat additive. Buckwheat extracts, derived from grains or sprouts, as concentrated sources of phenolic compounds added to pork products have been shown to effectively inhibit lipid oxidation and microbial growth [Hęś *et al*., 2017; Pietrzak *et al*., 2022]. For example, aqueous and ethanolic extracts of buckwheat hulls reduced the formation of thiobarbituric acid reactive substances (TBARS) and extended the induction time of lipid oxidation of chicken meatballs during 14 days of refrigerated storage, while improving their microbiological stability [Pietrzak *et al*., 2022]. These extracts also helped in maintaining the sensory qualities of the chicken meatballs. A study by Hęś *et al*. [2017] has shown that frozen pork meatballs enriched with buckwheat hull extract (additive at the level 0.5%) demonstrated lower peroxide content and TBARS values after 180 days of storage compared to those treated with a synthetic antioxidant like butylated hydroxytoluene, BHT (additive at the level 0.02%). These studies highlight the potential of buckwheat hull extracts in extending meat products' shelf life and preserving their quality by mitigating lipid oxidation.

In our latest research [Atambayeva *et al*., 2023], we explored the benefits of incorporating ground green buckwheat (untreated buckwheat) sprouts into horsemeat and chicken patties, aiming to improve their quality, extend their shelf life, and boost their safety profile. Adding ground green buckwheat sprout to the patties significantly improved nutritional values, including protein and lipid content, cooking performance, and moisture and lipid preservation, alongside enhancing antioxidant properties, as seen in increased total phenolic content and DPPH radical scavenging activity. Notably, ground green buckwheat sprout application slightly altered color parameters (L^*, a^*, b^*), indicating changes in appearance. Sensory evaluation also revealed that patties were more acceptable and juicier to consumers.

■ Bakery products and pasta

The addition of buckwheat hulls, sprouts, and extracts to bakery products can significantly enhance their nutrient and bioactive compound profiles and provide unique flavors and textures. Each form of buckwheat brings specific characteristics and benefits when incorporated into baked goods such as breads, muffins, and cookies (**Table 5**). Liu *et al*. [2022] and Zhang *et al*. [2017] have documented the significant nutritional properties of buckwheat hull, noting its richness in bioactive compounds compared to buckwheat flour. Furthermore, Dziadek *et al*. [2016] conducted a study on six different cultivars and strains of common buckwheat, including whole seeds, dehulled seeds, and hulls, finding that the hulls contained the highest levels of dietary fiber and total phenolics, as well as exhibited the greatest antioxidant activity among the samples tested. Also, it has been shown that common bakery products can benefit from the inclusion of buckwheat flour or hull, which not only enhances their antioxidative potential but also improves sensory and storage properties [Wronkowska *et al*., 2019, 2023]. Phenolics of buckwheat hulls provide or enhance antioxidant capacity. Their addition can also help in reducing acrylamide formation during baking, a compound that poses health risks due to its potential carcinogenic effects [Teng *et al*., 2018]. Phenolic extracts from both common buckwheat (*F. esculentum* Moench) and tartary buckwheat (*F. tataricum* Gaertn.) have been incorporated into breadmaking processes and specifically, these extracts, sourced from the seeds and sprouts of tartary and common buckwheat resulted in notable reductions in acrylamide content [Melini *et al*., 2024]. The reductions were quantified as 23.5% for tartary buckwheat seeds, 27.3% for tartary buckwheat sprouts, 17.0% for common buckwheat seeds, and 16.7% for common buckwheat sprouts, enhancing the health benefits of the breads produced. Moreover, the antioxidant properties of the phenolic compounds

Table 5. Effect of buckwheat, buckwheat sprouts, hulls, and their extracts on food properties.

