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**Cereal by-products, a potential medium for microorganisms and human health**

**Abstract**

Cereal by-products, including bran, germ, husk, and brewer’s spent grain, are nutrient-rich residues produced during cereal processing. Traditionally considered waste or relegated to animal feed, these by-products have gained recognition for their valuable nutritional composition, containing dietary fibers, essential minerals (iron, zinc, copper, magnesium), B-complex vitamins, and bioactive compounds such as phenolics, lignans, and phytoestrogens. These constituents contribute significantly to human health by exhibiting antioxidant, anti-inflammatory, and cholesterol-lowering properties. Furthermore, cereal by-products present a promising low-cost substrate for microbial cultivation due to their abundance in complex carbohydrates, proteins, and fermentable sugars. Microorganisms such as lactic acid bacteria, yeasts, and fungi thrive on these substrates, facilitating the production of bioactive metabolites, enzymes, organic acids, and probiotics. Their use spans multiple sectors including food, agriculture, pharmaceuticals, and biofuels, aligning with the goals of sustainable development and circular economy. Valorization of cereal by-products not only reduces environmental pollution and agro-industrial waste but also enhances economic efficiency by opening new revenue avenues. This review emphasizes the nutritional and functional properties of cereal by-products, their potential to support microbial growth, and their contribution to sustainable industrial innovations, while also highlighting the need for future research on formulation development and fermentation optimization.

**Keywords**  
Cereal by-products, microbial substrate, sustainable development, circular bioeconomy, agro-industrial waste, bioactive compounds

**Introduction**

Cereals are the edible seeds of the Poaceae family of grasses, also referred to as Gramineae grown for their edible grain, a fruit-seed combo where starchy endosperm and nutrient-rich layers surround the plant embryo. Cereals that are most significant to the world economy are rye, wheat, corn, rice, barley, sorghum, millet and oats (Shavanov 2021). Among these, rice and wheat are the most common crops in Asian and Western nations, respectively (Samal *et al* 2022). With a production of over 2 billion tonnes annually, cereals are among the most significant food sources for human consumption. Unfortunately, for a variety of reasons, about 30% of this amount is lost or wasted (Łaba *et al* 2022).

The agro-industrial sector is a significant contributor to global food production, but it also generates large quantities of waste, particularly in the form of cereal by-products. These by-products, including wheat bran, rice bran, corn husks and barley husks, are often underutilized despite their rich nutrient content (Skendi *et al* 2020). Conventional microbial growth media, such as synthetic or refined substrates, can be expensive and resource intensive. Therefore, exploring alternative, cost-effective and sustainable sources for microbial cultivation has gained increasing attention in recent years (Kumari and Rani 2024).

Microorganisms play a crucial role in various industries, including agriculture, biotechnology, pharmaceuticals and environmental management. They are extensively used in fermentation processes, biofertilizer production, bioremediation and probiotic formulations (Kalsoom *et al* 2020). However, the high cost of traditional microbial culture media, such as nutrient-rich broths and agar-based formulations, limits their large-scale application. The utilization of cereal by-products as microbial substrates presents an eco-friendly and economical alternative, reducing production costs while simultaneously addressing the challenge of agricultural waste disposal (Kumari and Rani 2024).

Cereal by-products contain essential nutrients that support microbial growth, making them an excellent substrate for use as microbial culture media. Their use not only helps in reducing agro-industrial waste but also provides an economical means for large-scale microbial production in various industries including biofertilizers, probiotics, bioremediation and fermentation-based industries (Galanakis 2022). Additionally, the incorporation of cereal by-products in microbial cultivation aligns with the principles of circular economy and sustainable agriculture by promoting waste valorization (Skendi *et al* 2020).

Recent studies have demonstrated that cereal by-products can enhance microbial biomass yield and metabolic activity, making them a promising substrate for industrial microbial applications. However, challenges such as compositional variability, potential contamination and standardization of culture conditions need to be addressed for their effective implementation. This review aims to comprehensively explore the potential of cereal by-products as microbial growth media, highlighting their nutritional composition, applications in various industrial sectors, challenges and future research directions. Understanding the feasibility and optimization of cereal by-products as microbial substrates will contribute to more sustainable biotechnological advancements and agricultural practices.

**1. Nutritional composition of cereal by-products and its importance for human health**

Cereal processing generates a wide range of by-products that are rich in valuable nutrients and bioactive compounds. Among these, the by-products from dry milling such as bran, germ and the aleurone layer of the endosperm are particularly noteworthy (Fărcaș *et al* 2021). These components are abundant in dietary fiber, essential minerals (such as iron, zinc, copper and magnesium), B-complex vitamins, lignans, phytoestrogens and phenolic compounds (Mittu *et al* 2023). Such compounds are known for their antioxidant, anti-inflammatory and cholesterol-lowering properties, which contribute to the prevention of chronic diseases like cardiovascular disorders, diabetes and certain cancers (Rawat *et al* 2023). The actual nutritional composition of these by-products can vary significantly depending on the cereal type and the milling method (wet or dry). However, all these fractions retain a high concentration of nutrients that make them far more than agricultural residues. Traditionally, they used as livestock feed, these nutrient-dense materials are now increasingly recognized as valuable ingredients for human consumption and industrial applications. By-products from cereal-related processes such as malting, brewing and distilling have also gained attention for their potential in food, feed, pharmaceutical, cosmetic and biofuel industries. Their use supports the development of functional foods, nutraceuticals, biodegradable packaging materials and prebiotic formulations (Skendi *et al* 2020). Moreover, utilizing cereal by-products contributes to environmental sustainability by minimizing agro-industrial waste and promoting circular economy practices. Economically, the valorization of cereal by-products adds value to the agro-food supply chain, reduces waste disposal costs and offers new revenue streams for processors and farmers. Thus, understanding and leveraging the nutritional potential of these by-products not only promotes human and environmental health but also fosters innovation in food systems and sustainable development strategies (Dar 2024).

