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Review Article

Biochemical Composition and Technological Applications of Cereal Bran: A Multi-Sectoral Review

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Abstract

Cereal bran, a major byproduct of grain milling, has traditionally been undervalued and used mainly as animal feed or discarded as waste. Emerging evidence, however, identifies cereal bran as a nutritionally dense and functionally versatile bioresource rich in dietary fiber, proteins, lipids, essential vitamins and minerals, and diverse bioactive phytochemicals. These constituents impart key technological properties, including water-holding, emulsifying, foaming, and gelling capacities, and contribute to health-promoting effects such as antioxidant, anti-inflammatory, hypolipidemic, glycemic-regulatory, and gut microbiotamodulating activities. This review summarizes the biochemical composition and functional potential of major cereal brans, namely wheat, rice, oat, rye, and maize. Recent advances in green processing technologiessuch as ultrasound- and microwave-assisted extraction, enzymatic treatments, fermentation, and non-thermal stabilizationhave significantly enhanced the recovery, bioavailability, and stability of bran-derived ingredients while reducing antinutritional factors and oxidative instability. Beyond food and nutraceutical applications, cereal bran is increasingly explored for biofuels, cosmetics, biodegradable packaging, and biorefinery-based products, supporting circular bioeconomy goals. Despite challenges related to processing costs, consumer awareness, and regulatory acceptance, cereal bran valorisation offers a sustainable pathway for waste reduction, resource efficiency, and value addition.

Key words: Bran valorisation, Green extraction technology, Dietary Fiber functionality, Biorefinery

1. Introduction

Cereal brans are substantial by products of grain milling, accounting for 10-20% of global cereal grain production, with an annual output of 2.1 billion metric tonnes from wheat, maize, corn, rice, millet, barley, and oats (Hadidi *et al.*, 2023). About 55% of the world's cereal waste is generated in Asia, where large quantities of inedible parts of grains (straws, husks, bran, and hard shells) are often discarded (Akanbi *et al.,* 2020). Despite being produced in substantial amounts during cereal grain processing, bran has been largely underexploited and commonly relegated to low-value uses such as animal feed or direct disposal (Tufail *et al.*, 2022).

Cereal bran is nutritionally rich, containing high levels of dietary fiber, proteins, lipids, essential vitamins and minerals, and a wide array of bioactive phytochemicals such as phenolic acids, flavonoids, sterols, and tocopherols. In addition to its nutritional value, bran exhibits important functional properties, including water-holding, oil-binding, emulsifying, foaming, and gelling capacities, which enhance its applicability in food formulations(Idris *et al.*, 2003, Hadidi *et al.*, 2023). Furthermore, accumulating evidence highlights its health-promoting effects, including antioxidant, anti-inflammatory, hypolipidemic, glycemic-regulatory, and gut microbiotamodulating activities (Zhu *et al.*, 2023). However, the view is shifting as research and industry increasingly recognize the nutritional and functional value of these byproducts, especially in the context of circular bioeconomy strategies and waste valorisation approaches. The bioeconomy refers to an economic system based on the sustainable production and conversion of renewable biological resources, including non-food biomass from plants and trees, through biorefinery processes to generate food, health-related products, biofuel, cosmetic formulation, biodegradable and edible packaging material (Ravichandran and Dixit, 2025).The circular bioeconomy represents a notable shift from the conventional linear take-make-use-dispose economic model, prioritizing the sustainable utilization of biomass and the conversion of waste streams into valuable products.

The literature considered in this review was identified through a structured search of major scientific databases, including Scopus, Web of Science, PubMed, and Google Scholar. Relevant keywords related to cereal bran, processing and extraction technologies, functional properties, and circular bioeconomy concepts were employed. Peer-reviewed original research articles, review papers, and selected reports published mainly over the past two decades were systematically screened and critically evaluated to identify prevailing research trends, existing knowledge gaps, and future research prospects.

