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Review

Wheat and Wheat-Derived Beverages: A Comprehensive Review of Technology, Sensory, Biological Activity, and Sustainability

Thinzar Aung[1] and Mi Jeong Kim[1,2]

[1]Department of Food and Nutrition and [2]Interdisciplinary Program in Senior Human Ecology, Changwon National University, Gyeongnam 51140, Korea

ABSTRACT: At present there is heightened demand for beverages that functionally improve human well-being. Wheat and wheat derivatives are excellent sources of nutrients and bioactive phytochemicals including phenolic compounds, dietary fiber, gamma amino butyric acid, and amino acids. Generally, wheat flour has been used extensively in baking and confectionery production, and wheat germ, and bran are byproducts that can be used to fortify some foods. However, limited attention has been paid to the use of wheat and wheat derivatives for beverage production. Our study therefore aimed to fill this gap by comprehensively exploring various aspects of wheat beverages. This review scrutinizes the use of wheat and wheat derivatives in beverage preparation, including processing methods, sensory perception, and biological properties, and also sheds light on the challenges and future perspectives of the wheat beverage industry. Our study offers valuable insight into the use of wheat for the design of functional, nonalcoholic plant-based beverages.

Keywords: bioactive compounds, biological activity, functional beverages, wheat, wheat derivatives

INTRODUCTION

Wheat (*Triticum* spp.) is one of the most important cereal crops worldwide and plays a vital role in global food security (Acevedo et al., 2018; FAO, 2020). Wheat offers high nutritional value, and is cultivated in many regions, including Asia, Europe, Oceania, America, and Africa, where it has been adapted to diverse climatic conditions (FAO, 2020). Wheat grains are composed of several parts, including the bran, germ, and endosperm, each of which contributes different elements to the overall wheat nutritional profile (Luthria et al., 2015). Major nutrients of wheat include carbohydrates, primarily in the form of starch, proteins, and essential vitamins, and minerals such as iron, zinc, magnesium and selenium (Shewry and Hey, 2015). Beyond these macro- and micronutrients, wheat also provides dietary fiber and bioactive components, including phenolic compounds, carotenoids, and phytosterols, that have been linked to potential health benefits, including reduced risk of chronic diseases such as cardiovascular disease, diabetes, and cancer (Dapčević-Hadnađev et al., 2018).

Given their diverse nutritional profiles, wheat flour, germ, and bran are used in different foods. Wheat flour is a common ingredient in many food products, including bread, pasta, pastries, and cakes (Dewettinck et al., 2008). Wheat germ is regarded as a valuable by-product of wheat milling and can be used in raw or processed forms for the fortification of bread, noodles, pasta, and beverages (Boukid et al., 2018). In contrast, wheat bran is used to fortify products with a higher content of dietary fiber, phenolic compounds, phytochemicals, vitamins, and minerals (Dapčević-Hadnađev et al., 2018). Moreover, the recent surge in the popularity of cereal-based nonalcoholic beverages as alternatives to traditional dairy- or fruit-based beverages highlights the importance of the reported health benefits, which may be due to higher bioactive component content and robust antioxidant properties (Basinskiene and Cizeikiene, 2020). The global functional beverage market, valued at USD 110.15 billion in 2020, is expected to reach USD 200.08 billion by 2030, representing an annual increase of 5.9% compound annual growth rate from 2021 to 2030 (Kamble and Deshmukh, 2021). Therefore, the growth in the production and consumption of wheat-based beverages has sparked interest in exploring innovation in beverage production and recipe, as well as in their potential health benefits.

Although wheat is widely used in alcoholic beverages, such as beer, and whiskey, its use as a major ingredient in nonalcoholic beverages has only recently been recognized

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Correspondence to Mi Jeong Kim, E-mail: mjkim@changwon.ac.kr

as a novel opportunity for functional product development. Wheat-based beverage processing involves various steps, including germination, roasting, steaming, and fermentation (Aung et al., 2022a, 2022b). Moreover, the sensory profiles of wheat beverages vary depending on the specific methods used during preparation (Aung et al., 2022a, 2022b). However, to date studies of the potential applications of wheat and wheat derivatives for functional beverage preparation remain limited. Therefore a deeper exploration of the processing techniques, functionality, sensory acceptability, and potential health benefits of functional wheat beverages is essential, as is a discussion of addressing challenges associated with beverage production, including ingredient, and product availability, affordability, and environmental sustainability. In this review, we explore the nutritional, and sensory aspects of wheat- and wheat-derived beverages using various processing methods. In doing so we draw on relevant research studies and scientific literature to provide a comprehensive overview.