Food product	Type of buckwheat	Buckwheat incorporation: type and level	Type of effect	Reference
Meat products				
Pork + Chicken (meatballs)	*Fagopyrum esculentum* Moench	Buckwheat hulls: extract	• Did not affect the total colour difference parameter; • Achieved high acceptability; • The total plate count was lower during 14 days of storage; • The effective inhibition of lipid oxidation processes.	Pietrzak *et al.* [2022]
		Buckwheat hulls: extract	• Controlled peroxide and TBARS values • A higher free radical scavenging activity • Higher Fe(II) ion chelating ability • Prolonged shelf life	Hęś *et al.* [2017]
Pork (frankfurter-type sausages)	*Fagopyrum esculentum* Moench	Buckwheat hulls: 3%	• Buckwheat hulls (3%): more cooking, less storage loss. • Sausages' the firmness increased after two weeks' storage • Increased the content of manganese, calcium, potassium and magnesium	Salejda *et al.* [2022]
Horsemeat (patties)	*Fagopyrum esculentum* Moench	Ground green buckwheat sprouts: 5%	• Enriched the contents of protein and fat, cooking efficiency, retention of moisture and fat, total phenolic levels, and DPPH radical scavenging capacity • Green buckwheat sprouts maintained their color throughout the storage period	Atambayeva *et al.* [2023]
		Buckwheat extract: 0.5% and 1%	• Improved horse-meat product oxidative stability, quality, sensory, and color	Uzakov *et al.* [2020]
Bakery products				
Bread/rolls	*Fagopyrum esculentum* Moench	Adding 3% of buckwheat hull to wheat flour	• Reduction in GSH and GSSG content • Increased of content of α-, β-,γ-, and δ-tocopherols • Increase in the value of the antioxidant capacity after the baking process	Wronkowska *et al.* [2023]
		Buckwheat hull: mixed rye/wheat flour with 4% of roasted buckwheat hull, wheat flour with 3% of raw buckwheat hull	• Bread containing 4% roasted buckwheat hulls exhibited the highest levels of TPC and AC • Showed positive effects on sensory qualities, consumer acceptance, and microbial qualities after storage	Bączek *et al.* [2023]
	Tartary buckwheat, common buckwheat	Seed and sprout extracts from tartary and common buckwheat	• Reduced acrylamide level in bread • All four buckwheat extracts reduced acrylamide levels in the asparagine/glucose system • Did not affect the crust color, aroma, taste, crumb appearance, and hardness of the bread.	Jing *et al.* [2019]
	Fagopyrum esculentum	Buckwheat hull	• Reduced baking loss and increased firmness • Prevented amylopectin retrogradation and starch recrystallization • Retained more moisture and reduced staling	Wang *et al.* [2023]
		Buckwheat sprouts flour (10%)	• Increased total antioxidant activity • Enhances nutritional content without compromising texture or taste	Sturza *et al.* [2020]
	Fagopyrum tataricum (Xinong 9940)	Tartary buckwheat sprouts	• Higher bioactive compounds and functional value • The optimal addition is 8% of sprouts flour to achieve the acceptability of consumers	Xu *et al.* [2014]
	Common buckwheat	Mix of buckwheat flour and buckwheat sprouts: 10–30 % addition to wheat flour	• Ingredient to produce reconstituted rice • Contained higher levels of flavonoids, other phenolics, and flavor compounds	Kang *et al.* [2024]
Other products				
Fish products	*Fagopyrum tataricum* Gaertn	Tartary buckwheat: extract 0.5% to 1.5% (*w/v*) addition to chitosan	• Preserved quality and exhibited an extended shelf life at 0°C. • Offers potential for application in coatings	Yang *et al.* [2019]
Pasta	Common buckwheat	Ground buckwheat hull	• Exhibited a reduction in the optimal cooking time • An increase in weight index and cooking loss • Enhancement in total phenolic content and antioxidant activity	Sujka *et al.* [2022]
Noodles	Fagopyrum esculentum	Mixed dough with 1–5 grams buckwheat bran/hull in 100 g wheat.	• Improved properties of dough and characteristic of noodles • Improved rheological and tensile properties	Liu *et al.* [2022]

Table 5 continued. Effect of buckwheat, buckwheat sprouts, hulls, and their extracts on food properties.

Food product	Type of buckwheat	Buckwheat incorporation: type and level	Type of effect	Reference
Yogurt	Common buckwheat	Micronized buckwheat hulls	• Decreased total acidity and syneresis • Reduced the colour brightness and increased the intensity of the red and yellow colours • Demonstrated the beneficial effect on *L. bulgaricus*	Znamirowska *et al.* [2020]
Chocolate cream		Ground buckwheat hull	• Increased antioxidant activity • Increased fibers content in desserts	Matseychik *et al.* [2021]
Spice		Buckwheat sprouts	• Increased protein content by 1.38 times • Reduced mass fraction of carbohydrates by 1.57 times • Reduced the mass fraction of fat by 2 times	Serikbaeva *et al.* [2021]
Tea	*Fagopyrum esculentum* Moench	Buckwheat hulls	• Showed lower antioxidant capacity and inhibitory activity	Zielińska *et al.* [2013]

TBARS, Thiobarbituric acid reactive substances; DPPH radical, 2,2-diphenyl-1-picrylhydrazyl radical; GSH and GSSG, glutathione in reduced (GSH) and oxidized (GSSG) form; TPC, total phenolic content; AC, antioxidant capacity.

in buckwheat hulls have been shown to contribute to improved shelf life and nutritional value of the bakery products without adversely affecting their sensory qualities like taste and texture [Jing *et al*., 2019]. However, it is important to note that excessive inclusion of hulls could lead to a denser, dryer product; hence their amount needs to be balanced to maintain product quality.