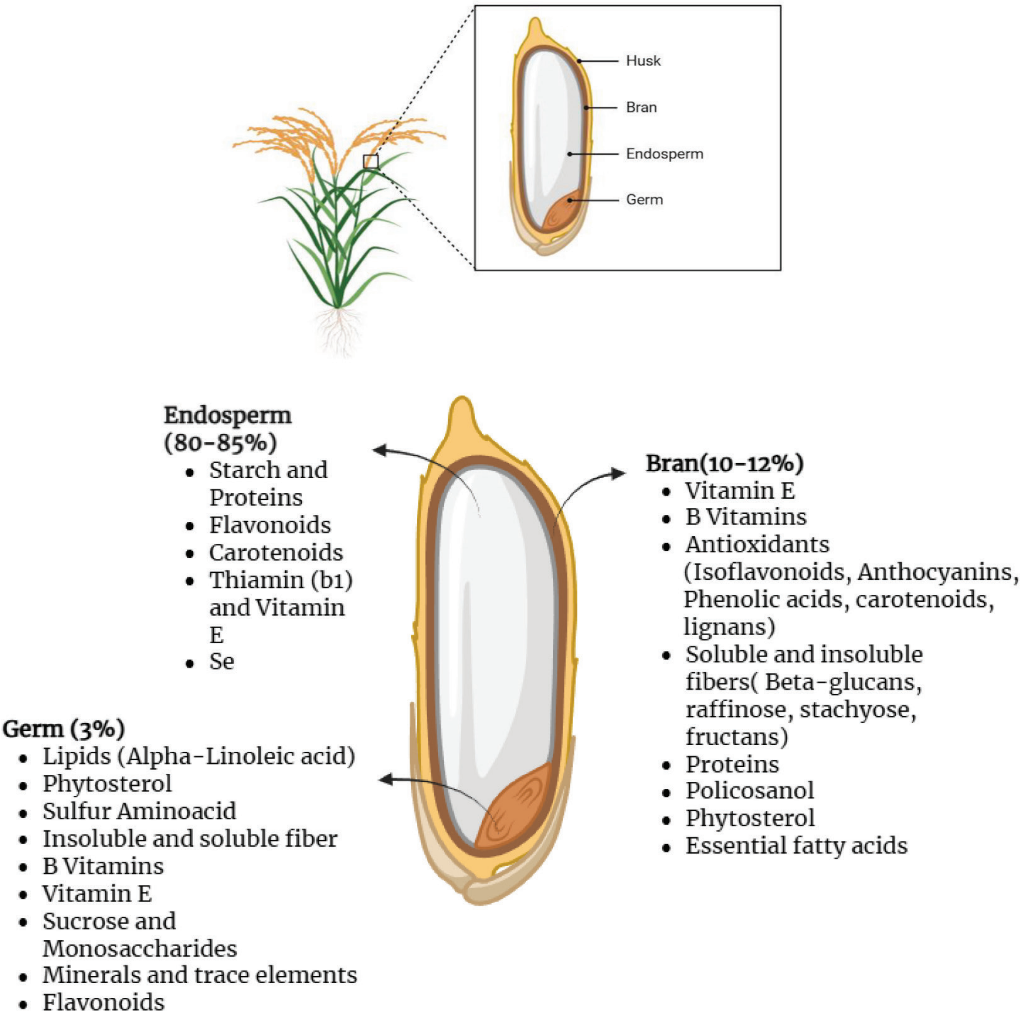

Figure 1: Diagrammatic illustration of the major anatomical (a) and nutritional (b) fractions of a cereal grain (Garutti *et al.,* 2022) (Illustrations were self-created using BioRender website)

2. Classification and Sources of Cereal Bran

One of the main byproducts of processing and milling cereals is cereal bran, which makes up the outer layers of grain kernels. In cereal species like wheat, rice, maize, barley, oats, sorghum, and millet, it contains the pericarp, testa, aleurone, and residual germ fractions. It is also rich in dietary fiber and bioactive chemicals. Despite its nutritional and physiological potential, bran is frequently overlooked and separated throughout the refining process(Borrelli and Ficco, 2025).

Depending on the grain source, bran is categorized as wheat bran, obtained from wheat milling and rich in insoluble fiber and B-complex vitamins (Viuda-Martos *et a*l., 2019).rice bran, produced during rice polishing and known for its oil, fiber and micronutrient content (Reema *et al*., 2021).maize (corn) bran, a fiber-dense by-product of corn processing.barley bran, valued for its β-glucan content.oat bran, which contains high levels of soluble fiber and protein (Luna-Vital *et al*., 2017).sorghum bran, recognized for its antioxidant and phenolic compounds and millet brans, derived from various millets and characterized by their fiber, mineral and phytochemical richness (Ahmad *et al*., 2018).

3. Biochemical Composition of Cereal Bran

Cereal bran contains substantial levels of dietary fiber, proteins, lipids, vitamins, minerals, and a range of bioactive compounds, including polyphenols and other phytochemicals (Qin *et al*., 2025). Its schematic representation is given in Figure 1. This diverse chemical profile contributes to multiple functional properties, such as water solubility, binding and emulsifying capacity, foaming and gelling behavior, and good thermal stability. These attributes are comparable to those of widely used plant-based protein ingredients, enabling cereal bran to play both nutritional and technological roles in food systems (Ma *et al*., 2024). In cereal bran, functional behavior is governed by protein-fiber interactions rather than protein concentration alone, allowing it to exhibit functionality comparable to plant protein ingredients in selected food applications (Hadidi *et al*., 2023).