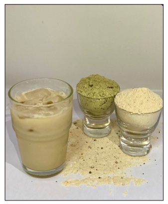
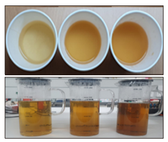
STRUCTURE AND COMPOSITION OF WHEAT AND WHEAT DERIVATIVES

Whole wheat grains contain three main parts, i.e., the endosperm, bran, and germ. The endosperm accounts for 82∼83% of the grain and primarily contains starch and gluten proteins. In contrast, the bran, and germ make up 13∼14% and 3% of the grain, respectively (Tosi et al., 2018). Typically, the starchy endosperm is extracted to produce a flour fraction by eliminating the outer kernel layers, bran, and germ as byproducts (Dapčević-Hadnađev et al., 2018). However, the use of the bran and germ has become more common due to their nutritional properties and functional attributes, both of which may confer health benefits (Dapčević-Hadnađev et al., 2018). The predominant storage component in the endosperm is starch, followed by proteins, cell wall polysaccharides, and minor components including lipids, terpenoids, phenolics, minerals, and vitamins (Shewry et al., 2013). The majority of bioactive compounds in the wheat grain are located in the bran fraction, which contains non-starch polysaccharides, arabinoxylans, cellulose, fructans, β-glucans, lignin, minerals, vitamins and other bioactive compounds (Sapirstein, 2016; Dapčević-Hadnađev et al., 2018). Moreover, dietary fiber is significantly more abundant in the wheat bran fraction than in the other parts of wheat grains. The phenolic compounds present in wheat can be categorized into two subclasses: hydroxybenzoic acid derivatives, including vanillic, syringic, *p*-hydroxybenzoic, and gallic acids; and hydroxycinnamic acid derivatives, including ferulic, sinapic, *p*-coumaric, and caffeic acids (Luthria et al., 2015). Flavonoids are also abundant in the wheat bran fraction, where carotenoids such as lutein, zeaxanthin, cryptoxanthin, and carotene are strongly associated with grain color (Luthria et al., 2015). The wheat germ contains high amounts of protein, sugar, lipid, dietary fiber, minerals, and other bioactive constituents, including tocopherols, carotenoids, thiamin, and riboflavin (Brandolini and Hidalgo, 2012; Dapčević-Hadnađev et al., 2018). Due to its elevated lipid content, the wheat germ is often used for oil extraction (Dapčević-Hadnađev et al., 2018). Moreover, the wheat germ is also an excellent source of amino acids and bioactive peptides, making it a valuable food supplement (Brandolini and Hidalgo, 2012; Dapčević-Hadnađev et al., 2018). Tocols (i.e., tocopherols and tocotrienols), are lipophilic antioxidants present in wheat that are primarily located in the germ fraction, where they account for 80% of total tocopherol content (Hejtmánková et al., 2010). Phytosterols and steryl ferulates, which are predominantly found in the bran and germ fractions of wheat grains, may contribute to functional health by lowering cholesterol levels (Luthria et al., 2015; Xiong et al., 2022). These bioactive components confer antioxidant, anti-inflammatory, anti-thrombotic, anti-allergenic, anti-microbial, and anti-carcinogenic properties. This activity consequently reduces the risk of oxidative stress-induced diseases, including cardiovascular diseases and cancers (Basinskiene and Cizeikiene, 2020).

WHEAT AND WHEAT-BASED NONALCOHOLIC BEVERAGES

Throughout the world, traditional fermented wheat beverages have been consumed for centuries. These include boza (also known as bosa), which can be made from maize, wheat, rice, or semolina flours (Hancioğlu and Karapinar, 1997; Ucak et al., 2022); borş, made from wheat bran and corn meal (Pasqualone et al., 2018); and rejuvelac, made from germinated quinoa or wheat grains (Peñaranda et al., 2021) (Table 1). Borş, also referred to Borş de tarate, is a traditional fermented beverage that is widely consumed in Romania, where it is enjoyed as a plain drink or as an ingredient in sour soup (Pasqualone et al., 2018). Wheat bran serves as the primary ingredient of borş, with cornmeal and herbs, including cherry leaves, lovage, and dill, often used as flavoring agents (Pasqualone et al., 2018). During production, ingredients undergo spontaneous fermentation for 2∼4 days in wooden or glass containers using a natural starter containing lactic acid bacteria (LAB). This fermented mixture is then pasteurized prior to consumption (Grosu-Tudor et al., 2019). In batch samples, one or two species of *Lactobacillus* were identified, and in both commercial, and homemade borş samples, numerous bacteria species−including *Lactobacillus amylolyticus*, *Lactobacillus fermentum*, *Lactobacillus plan-*