Raw and roasted buckwheat hulls markedly raised the content of bioavailable phenolic compounds and antioxidant capacity of the baked goods [Bączek *et al*., 2023; Wronkowska *et al*., 2023]. Incorporating raw and roasted buckwheat hull into bakery products notably improved their measured parameters over control samples; notably, before digestion, bread containing 4% roasted buckwheat hull exhibited the highest TPC at 1.80 mg gallic acid eq/g dry matter (dm), and after *in vitro* digestion, the soluble fraction of the examined bakery products showed a 75–90% higher TPC and antioxidant capacity compared to the insoluble fractions [Bączek *et al*., 2023]. Wronkowska *et al*. [2023] observed an increase in contents of α-, β-, γ-, and δ-tocopherols during the production stages of wheat rolls, with the highest levels found in rolls containing 3% buckwheat hull. However, there was a significant reduction in the content of glutathione in reduced (GSH) and oxidized (GSSG) form during baking. The authors concluded that the rise in antioxidant capacity post-baking might be due to the formation of new antioxidant compounds.

The effect of the size of buckwheat hull powder particles on bread quality, comparing tissue-scale (500–100 μm) to cell-scale (50–10 μm) powders, was examined by Wang *et al*. [2023]. The study used a 3% (*w/w*) content of buckwheat hull in the bread formulation and authors found that while tissue-scale buckwheat hull powder minimally affected loaf volume and crumb firmness, the cell-scale buckwheat hull powder significantly decreased volume, reduced baking loss, and increased firmness. Also, the cell-scale buckwheat hull powder better prevented amylopectin retrogradation and starch recrystallization, retained more moisture, and reduced staling compared to the tissue-scale buckwheat hull powder.

Fresh bread's sensory qualities and acceptability were improved when 0.3–0.5% buckwheat hull hemicelluloses were added to bread wheat flour [Hromádková *et al*., 2007]. Buckwheat hull hemicelluloses reduced crumb hardness during storage, yielding a softer, more elastic bread compared to the control. Over time, buckwheat hull hemicelluloses enhanced breads maintained superior softness and elasticity, suggesting buckwheat hull hemicellulose potential to improve bread made from medium-quality wheat flours.

Sturza *et al*. [2020] found that the addition of sprouted buckwheat flour (10%) and buckwheat grain flour (20%) into wheat flour in buns increased total antioxidant activity by 59.04% compared with non-sprouted buckwheat flour, and results showed that replacing wheat flour with 20% buckwheat and 10% sprout flours enhanced the nutritional content without compromising texture or taste, receiving high consumer ratings. Similarly, an optimal addition of 8% was found in incorporating tartary buckwheat sprouts into Chinese steamed bread and was shown to optimize both its functional qualities (texture, taste, structural integrity, and overall quality) and consumer satisfaction [Xu *et al*., 2014].

Pasta is esteemed not only for its delightful culinary attributes but also as an essential element of a nutritious diet, thanks to its healthful and gastronomic properties. In an exploration of alternative pasta formulations, the substitution of semolina with ground buckwheat hulls was examined, leading to an increase in fiber content from 4.31% to 14.15% when 20% hulls were incorporated [Sujka *et al*., 2022]. This adjustment notably decreased cooking times and raised both the weight index and cooking loss, while significantly enriching the phenolic content and antioxidant activities. However, the use of buckwheat hulls exceeding 10% resulted in the pasta acquiring an unfavorable aroma and taste. Despite these sensory challenges, such modifications hold promise for boosting the nutritional value of products. Liu *et al*. [2022] compared the properties of dough made from wheat flour with addition of buckwheat bran or buckwheat hull and analyzed the quality of noodles from both types of doughs. Due to a higher fibre content in doughs made from enriched flours (both additives), their starch pasting properties were declined compared to the control without additives; however, when 4% buckwheat bran or hull was used, the hardness and chewiness of dough was acceptable; gluten network was still formed. Moreover, the cooking loss of noodles with buckwheat bran was lower than of the product with buckwheat hulls.

Other products

Incorporating buckwheat hulls into dairy products such as yogurt can enhance their nutritional profile and functional properties. Adding buckwheat hulls to yogurt has been shown to decrease total acidity and reduce syneresis, thereby improving texture and stability [Znamirowska *et al*., 2020]. Moreover, the phenolics of buckwheat hulls enhance the antioxidant capacity of the yogurt and can contribute to improved shelf life and health benefits. This is because phenolic compounds are well-recognized for their dual role in enhancing the longevity of perishable items and contributing health advantages, which supports the formulation of foods free from synthetic additives [Martillanes *et al*., 2017; Matsumura *et al*., 2023]. The addition of buckwheat hulls positively affected the microbiological properties of yogurt, promoting the growth of beneficial bacteria like *Lactobacillus bulgaricus* [Znamirowska *et al*., 2020].