Additionally, cereal brans exhibit notable therapeutic effects, including antioxidant, anti-inflammatory, hypolipidemic, and glycemic-regulating activities, largely attributed to their bioactive constituents (Table 1) (Nemes *et al.,* 2022). The proteins present in cereal bran are also recognized to be of good quality, underscoring their potential in both food and pharmaceutical applications, especially in the context of a growing global demand for sustainable protein sources as the population approaches an estimated 9.7 billion by 2050 (Hadidi *et al.,* 2023).

Although all cereal brans are rich in dietary fiber and bioactive compounds, notable differences exist in their nutritional composition and functional behavior. Wheat and maize brans are predominantly sources of insoluble fiber, whereas oat and barley brans are distinguished by their high soluble β-glucan content. Rice bran stands out due to its higher lipid and micronutrient concentrations, while sorghum and millet brans are particularly rich in phenolic compounds with strong antioxidant potential. These compositional differences influence their technological performance, health benefits, and suitability for specific food and industrial applications, underscoring the need for cereal-specific processing and valorisation strategies.

4. Functional and Physicochemical Properties

Cereal bran exhibits a wide range of physicochemical and functional properties that are critical for its utilization in food and nutraceutical applications. Physicochemically, bran components show variations in particle size, bulk density, solubility, swelling capacity, viscosity, and water- and oil-holding capacity, which strongly influence processing behavior, texture, and shelf stability of food products(Alan *et al*., 2012). These properties are mainly attributed to the structural features of dietary fibers such as arabinoxylans, cellulose, hemicellulose, and β-glucans, as well as associated proteins and phenolic compounds, which govern hydration, binding, and interactions with other ingredients (Ariyarathna *et a*l., 2025).

From a functional standpoint, cereal bran enhances water absorption, dough handling properties, and texture, while also contributing to fiber enrichment, antioxidant activity, and improved nutritional quality of foods. Its ability to bind water and lipids aids in fat replacement, moisture retention, and satiety enhancement, making bran a valuable functional ingredient in bakery, cereal-based, and health-oriented food formulations (Wang *et al*., 2020).

Table 1: Nutritional and functional attributes of major cereal brans

Cereal bran type	Macronutrient Profile	Key bioactive constituents	Documented Health benefits	References
Wheat bran	Moisture (12%), protein (13%), Fat (3.5-3.9%), Carbohydrates (56%)	Dietary fibers, polyphenolic compounds, sterols, lignans, pytic acids, beta glucans, tocopherol, essential fatty acids	Gastrointestinal benefits, reduce the risk of metabolic disorders and cardiovascular disease, Anticancer properties	Viuda-Martos *et al.*, 2019 Deroover *et al.*, 2019
Rice bran	Protein (11-17%), Fat (12-22 %), Dietary fiber (10-15%), Ash (8-17%), Carbohydrate (60%)	Alpha- Oryzanol, tocopherols, tocotrienols, phytosterols, phospholipids, squalene, phenolics	Exhibits antioxidant, anticancer, anticholesterolemic properties, supports metabolic and digestive health	Reema *et al.*, 2021 Tan *et al.,* 2023
Oat bran	Starch (60%) Lipid (5-9%) Dietary Fibers (2.3-8.5%) α-Tocotrienols and α-tocopherols Iron: 0.047 % Calcium: 0.54 %	Soluble β-glucans, antioxidants, vitamins, minerals	Improves cholesterol levels, supports glycemic control, enhances satiety and reduce colorectal cancer risk	Paudel *et al.*, 2021
Rye bran	Rich in dietary fiber (14-21%), especially arabinoxylan (AX), fructans, cellulose	Phenolic acids (ferulic, sinapic, p-coumaric, caffeic), flavonoids (flavones, anthocyanidins)	Strong antioxidant and anti-inflammatory action; potential anticancer effects (e.g., prostate cancer); enhances functional food properties	P and Joye, 2020
Maize (Corn) bran	Starch (9-23%), protein (10-13%), lipids (2-3%), Ash (2%)	Dietary fiber (heteroxylans) Phenolic compounds (Ferulic acid, vanillic acid, caffeic, p-coumaric), Pigments (Anthocynnins)	Offers strong antioxidant and antimicrobial potential, supports digestive health	Hussain *t al.,* 2024, Viuda-Martos *et al.*, 2019, Luna-Vital *et al.*, 2017

5. Technological Processing of Cereal Bran

However, due to the high lipase and lipid content, they are prone to rapid rancidity, making stabilization essential to maintain nutritional quality and shelf-life. Stabilized bran enables safe and consistent utilization in health-oriented food products (Kittur *et al.,* 2024). Green stabilization methods for cereal and millet brans include non-thermal processes like high-pressure processing, ultrasound, and pulsed electric fields, which inactivate lipase while preserving nutrients. Eco-efficient mild thermal techniques, such as microwave and infrared heating, also reduce rancidity with lower energy use. They are termed green because they reduce energy intensity, avoid chemical stabilization, preserve nutritional quality, and enable sustainable valorization of cereal by-products. These approaches maintain bran's nutritional and functional value for safe food application (Preeti *et al.,* 2025).