Table 1. Wheat and wheat-derived beverages

Name	Beverage type	Raw materials	Process	Image	Country of origin	Source (URL)	Reference
Borş/bors	Fermented beverage	Wheat bran, corn meal, and herbal additives	Fermentation with lactic acid bacteria isolated from starter of borş such as, *Lactobacillus amylolyticus*, *Lactobacillus fermentum*, *Lactobacillus plantarum*, *Lactobacillus casei*, *Lactobacillus buchneri*, *Lactobacillus panis*, *Lactobacillus brevis*, *Lactobacillus oris*, and *Enterococcus duran*		Romania	https://www.pulcetta.com/2013/03/bors-fermented-wheat-bran.html https://www.secretromania.com/romanian-bors-recipe-borscht/	Pasqualone et al., 2018
Boza/bosa	Fermented beverage (sweet colloid beverage)	Maize, wheat, and rice/semolina flours	Fermentation with lactic acid bacteria (i.e., *Leuconostoc paramesenterioides*, *Lactobacillus sanfrancisco*, *Leuconostoc mesenterioides*, *L. fermentum*, or *Leuconostoc oenos*) and yeast (i.e., *Saccharomyces uvarum* or *Saccharomyces cerevisiae*)		Turkey, Egypt, and some African countries	https://doi.org/10.1016/J.LWT.2021.112465	Hancioğlu and Karapinar, 1997; Ucak et al., 2022
Rejuvelac	Fermented beverage	Germinated quinoa/wheat	Germination of wheat grains, fermentation with lactic acid bacteria (such as *Lactobacillus acidophilus*, *Pediococcus*, and *Weissella*)		Lithuania	https://www.superfoodevolution.com/rejuvelac.html	Chen et al., 2020
Sunsik	Ready-to-drink	Germinated wheat, barley, brown rice, adlay, black bean, oat, and herbal plant extract	Steaming, drying, roasting, and grinding ingredients together, or fermentation with *Bifidobacterium longum* KCTC 5081 plus Bionuruk-R (a combined culture of *Rhizopus*, *Aspergillus usami*, and *Aspergillus oryzae* that contains no *Bifidobacterium* or yeast)		Korea		Kim et al., 2020 Koh et al., 2014
Wheat beverage	Wheat tea	Germinated wheat	Germination, steaming, roasting, infusion or boiling/brewing, and serving hot or cold		Korea	https://www.mdpi.com/2304-8158/11/3/481	Aung et al., 2022b

tarum, *Lactobacillus casei*, *Lactobacillus buchneri*, *Lactobacillus panis*, *Lactobacillus brevis*, *Lactobacillus oris*, and *Enterococcus durans*—were found (Grosu-Tudor et al., 2019). To create specific flavor profiles, various herbs and leaves, including thyme, dill, sour cherry tree, or lovage, is generally added during initial fermentation (Nicolau and Gostin, 2016).

Boza, a Turkish beverage, is a LAB-fermented cereal beverage prepared from millet, maize, wheat, or rice semolina before being mixed with sugar or saccharine (Hancioğlu and Karapinar, 1997; Kabak and Dobson, 2011; Ucak et al., 2022). Also known as bousa or bouza in Egypt and some other African countries, boza is produced using a variety of methods, each of which yields similar beverages (Arici and Daglioglu, 2002). The fermentation process of boza involves taking advantage of the synergy between LAB and yeast, which converts sugars into organic acids and other metabolites. The dominant LAB identified in boza include *Lactobacillus*, *Lactococcus*, and *Leuconostoc* spp. (Ucak et al., 2022). Furthermore, yeast strains such as *Saccharomyces carlsbergensis*, *Saccharomyces cerevisiae*, *Streptococcus* spp., *Micrococcus* spp. have been reported (Arici and Daglioglu, 2002). Many LAB species, including *Leuconostoc paramesenterioides*, *Lactobacillus sanfrancisco*, *Leuconostoc mesenterioides*, *L. fermentum*, *Leuconostoc oenos*, and yeast species, including *Saccharomyces uvarum*, and *S. cerevisiae*, have also been identified in boza (Hancioğlu and Karapinar, 1997). Moreover, the results of a metagenomic study permitted the detection of 200 LAB and yeast strains. Of these, *Lactococcus lactis*, *Leuconostoc* spp. (i.e., *Leuconostoc pseudomesenteroides*, *Leuconostoc lactis*, and *Leuconostoc citreum*) and *Lactobacillus* spp. (i.e., *Lactobacillus plantarum*, *Lactobacillus paracasei*, *Lactobacillus brevis*, and *Lactobacillus delbrueckii* subsp. *delbrueckii*) are the dominant LAB communities (Ucak et al., 2022). The production of boza includes several steps: first, raw materials are prepared by cleaning the ingredients, meaning that the hull, and bran are removed. This involves boiling for 1∼2 h in water with continuous stirring, cooling, and straining, the addition of sugar (up to 20% w/w), fermentation with LAB, and yeast for approximately 24 h at 15∼25°C, then cooling for consumption or trade (Arici and Daglioglu, 2002). The fermentation process itself can be divided into two stages: alcoholic fermentation, which releases carbon dioxide bubbles, and lactic acid fermentation, which generates an acidic flavor (Arici and Daglioglu, 2002).