Using buckwheat by-products, specifically hull fine powder and melanin, in dessert formulations like chocolate cream and honeysuckle mousse enhanced their sensory appeal and physicochemical properties, including antioxidant capacity [Matseychik *et al*., 2021]. Sensory evaluations and antioxidant contents determined optimal inclusion rates at 1.5 g and 0.037 g *per* serving, respectively. These additions not only boosted antioxidant intake, covering over 15% of daily needs, but also increased dietary fiber content, making these desserts functional products.

An optimized blend of sprouted buckwheat, wheat, black rice, and purple potato flours was developed to create reconstituted rice with enhanced flavor and a reduced glycemic index (GI) [Kang *et al*., 2024]. This innovative formulation produced rice with distinctive colors and a robust cereal flavor, enriched with a superior nutritional profile and medium GI values, offering significant benefits for blood glucose management.

Research into the influence of temperature and germination duration on vitamin enrichment in buckwheat led to its potential use in a novel seasoning [Serikbaeva *et al*., 2021]. Optimal sprouting conditions – (21.5°C for three days using the Bogatyr variety) – resulted in the highest levels of vitamins B, E, and C at 4.591 mg/100 g. A seasoning blend incorporating 30% of these sprouted buckwheat grains excelled in protein, vitamin content, and both micro- and macronutrient levels, additionally exhibiting a 25% enhancement in antioxidant activity.

Yang *et al*. [2019] found that mixtures of tartary buckwheat extract and chitosan were more effective in extending the shelf life of coated tilapia (*Oreochromis niloticus*) fillets compared to chitosan only during storage at 0°C for 18 days. The shelf life has been extended from 6 days for fish coated with chitosan to up to 15 days when the coating with the addition of tartary buckwheat extract was used.

STRENGTHS AND LIMITATIONS OF CURRENT REVIEW

This systematic review offers a first direct comparison of the properties of buckwheat sprouts, hulls, and extracts, their health benefits, and their use in developing new functional foods under a zero-waste principle. However, there are limitations to note. Despite our comprehensive search strategy, not all online databases were covered, and some articles, particularly non-English ones, may have been overlooked. Also, the high variability in study designs, such as different parts of the plant used, extraction methods, and units of measure, made it difficult to quantitatively synthesize the data, leading us to focus primarily on a narrative summary of the most pertinent findings.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Buckwheat hulls, sprouts, and extracts are rich in carbohydrates, proteins, fiber, and bioactive compounds, with sprouts and extracts notably high in flavonoids, mainly rutin. Although often discarded, buckwheat hulls are a valuable source of dietary fiber and carbohydrates. The presence of bioactive compounds across all buckwheat derivatives contributes significantly to their health-promoting qualities, making them vital for inclusion in human diets. These derivatives are particularly beneficial for individuals with celiac disease, offering a safe, gluten-free food option. Nonetheless, the impact of food processing on the nutritional quality of buckwheat products poses a challenge to the industry, necessitating a careful approach to the transformation of raw materials.

Future research on buckwheat hulls, sprouts, and extracts holds immense potential for advancing sustainable food production and zero-waste principles in the food industry. Particularly, the exploration of buckwheat hulls as a value-added ingredient in various food products can significantly contribute to waste reduction and resource efficiency. Studies can focus on optimizing processing methods to enhance the nutritional and functional properties of buckwheat hulls, enabling their broader use in foods like bakery products, beverages, and dietary supplements. Moreover, research into the bioactive components of green (thermally untreated) buckwheat sprouts and extracts could lead to innovative applications in nutraceuticals and functional foods, further extending their health benefits. Such investigations are vital not only for maximizing the utility of all buckwheat plant components but also for promoting sustainability through the adoption of a no-waste approach in food processing and product development. This aligns with global efforts to achieve more sustainable food systems by reducing food waste and enhancing the nutritional value of food products. Thus, the findings from this review, highlighting the rich bioactive profiles of buckwheat hulls, sprouts, and extracts provide functional food developers with valuable insights into creating products that are both nutritious and aligned with health-conscious consumer preferences. Utilizing these components can help in formulating foods that not only meet daily nutritional needs but also offer targeted health benefits such as enhanced cardiovascular health, improved digestive function, and potent antioxidant protection.

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CONFLICT OF INTERESTS

No potential conflict of interest was reported by the authors.

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