6. Applications of Cereal Bran in Different Sectors

Precise global distribution data on cereal bran utilization are not uniformly reported, multiple studies indicate that animal feed remains the dominant application, with increasing integration into food (mainly oil extraction from rice bran and bakery) and nutraceutical products due to its dietary fiber and phytochemical profile. Meanwhile, specialized applications in protein hydrolysate production, cosmetic formulations, and biorefinery processes are emerging and gradually expanding. Several researchers are working to extract and use these components more efficiently, while also addressing challenges like antinutritional factors, poor digestibility, and potential allergenic effects (Skendi *et al.*, 2020).

Recent advances in processing technologies have made it easier to isolate beneficial compounds such as antioxidants, phenolics, vitamins, dietary fiber, and enzymes. These extracted ingredients are finding applications in a wide range of industries, including food and nutraceuticals, animal feed, pharmaceuticals, cosmetics, and even the development of biodegradable packaging materials. Innovative methods such as ultrasound-assisted (Martins *et al.,* 2023), microwave-assisted (Bitwell *et al.*, 2023), and enzyme-assisted extraction (Streimikyte *et al.*, 2022) have shown better efficiency and lower resource use than traditional chemical extraction, making the process more environmentally and economically sustainable (Tufail *et al.,* 2022).

6.1 Food

Cereal and millet brans are incorporated into bakery items, beverages, and functional food formulations to enhance dietary fiber, protein, and bioactive content. Water-extractable arabinoxylan from rye bran has been employed for the microencapsulation of honey, resulting in enhanced antioxidant activity, improved biostability and increased bioavailability of the encapsulated bioactive compounds, while also reducing the amount of carrier material required (Kowalska *et al.*, 2021). Dephytinized rye bran has been utilized to enrich pasta, leading to increased ash, protein and fat content, as well as elevated total phenolic content and antioxidant activity in the final product (Levent *et al.*, 2020). Dry rye bran and rye bran treated with hydrolytic enzymes and fermented with baker's yeast were partially incorporated into wheat flour during bread production, leading to a substantial increase in free phenolic acids, with over a 100-fold rise in ferulic acid content in bread enriched with both bioprocessed and unprocessed bran (Koistinen *et al.*, 2016). Fermented and acidified rye bran was applied as an additive to rye flour extrudates, improving texture by reducing hardness and increasing crispness, while also elevating the soluble dietary fiber content. Rye bran was used to partially replace 20% and 40% of corn grits in snack production, producing final products with increased dietary fiber content (average 9.04%) (Nikinmaa *et al.,* 2020)

6.2 Bio fuel

Cereal bran, as a lignocellulosic by-product of grain milling, offers potential as a renewable feedstock in integrated biorefinery systems. Its cellulose and hemicellulose fractions can be converted into fermentable sugars for bioethanol, while the lipid-rich fraction of rice bran has been investigated for biodiesel and hydrotreated fuel production, offering a sustainable alternative to fossil fuels in second-generation biofuel strategies(ElMekawy *et al.*, 2013).

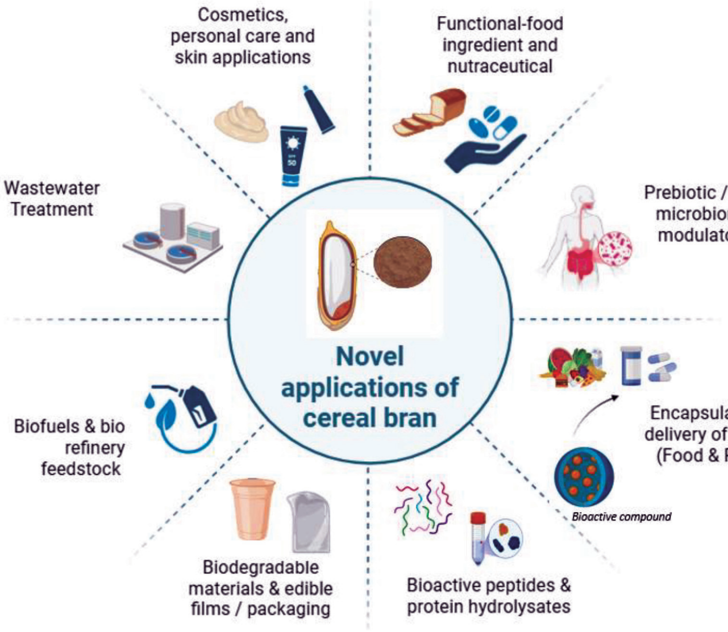

Figure 2: Multifaceted applications of cereal bran

(Illustration was self-created using BioRender website)