Rejuvelac, a beverage based on fermentation of sprouted grains, is generally prepared by germinating quinoa or wheat grains and fermenting them with LAB (Peñaranda et al., 2021). This beverage originated as a tonic, and was invented by Ann Wigmore in Lithuania during the 1960s (Katz, 2012). Germination is a key step in the preparation of rejuvelac. According to the method published by Peñaranda et al. (2021), wheat grains are first immersed in a hypochlorite solution, then washed with sterile water, soaked in water, and germinated at 20±2°C for 12∼24 h. Once germinated, wheat grains are then continuously treated with hypochlorite solution and sterile water and fermented with *Lactobacillus acidophilus* for 24 h at 25°C. The predominant bacteria in rejuvelac starter cultures include species from the genera *Pediococcus* and *Weissella* (Chen et al., 2020). Another beverage featured a combination of germinated wheat, wheat bran, oats, and guar gum that was fermented with *L. acidophilus*-NCDC14 to produce a probiotic beverage similar to rejuvelac (Sharma et al., 2014).

Sunsik, a ready-to-drink beverage based on various cereal grains, is traditionally consumed in Korea (Kim et al., 2020). Sunsik is prepared from varying amounts of different cereals (including brown rice, black beans, wheat, barley, oats, and adlay), sea algae (i.e., kelp and seaweed), carrots, and lotus roots, cabbage, and sesame leaves, nuts (i.e., peanuts, walnuts, and pine nuts), fruits (i.e., bananas and apples), milk powder, glucose, salt, calcium, and added vitamins (Lee et al., 2007; Jung and Lee, 2010; Kim et al., 2020). Main ingredients, such as brown rice, are first processed by steaming, drying, and roasting. In contrast, the other ingredients are generally ground together for individual batches of sunsik production (Koh et al., 2014). In a study examining the use of wheat and herbal plant extracts as additional ingredients to improve nutritional quality, wheat was first germinated and ground into a powder before being added to sunsik preparations (Kim et al., 2020). Relative to commercial sunsik, the inclusion of germinated wheat resulted in sunsik formulations that showed improved quality characteristics, including higher levels of γ-aminobutyric acid (GABA), total phenolics, total flavonoids, higher antioxidant activity [including both 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity (DPPH) and Trolox equivalent antioxidant capacity (TEAC)], and higher water solubility index (Kim et al., 2020). In another study, sunsik supplemented with mealworm also exhibited higher palatability and significantly increased total phenolic and antioxidant activities (including DPPH and reducing power) (Park and Kim, 2018). Although the dry form of sunsik can be consumed directly by dissolution in water or milk, fermenting sunsik with *Bifidobacterium longum* KCTC 5081 and Bionuruk-R—a combined culture of *Rhizopus*, *Aspergillus usami*, and *Aspergillus oryzae* without *Bifidobacterium* or yeast—was reported to improve beverage amino acid content, oxidative stability, and physicochemical properties (Koh et al., 2014).

Wheat beverages or wheat tea, which were initially reported in Korea, are prepared via the germination, steaming, and roasting of wheat before being served as a boiled drink or an infusion (Aung et al., 2022a, 2023). This type of beverage preparation is similar to methods used for herbal teas and other cereal-based teas such as barley tea.

Wheat germination and roasting distinctly enhance bioactive compounds, including total phenolics, flavonoids, amino acids, GABA, and volatiles. This in turn increases antioxidant activities, such as DPPH and TEAC (Aung et al., 2023). Roasting germinated cereals also creates a unique flavor profile, which has been attributed to the elimination of ethanoic acid, acetic acid, and other undesirable volatiles generated during germination (Kim et al., 2021). Two methods of beverage preparation, infusion, and boiling, were compared and found to differ significantly in sensory attributes and consumer acceptability (Aung et al., 2022b). A hot beverage is prepared by infusing roasted germinated wheat in hot water (approximately 100°C). Conversely, a cold beverage is prepared by boiling roasted germinated wheat in water for 30 min, then allowing it to cool before storing it at 4°C. These two different ways of consuming wheat beverages appear to depend on consumer preferences.

PROCESSING TECHNIQUES FOR WHEAT BEVERAGE PREPARATION

Although wheat flour is extensively used for baking and confectionery production, its use in nonalcoholic beverage production remains limited. The direct use of wheat flour in beverages may be uncommon due to its poor solubility in cold water and its potential to negatively alter beverage taste. Therefore, suitable preparation methods that can enhance the flavor, nutritional value, and health benefits of the final product are highly valuable wheat and wheat derivative-based beverages. To fulfill this need, new techniques, and formulations must be explored to improve wheat-based beverages. These beverages require different formulations to improve their bioactive components and eliminate antinutrient components. Such improvements can be achieved by wheat germination to enhance bioactive components, roasting to enrich the flavor of the wheat beverage, and treatments such as enzymatic hydrolysis or fermentation to maximize the solubility of wheat components.

GERMINATION

Germination is an important raw material processing step that includes the breakdown of starch and sucrose into mono- and disaccharides with the help of enzymes such as amylase or invertase (Peñaranda et al., 2021). Wheat germination has been shown to enhance nutritional quality, including increased GABA, and phenolic compounds, owing to the activation of endogenous enzymes for starch and protein breakdown. This in turn also increases the solubility and antioxidant activity of the final product (Kim et al., 2020). In addition to protein digestibility and bioavailability, germination can also enhance the organoleptic characteristics of cereals including wheat, buckwheat, oat, barley, and quinoa (Lan et al., 2023). Generally, the steps involved in germination include cleaning, washing, sterilization, soaking, and sprouting. The sterilization step commonly uses sterilizing agents such as sodium hypochlorite (0.05～0.1%) and ethanol (70～95%) (Lan et al., 2023).

In contrast, cold beverages are prepared by boiling roasted and germinated wheat in water for 30 min, then allowing it to cool before storing it at 4°C. Grains were prepared by soaking in distilled water for 12～72 h at 10～60°C. Other compounds such as polysaccharides, phytochemicals, and amino acids are also added as needed to enrich grain functionality and metabolic activity (Oliveira et al., 2022). During germination, hydration improves the nutritional, and functional properties of grains by increasing the solubility of proteins, starches, and the phenolic and flavonoid compounds required for further germination processes (Verma et al., 2021). During germination, soluble proteins, nutrients, and bioactive compounds are also transformed by enzymes, including endogenous hydrolases, α-amylase, and lipases (Lan et al., 2023). Moreover, soaking time and germination conditions have been found to affect the release of bioactive components, protein solubility, and antioxidant activity during chickpea germination (Kim et al., 2022). Germination can also reduce the bioavailability of anti-nutritional compounds such as phytate (Hübner et al., 2010; Azeke et al., 2011). However, concerns exist regarding the formation of undesirable flavors associated with microbial contamination during germination (Bourneow and Toontam, 2019). To avoid this, Kim et al. (2021) suggested the use of pre- or posttreatments, including periodic washing with electrolyzed water, cold plasma steam treatment, radiation, and roasting. Ultrasonication before germination was shown to shorten grain germination time, stimulate GABA synthesis, and increase the flavonoid content and antioxidant activity of wheat flour (Naumenko et al., 2022). Steaming, a key post-germination treatment, is known to activate trypsin inhibition and lipoxygenase, both of which are related to off-flavors of germinated wheat.

ROASTING

Roasting is a unique beverage preparation process that can enhance nutritional value and product quality by various means. First, roasting can affect product physicochemical, structural, and sensory characteristics as well as component digestibility and bioavailability. Generally, roasting involves an intense thermal treatment conducted at temperatures ranging from 150～300°C for 8～25 min in an oven or roaster (Sruthi et al., 2021). Specific roasting conditions, including time, and temperature, significantly affect the components present in grain products. Researchers have therefore focused on studying how roasting conditions cause changes in the physicochemical characteristics, structural profiles, bioactive components, antioxidant activities, and bioavailability of grain components (Aung et al., 2022b).