Rye bran is a promising feedstock for bioethanol production due to its high content of fermentable sugars, including glucose, xylose and arabinose. Acid enzymatic hydrolysis of rye bran has been shown to yield significant amounts of these sugars, which serve as effective substrates for microbial fermentation and biofuel production. Studies have shown that cereal bran can serve as an effective binder in biofuel pellet production. Rye bran mixed with sawdust improves pellet quality, increases calorific value, reduces ash content and lowers granulator power requirements (Obidziński *et al.*, 2021).

Wheat bran has also been used as an additive with cherry stones, enhancing pellet quality and supporting its role in sustainable biofuel production. Additionally, rye bran has been utilized in the production of cellulose nanocrystals (CNCs), which can be used as reinforcing agents in composite materials, contributing to sustainable energy and material production (Dziki, 2022).Wheat bran contains a significant amount of dietary fiber and bioactive compounds, making it a potential source for bioethanol production. Pretreatment methods such as acid and alkaline treatments have been applied to wheat bran to enhance its bioactive composition and antioxidant activity, which can be beneficial in biofuel production processes (Nemes *et al.*, 2024).

Yeast fermentation of rice bran, rice polish, and de-oiled rice bran not only improves their nutritional quality but also generates ethanol, highlighting their potential as substrates for biofuel production within cereal-based biorefinery systems(Islam *et al.*, 2025).

6.3 Cosmetics

Bran derivatives such as wheat bran extracts and rice bran oil contain antioxidant, emollient, and bioactive compounds that support their use in cosmetic applications. These include enhanced emulsion stability, skin-whitening effects, enzyme inhibition relevant to anti-aging, and improved skin hydration and elasticity, making them promising natural ingredients in skincare formulations. Rye bran is rich in bioactive compounds such as phenolic acids, alkylresorcinols, and lignans, which have antioxidant and anti-inflammatory properties. These compounds make rye bran a valuable ingredient in cosmetic formulations aimed at skin protection and anti-aging. Fermentation and enzymatic processing of rye bran have been shown to enhance the bioavailability of these bioactive compounds, further increasing its potential in cosmetic applications(Zduńska *et al.*, 2018). Rye bran has been utilized as a substrate for the production of enzymes, such as cellulases and hemicellulases, capable of hydrolyzing various lignocellulosic materials. These enzymes release reducing sugars, which can be further employed for bioethanol and other biofuel production. In addition, enzymatic processing of rye bran can enhance the recovery of bioactive compounds, including phenolics and antioxidants, which have potential applications in food and cosmetic industries (Mihajlovski *et al.,* 2020).

Wheat bran extracts (WBEs) have gained attention in the cosmetics industry due to their antioxidant, enzyme-inhibitory and anti-aging properties. WBEs have demonstrated the potential to enhance the stability of cosmetic emulsions, improve skin hydration and inhibit enzymes linked to skin aging, positioning WBEs as potentially natural alternatives to synthetic ingredients in skincare and anti-aging products (Kobayashi *et al.,* 2025). Recent research indicates that wheat bran extracts (WBEs) can inhibit enzymes such as collagenase and elastase, which are responsible for the degradation of structural proteins in the skin. This enzymatic inhibition may help slow the skin-aging process. Moreover, the synergistic interaction of multiple bioactive compounds present in wheat bran is likely to enhance its overall anti-aging effects, surpassing the impact of individual constituents (Mikhailova *et al.*, 2023).

Cereal bransincluding those derived from rice, maize (corn), barley, oats, and sorghumhave attracted increasing attention for their applicability in cosmetic and bioenergy-oriented valorization pathways. Among these, rice bran is particularly notable due to its relatively high lipid content and the presence of distinctive bioactive compounds such as γ-oryzanol, tocopherols, tocotrienols, and diverse phenolic constituents, which impart antioxidant, photoprotective, and skin-conditioning properties and have facilitated its incorporation into a range of cosmeceutical formulations (Fărcaș *et al.*, 2021). Maize bran, characterized by a high proportion of insoluble dietary fiber and associated phytochemicals, also contains antioxidant compounds that may function as stabilizing or protective agents in topical applications(Galanakis, 2022). Similarly, barley bran provides significant levels of β-glucans and phenolic acids, which have been associated with antioxidant and skin-beneficial effects and are being explored for use in cosmetic and biomaterial contexts (Feng *et al.*, 2024). Oat bran is distinguished by its content of soluble β-glucans and unique phenolic compounds such as avenanthramides, which exhibit anti-inflammatory and soothing activities and have found application in dermatological products designed for sensitive or compromised skin. In addition, sorghum bran, rich in diverse flavonoids and phenolic acids, presents further opportunities for cosmetic utilization owing to its antioxidant and potential UV-protective properties(Tufail *et al.,* 2022).

6.4 Edible packaging

The food industry widely adopts biodegradable materials for their ability to protect products during storage and transport. Owing to their biodegradability, low toxicity and biocompatibility, these materials serve as sustainable alternatives to conventional packaging, helping reduce carbon emissions and energy use (Shao *et al.*, 2021).

A recent study investigated the development of biobased nanocomposite films for food packaging by incorporating cellulose nanocrystals (CNCs) extracted from rye bran into a rye arabinoxylan matrix. The incorporation of CNCs significantly enhanced the films' thermomechanical properties, including tensile strength and elasticity, while maintaining competitive water vapor permeability. Furthermore, the films demonstrated excellent optical transparency and uniform microstructure, indicating their potential as sustainable, high-performance edible or biodegradable packaging materials for food applications (Trifol *et al.*, 2025). Research has explored advancements in biodegradable food packaging materials derived from wheat. These materials offer a sustainable alternative to conventional single-use plastics through their starch, gluten and fiber components. The study highlights fabrication processes such as solvent casting and extrusion, demonstrating their potential in enhancing the shelf life and quality of packaged foods (Alibekov *et al.*, 2024). Purwoto *et al.* (2021) developed edible films using rice bran blended with starch and carrageenan, optimized through Response Surface Methodology and reported improved tensile strength, flexibility and moisture barrier properties suitable for candy packaging. Together, these studies demonstrate the versatility of cereal brans inadvancing eco-friendly packaging solutions.

Ochoa-Yepes *et al.* (2022) reported the development of edible films through extrusion of cassava starch incorporated with varying levels of wheat or oat bran. Incorporation of wheat bran at approximately 10% notably enhanced the films' mechanical properties, including Young's modulus, tensile strength and toughness, while simultaneously lowering moisture content. Importantly, these improvements were achieved without compromising the films' thermal stability or biodegradability. Another study explored the development of composite films formulated from barley bran protein and gelatin, with the addition of grapefruit seed extract as a natural antimicrobial agent. Application of these films in salmon packaging demonstrated a marked reduction in *Escherichia coli* and *Listeria monocytogenes* populations over a 15-day storage period, highlighting the potential of barley branbased protein films as active packaging materials for enhancing food safety and extending shelf life. Highland barley bran has been utilized as a substrate for fermentation with *Aureobasidium pullulans* to produce polysaccharide-based films. Post-fermentation evaluation revealed notable enhancements in polysaccharide content, along with improved barrier, rheological and mechanical characteristics. These modifications collectively increased the functional suitability of the films for applications in edible and biodegradable food packaging (Liu *et al.*, 2020).The potential of cereal brans extends across various domains, including functional foods, nutraceuticals, cosmetics, biofuel production and edible packaging. Their use contributes to improved nutritional and functional properties while supporting sustainable practices through the valorization of agro-industrial by-products.

7. Health Benefits Associated with Cereal Bran Consumption

Cereal bran is a great source of dietary fiber and a number of bioactive substances that are important for human health, such as flavonoids and polyphenols. Strong antioxidant activity, better gut health, and a lower risk of non-communicable diseases are all linked to these constituents (Table 3). Cereal bran intake had no significant impact on HDL-cholesterol, triglycerides, waist circumference, or BMI, but contributed to reductions in blood pressure, total and LDL-cholesterol and fasting blood glucose. Oat bran, in particular, was effective in improving lipid profiles in dyslipidemic individuals and lowering blood pressure in obese or hypertensive patients (Punia *et al.,* 2021; Zhu *et al.*, 2023).