Roasting equipment and protocols can also yield end products of different qualities. Heating with continuous stirring is a common part of conventional roasting methods, including pan roasting, oven roasting, and sand roasting, as well as more technical forms of roasting, including microwave roasting, forced convection continuous tumble roasting, RevTech roasting, superheated steam roasting, and infrared roasting (Sruthi et al., 2021). Roasting also induces various chemical changes, such as the Maillard reaction, protein denaturation, and lipid oxidation (Sruthi et al., 2021). The Maillard reaction provides a distinct flavor and aroma owing to the liberation of volatile compounds caused by reactions between reducing sugars and amino acids (Aung et al., 2023). However, the Maillard reaction can also generate detrimental products, such as acrylamide, furaldehyde, and hydroxymethylfurfural, which have mutagenic and carcinogenic effects (Ghazouani et al., 2021). Roasting germinated cereals can also create a unique flavor profile via the elimination of ethanoic and acetic acids and other undesirable volatiles generated during germination (Kim et al., 2021). In a previous study, germinated wheat that was subsequently roasted showed enhanced production of phenolic acids (including gallic, caffeic, syringic, ferulic, and *p*-coumaric acid) and volatiles (including *n*-butanol, furfural, ethyl pentanoate, 1-propanol, 3-mercapto-2-pentanone, and heptane). It also showed lower levels of amino acids, fat, ash, and moisture (Aung et al., 2023). Product color is a significant indicator of roasting. Caramelization and browning reactions are associated with darker color development in seeds and grains (Sruthi et al., 2021). Overall, roasting aids in enriching health-promoting ingredients in beverage formulations and can produce desirable flavors and aromas. Roasted wheat is generally prepared by infusion or brewing with water and can be served either hot or cold (Aung et al., 2022b; Patra et al., 2023). Roasted wheat prepared by infusion and boiling methods exhibit strongly different flavor profiles and nutraceutical characteristics. For example, wheat tea served chilled is characterized by higher levels of volatiles and amino acids, stronger sourness, and a more pronounced umami taste than infused wheat tea (Aung et al., 2022a).

FERMENTATION

Fermentation is widely used in the production of cereal beverages and involves the conversion of carbohydrates into secondary metabolites (i.e., peptides, phenolics, hydrocarbons, cyclic compounds, and acids) by microorganisms such as bacteria, yeast, and fungi (Alu'datt et al., 2019). In addition to the generation of secondary metabolites, fermentation also enhances beverage sensory attributes including color, flavor, and aroma. Fermentation can also reduce the abundance of antinutrients in cereal grains, including phytic acid, tannins, and polyphenols (Blandino et al., 2003). Cereal fermentation has also been found to extend the shelf life of beverages since higher acidity inhibits spoilage and microbial growth (Xiong et al., 2022). To achieve the desired quality and nutritional value of fermented wheat beverages, it is important to optimize fermentation conditions, including the type of bacteria, pH, temperature, and substrate composition. Most plant-based beverages are produced via fermentation with LAB, including *Lactobacillus* (e.g., *Lactobacillus* spp., *L. casei*, *Lactobacillus helveticus*, *L. fermentum*, *L. Lactobacillus reuteri*, *L. acidophilus*, *Lactobacillus rhamnosus*, and *Lactobacillus johnsonii*), *Bifidobacterium* (e.g., *Bifidobacterium animalis* ssp. *Lactis*), *Streptococcus* (e.g., *Streptococcus thermophilus*), and *Enterococcus* (e.g., *Enterococcus faecium*) (Boukid et al., 2023). *Lactobacillus* and *Bifidobacterium* species are probiotic microorganisms that have been designated as generally recognized as safe (Charalampopoulos et al., 2002; Sharma et al., 2014). Yeast generally used for fermenting cereals for beverage preparation include fungi from the genera *Saccharomyces* and *Candida* as well as molds from the genera *Aspergillus*, *Fusarium*, and *Penicillium* (Blandino et al., 2003). According to a recent report, wheat germ fermented using *L. plantarum* and *S. cerevisiae* showed significant improvement with respect to total phenolic content, GABA content, dimethoxy benzoquinone, and DPPH radical scavenging activity (Bayat et al., 2022). The wheat germ contains beta-glucosidase and peroxidase enzymes that contribute to the generation of dimethoxybenzoquinone during fermentation (Bayat et al., 2022). The release of bioactive peptides during fermentation may also increase antioxidant activity via microbial hydrolysis, which can in turn lead to an improvement in the functional properties of wheat byproducts.

Given these advantages, the potential probiotic, and beneficial health properties of fermented wheat beverages such as borş, boza, and rejuvelac have been investigated by various studies (Arici and Daglioglu, 2002; Zorba et al., 2003; Kancabaş and Karakaya, 2013; Nicolau and Gostin, 2016; Ucak et al., 2022). In addition, fermentation can extensively reduce the abundance of anti-nutritional compounds, including phytic acids, lectins, trypsin, α-galactosides, and alkaloids, many of which can interfere with nutrient absorption (Galand et al., 2021). From a pharmaceutical standpoint, there is evidence suggesting that that fermented cereals might have a role in managing diabetes and potentially contributing to the reduction of oxidative diseases such as cancer, atherosclerosis, and arthritis (Garrido-Galand et al., 2021). Thus, fermentation may be an important step in the preparation of wheat-based beverages.