Rice bran has been reported to contain around 34% cellulose and 22% hemicellulose. The impact of natural cellulose on human energy intake, glycemic regulation and lipid metabolism remains largely unclear. In contrast, modified celluloses, such as high-viscosity hydroxypropyl methyl cellulose, have shown consistent health benefits. By increasing intestinal viscosity, limiting nutrient absorption and enhancing bile acid excretion, these modified fibers act similarly to soluble dietary fibers (Kulathunga *et al.*, 2023). Given its high cellulose content, cereal bran holds significant potential as a functional ingredient for fiber-enriched foods and nutraceuticals designed to support metabolic health (Sapwarobol *et al.,* 2021). Arabinoxylans, abundant in cereal brans like wheat, rice and oats, are hemicellulosicfibers known for their health benefits. They improve glycemic control, act as prebiotics by promoting beneficial gut microbiota, exhibit antioxidant and anti-inflammatory properties and may enhance immune function (Kulathunga *et al.*, 2023).

Wheat bran extracts (WBEs) consistently demonstrated a significant presence of phenolic compounds and antioxidant activity. Wheat bran is rich in phenolic compounds, notably ferulic acid, which exhibits potent antioxidant properties. These bioactive molecules help scavenge free radicals, thereby mitigating oxidative stress and potentially slowing cellular aging and the development of related diseases(Rudrapal *et al.,* 2022).

8. Sustainability and Circular Economy Perspective

Reframing cereal bran as a renewable, multifunctional ingredient rather than a waste product reflects a broader shift toward sustainable resource use. Within cereal processing systems, the concept of a circular bioeconomy can be operationalized through a bran-centeredbiorefinery approach, wherein cereal bran generated as a co-product of conventional milling is repositioned as a strategic feedstock for cascading valorization rather than a terminal by-product. Cereal bran is characterized by a complex biochemical composition, including dietary fibers, proteins, phenolic compounds, and fermentable carbohydrates, which enables its integration into sequential, multi-sectoral value chains spanning food, feed, material, and energy applications(Skendi *et al.,*

Table 3: Nutritional and therapeutic potential of bran fractions from major cereals

Functional food	Study design	Dose	Duration	Major outcomes	References
Rice bran oil	Randomized, open-label trial in Metabolic syndrome patients	30 g/day	8 weeks	Rice bran oil (RBO) supplementation significantly improved lipid and glycemic profiles by lowering total cholesterol, low-density lipoprotein cholesterol (LDL-C), fasting blood glucose and increasing high-density lipoprotein cholesterol (HDL-C). It also reduced malondialdehyde (MDA), metabolic score for insulin resistance (METS-IR) and triglyceride-glucose body mass index (TyG-BMI), with a marked rise in total antioxidant capacity (TAC), while showing no significant effects on body mass index (BMI), waist circumference, serum triglycerides, plasma polyphenols, or blood pressure.	Mahdavi-Roshan *et al.,* 2024
Wheat bran	Four groups of rats (7 rats each) were randomly assigned.	NC: Standard chow with grains, protein sources, oils, and micronutrients.	5 weeks	Body weight: Both treatment groups (LT and HT) showed a reduction in average body weight, with the HT group exhibiting a significant decline.	Junejo *et al.,* 2019

	Normal chow (NC) High-fat diet (HFD) Low treatment (LT) High treatment (HT)	HFD: Normal chow and egg yolk, pig oil, cholesterol and bile salts. LT: HFD supplemented with 100 g/kg superfine wheat bran. HT:HFD supplemented with 200 g/kg superfine wheat bran.		Lipid profile: Total cholesterol (TC) reduced by 3.75% (LT, 10% superfine wheat bran) and 19.03% (HT, 20% superfine wheat bran). Triglycerides (TG) reduced by 10.34% (LT) and 23.77% (HT). Low-density lipoprotein cholesterol (LDL-C) decreased by 13.45% (LT) and 18.07% (HT). High-density lipoprotein cholesterol (HDL-C) increased by 20% (LT) and 34.18% (HT). Oxidative stress: Malondialdehyde (MDA) levels decreased by 4.38% (LT) and 23.65% (HT), indicating reduced lipid peroxidation. Liver health: Superfine wheat bran supplementation reduced liver total cholesterol (TC), triglycerides (TG) and malondialdehyde (MDA), and improved liver structure compared to the high-fat diet (HFD) group.	
Brown rice bran powder (BRBP)	Open-label, controlled trial with 50 participants diagnosed with metabolic syndrome, randomly assigned.	Control group: Standard diet (SDiet) Intervention group: SDiet + 15 g/day BRBP	8 Weeks	Body weight and waist: Significant reductions in BMI and waist circumference in the BRBP group. Lipid profile: Total cholesterol and LDL-cholesterol decreased; HDL-cholesterol and triglycerides lower significantly. Blood sugar and insulin resistance: Fasting blood glucose and BMI index were significantly lower in the BRBP group. Antioxidant status: Activities of glutathione peroxidase and superoxide dismutase increased. Gastrointestinal health: Constipation was reduced. No significant change: Blood pressure, glutathione, catalase and triglycerides.	Ghorbani *et al.,* 2024
Rice bran	A pilot, double-blind, randomised placebo-controlled trial	30 g/day	24week	The intervention significantly enhanced the intestinal abundance of Firmicutes. There was also a tendency for an increase in Lactobacillus. The intervention group showed a slight increase in the Firmicutes/Bacteroidetes ratio after 24 weeks of rice bran consumption, while the control group's Firmicutes/Bacteroidetes ratio decreased. The intervention had no significant effect on the intestinal abundance of pathogenic bacteria such as Fusobacteria	So *et al.,* 2021
Wheat bran extract Arabinoxylan-Oligosaccharide	Randomized, placebo-controlled, double-blind study	15 g/day	12 Week	Improved stool consistency, altered gut microbiota (Increased Bifidobacterium) and improved postprandial glycemia compared to control.	Müller *et al.,* 2020

2020). In this framework, material flows originate from existing milling infrastructure, with bran streams subjected to downstream stabilization and fractionation processes that enable the separation of high-value components for primary valorization, such as functional food ingredients and nutraceutical extracts, while residual fractions are redirected toward secondary valorization streams, including fermentation-based biofuels, biochemicals, or biomaterials. This sequential utilization establishes a value-cascade hierarchy that prioritizes applications with higher economic and nutritional returns before lower-value energy recovery, thereby improving overall resource efficiency and reducing premature downcycling (Nemes *et al.*, 2022). Importantly, such cascading strategies can be integrated into existing milling operations with minimal structural modification, as they rely on downstream processing of already segregated bran streams rather than upstream changes to grain processing (Skendi *et al.*, 2020). Moreover, targeted extraction of food-grade compounds enhances the suitability of remaining biomass for non-food applications, creating functional synergies between food and industrial uses rather than direct competition (Tufail *et al.*, 2022). Nevertheless, competition among food, feed, fuel, and material uses necessitates prioritization strategies informed by economic value, nutritional impact, and regulatory constraints, particularly those governing food safety, solvent usage, and product classification, which collectively shape the feasibility of circular deployment of cereal bran within bioeconomy systems (Fărcaș *et al.*, 2021).

9. Challenges and Limitations

The broader use of cereal bran is limited by several factors. Inefficient debranning and processing equipment reduces production effectiveness, while the high costs of extracting bran oils and bioactive compounds make them less economically attractive compared to conventional sources. In addition, insufficient research on the safety, bioavailability and health benefits of bran restricts its market acceptance. Low awareness among consumers and industry stakeholders regarding its nutritional and functional value further hinders adoption. Cultural and social perceptions in certain populations may also discourage their use in human diets (Kittur *et al.*, 2024). Overcoming these barriers through the development of cost-efficient processing methods, comprehensive safety and efficacy studies and targeted consumer education could facilitate the wider application of cereal bran in food, nutraceutical and industrial contexts.

10. Future Prospects and Research Gaps

Cereal bran shows strong potential as a sustainable value-added ingredient, with future work focusing on processing strategies to improve its functional and nutritional qualities. Nonetheless, progress is constrained by poor standardization, limited research on underutilized cereals, and inadequate *in vivo* and clinical validation, which need to be addressed for broader application (Tufail *et al.*, 2022).

11. Conclusion

Cereal bran constitutes a nutritionally and technologically important by-product of cereal processing, distinguished by its rich biochemical profile, including dietary fiber, bioactive phytochemicals, vitamins, minerals, and antioxidant compounds that collectively contribute to its functional and health-related attributes. From a technological standpoint, its physicochemical and functional properties, such as water and oil binding, swelling capacity, and interactions with food matrices, support its application in food formulation, fiber fortification, and textural modification. Beyond food systems, cereal bran demonstrates substantial multi-sectoral relevance, with expanding applications in nutraceuticals, animal nutrition, bioenergy, and bio-based materials, thereby enhancing value addition across agri-food and industrial sectors. In this regard, the sustainable valorization of cereal bran through appropriate processing and biotechnological strategies aligns with circular bioeconomy principles, enabling waste minimization and resource efficiency. Overall, continued research, technological innovation, and standardization are critical to fully exploit cereal bran as a versatile, sustainable, and high-value bioresource.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

Author Contributions

All authors contributed equally to the conception, execution, analysis, and writing of the manuscript.

Ethical Approval

Ethical approval was not required for this study as it did not involve human or animal subjects.

Generative AI or AI/Assisted Technologies use in Manuscript Preparation

No

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