SENSORY PROFILE AND ACCEPTABILITY OF WHEAT-DERIVED BEVERAGES

Generally, wheat-derived beverages provide diverse sensory profiles that depend greatly on type and preparation method. For example, in fermented legume beverages, bean flavors related to specific volatile compounds, including *n*-hexanal, *n*-hexanol, acetate, isovalerate, and 2-methylbutyrate, can be reduced by *Bacillus subtilis*, *Lactobacillus* species, and/or edible fungi (Boukid et al., 2023). In a recent study of borş, a "ripe-fermented fruit odor (banana- and cider-like)," "cheese odor," "bran odor," "yogurt odor," "herbal-brilliant odor," "goat milk-cheese odor," and "pungent-sour odor" were all described as prominent odor characteristics (Pasqualone et al., 2018). The pungent-sour and goat milk-cheese odors were regarded as less favorable, and were found to be generated by volatiles such as alcohols and esters (Pasqualone et al., 2018). In another study, a viscous texture and an acidic flavor with a yogurt-like taste was described as characterizing another borş (Arici and Daglioglu, 2002). The rheological properties and sensory profiles of different boza preparations can vary (Genç et al., 2002). The sensory characteristics of boza, including its odor, mouthfeel, taste, and overall appearance, have been assessed using LAB starter cultures (Zorba et al., 2003). A combination of LAB with *S. cerevisiae*, *Leuconostoc mesenteroides* subsp. *mesenteroides*, *L. mesenteroides* subsp. *dextranicum*, *Lactobacillus confusus*, and *L. oenos* resulted in high scores for odor, taste, and overall appearance (Zorba et al., 2003). Boza preparations with higher sensory scores were described as having "uniform color," a "moderate sour and sweet flavor," a "smooth and robust taste," and "good fermenting capacity"; these characteristics were regarded as due to a high yield of carbon dioxide, a low alcohol content, outstanding flavor, and the presence of a symbiotic culture of LAB and yeast to produce various acids (Aila et al., 2020). A similar study of rejuvelac noted sensory attributes using the terms, "acid," "soft," "intense," "light," "sweet," "pleasant," "watery," "tasteless," "aromatic," "fresh," and "corn" (Peñaranda et al., 2021). This study suggested that overall perception can be improved by spontaneous fermentation. More recently, the consumer acceptability of hot and cold roasted-germinated wheat beverages was described using different sensory attributes —i.e., appearance, odor, taste, and overall acceptability— using a 9-point hedonic scale (Aung et al., 2022b). According to these authors, cold beverages generally showed higher sensory attributes and consumer acceptability than hot beverages. In addition, the intensity rating of hot and cold roasted-germinated wheat beverages was assessed using the attributes, "brownness," "grain odor," "nutty taste," "sweet taste," "bitter taste," and "after taste." These data showed that at both hot and cold temperatures roasted germinated wheat beverages were preferred by consumers.

BIOLOGICAL ACTIVITIES OF WHEAT-DERIVED BEVERAGES

The fermentation of cereals can improve their nutritional value and sensory properties. During fermentation, non-digestible poly-, and oligosaccharides present in cereal grains are broken down and the phytate content is degraded. This in turn increases the abundance of soluble iron, zinc, and calcium. The fermentation process also increases the levels of certain amino acids and generates volatile compounds that contribute to beverage flavor (Blandino et al., 2003). Thus, the biological activity of fermented beverages has been shown to provide various health benefits.

For instance, borş, a beverage fermented from wheat bran, is considered a probiotic product due to its high LAB content (Nicolau and Gostin, 2016). The main phenolic compound found in borş is ferulic acid, although other phenolics including 4-hydroxybenzoic acid, vanillic acid, syringic acid, *p*-coumaric acid, and sinapic acids are also present (Pasqualone et al., 2018). This may be related to wheat bran, the primary ingredient of borş, which is rich in fatty acids. Notably, cereal fermentation can also break down the cell wall, which releases soluble phenolics, and improves bioaccessibility. As a result, borş generally exhibits strong antioxidant activity as measured by Trolox equivalent antioxidant oxidant capacity, averaging 3～7 mmol/L Trolox (Pasqualone et al., 2018). In addition, *L. plantarum* L26 and *L. plantarum* L35, two bacteria isolated from borş, have shown antifungal, antibacterial, biosurfactant production, and antiadhesive properties (Cornea et al., 2016).

Boza, another fermented beverage, is a source of glucan, dietary fiber, vitamins A, B1, B2, B6, nicotinamide, and minerals including Ca, Fe, P, Zn, and Na (Ignat et al., 2020). It has been reported that boza protein hydrolysates and protein fractions both demonstrate increased ACE-inhibitory activity following *in vitro* digestion (Kancabaş and Karakaya, 2013). Thus, boza may serve as a healthy alternative to carbonated beverages due to the release of

ACE-inhibitory peptides during fermentation, which may be beneficial for treating hypertension.

Sunsik is a ready-to-drink beverage that may confer health benefits due to its high K, P, Na, and Zn content. Moreover, it is also a good source of Ca, which may be important for the elderly (Koh et al., 2014). Fermented sunsik has been found to show higher levels of antioxidative compounds, including γ-oryzanol, phenolic acids, and polyphenols, which are probably produced by Maillard reactions between amino acids and carbonyl compounds (Koh et al., 2014). Furthermore, sunsik fermentation breaks down proteins into amino acids, resulting in increased amino acid and GABA content. GABA content is notable since it is an inhibitory neurotransmitter that is active in the central nervous system (Koh et al., 2014).

Beverages prepared from germinated wheat may contain specific beneficial health components (Aung et al., 2023). For example, beverages prepared from germinated and roasted wheat were found to contain higher levels of bioactive components, including gallic acid, *p*-coumaric acid, ferulic acid, and caffeic acid. Moreover, they also exhibit higher antioxidant activity, as measured by both DPPH and TEAC (Aung et al., 2023). Wheat germination activates proteolytic enzymes, which liberate peptides, and free amino acids, whereas roasting germinated wheat transforms these amino acids into other bioactive components and phenolic acids.

CHALLENGES AND FUTURE PERSPECTIVES

One of the main limitations of using wheat for beverage production is the lack of appropriate processing techniques. In general, techniques such as milling, soaking, germination, roasting, and fermentation are suitable for wheat-based beverage preparation. However, preparation steps such as hydration and germination require long periods of time and high energy inputs to reach the desired moisture content and relative humidity. Therefore, clean technologies such as microwave irradiation, ozonation, ultrasound treatments, and pulsed electric field treatments may be required to enhance water uptake and/or subsequent germination (Polachini et al., 2023). Such technologies can reduce the hydration and germination periods, improve process kinetics, and enhance product quality. Therefore, modern processing technologies must be implemented to manufacture wheat-based beverages at scale.

In addition, the sensory perception of wheat-based beverages is a major concern for maintaining consumer interest. Proper technologies must be developed to remove "beany" flavors or undesired aromas in wheat-based beverages. Furthermore, most wheat beverages are currently produced using small-scale, innovative approaches, or using traditional methods. Commercial production can improve the economic sustainability of wheat-based beverage production. Finally, quality, safety concerns, and health benefits are understudied and should be emphasized further in the future.

In this review, we discuss the potential applications of wheat and wheat byproducts, such as wheat germ, and wheat bran, for the creation of unique and flavorful beverage formulations with beneficial health properties. Wheat, including its bran, and germ fractions, is a rich source of dietary fiber and bioactive components, including ferulic acids, gamma amino butyric acid, phytic acid, carotenoids, phytosterols, tocopherols, carotenoids, thiamin, and riboflavin. However, it is difficult to extract nutritional components due to the structural composition of wheat bran and germ. Therefore, pre-and/or post-treatments are required to enrich processed wheat materials in these components and to apply them during beverage production. Germination, roasting, and fermentation are commonly used techniques that have been evaluated in the scientific literature. However, the scientific evidence of the health-promoting properties of wheat beverages remains limited, as does the degree to which these properties can be preserved during commercial production. It is also crucial to emphasize the sensory acceptability and consumer awareness of the functional properties of these beverages. Further technologies and production methods are required to enhance these properties in both wheat- and wheat-derived beverages. In summary, this review addresses the potential of wheat-based functional beverages prepared using various processing techniques to facilitate research into novel functional beverage formulations.

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AUTHOR DISCLOSURE STATEMENT

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Concept and design: TA, MJK. Analysis and interpretation: TA. Data collection: TA. Writing the article: TA, MJK. Critical revision of the article: TA, MJK. Final approval of the article: all authors. Statistical analysis: TA. Obtained funding: MJK. Overall responsibility: MJK.

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