**1.1. Rice by-products**

Rice by-products are valuable agro-industrial residues generated during the dehusking and pearling of paddy. These include the **pericarp, seed coat, aleurone layer, partial endosperm, and embryo**. Approximately **30% of the paddy grain** constitutes by-products, including **husk (20%)**, **bran (8%)**, and **germ (2%)**. Among these, **rice bran** is particularly important due to its exceptional nutritional and functional profile. Rice bran is rich in macronutrients, comprising **11–18% fat**, **11–17% protein**, **10–14% dietary fiber**, **~9% ash**, and **45–60% nitrogen-free extract**. It also contains a dense concentration of **essential micronutrients** such as **magnesium (Mg), potassium (K), iron (Fe), manganese (Mn)**, **B vitamins**, **choline**, and **inositol** (Devi *et al* 2021). Moreover, trace elements like **zinc, calcium, sodium**, and **aluminum** are also present in substantial quantities, making it a potential supplement for addressing micronutrient deficiencies. The **bran layer holds the majority of the grain’s lipids**, but these are prone to oxidation due to enzymatic activity. To prevent **rancidity** and preserve the nutritional quality, early stabilization through **moisture reduction** and **thermal or enzymatic inactivation** is critical (Dubey *et al* 2019). Rice bran also harbors numerous **bioactive phytochemicals**, including **γ-oryzanol, tocopherols, tocotrienols, and phytosterols**, which exhibit **antioxidant, anti-inflammatory, anti-hyperlipidemic** and **anti-carcinogenic** properties. Compared to conventional vegetable oils, **rice bran oil contains higher concentrations of these minor constituents**, thereby providing additional **health benefits**, such as **reducing serum cholesterol**, **enhancing lipid metabolism**, and **preventing cardiovascular diseases** (Mutha and Maharana 2024). Importantly, **rice bran is gluten-free**, making it suitable for individuals with celiac disease or gluten sensitivity (Park and Kim 2023). Moreover, recent studies have identified **bioactive peptides** in rice bran that help **regulate blood pressure, oxidative stress, and insulin resistance**, indicating its promise in **managing hypertension and type 2 diabetes** (Saji *et al* 2019). From an **industrial perspective**, rice bran and its derivatives are being explored for use in:

* **Functional foods** and **nutraceuticals**
* **Pharmaceutical formulations** (e.g., γ-oryzanol-based supplements)
* **Biodegradable packaging**
* **Cosmetic applications** (anti-aging creams, sunscreens)
* **Biofuels** (conversion of rice bran oil into biodiesel)

Furthermore, the **valorization of rice by-products** contributes to a **circular economy**, minimizing agro-industrial waste and enhancing the economic sustainability of rice processing industries. This approach not only reduces environmental burden but also provides an opportunity to develop high-value products from low-cost raw materials (Kumari and Rani 2024).

**1.2. Wheat by-products**

Wheat bran (WB), a major by-product of wheat milling, is a nutritionally dense component rich in vitamins, carbohydrates, proteins, lignans, phenolic acids, alkylresorcinols, and dietary fibers. These compounds contribute significantly to the enhancement of the nutritional value of meals and are especially beneficial when incorporated into daily diets (Babu *et al* 2018). Due to its rich composition, WB is considered a natural, economical and sustainable source of value-added ingredients for the development of functional foods or the fortification of commercial products (Kumari and Rani 2024). One of the most significant attributes of wheat bran is its abundance of antioxidants, which not only enhance the safety, quality and shelf life of food products but also provide protective health benefits. These antioxidants scavenge free radicals, thereby interrupting oxidative chain reactions that contribute to chronic diseases such as cancer, cardiovascular diseases, neurodegenerative disorders (e.g., Parkinson’s disease), cell damage, and accelerated aging (Zou *et al* 2021). Lignan metabolites in WB exhibit anticancer effects and act as phytoestrogens, helping to modulate estrogen levels in the body. WB is also an excellent source of both soluble and insoluble dietary fiber, known to reduce blood plasma cholesterol, promote bowel regularity, and aid in the prevention of colorectal cancer (Zhao *et al* 2020). The inclusion of WB in the human diet has been associated with risk reduction for metabolic disorders and improved gastrointestinal health. The phenolic compounds in wheat bran play a critical role in preventing copper-induced oxidation of low-density lipoprotein (LDL) cholesterol, a primary cause of atherosclerosis that may lead to coronary heart disease. These phenolics interact with apolipoproteins, preventing copper from binding to or remaining on the LDL surface (Laddomada *et al* 2015). Furthermore, WB is a source of betaine and choline, which help protect organs against osmotic stress and regulate vascular risk factors. Betaine, in particular has been linked to reduced risk of coronary heart disease. WB also contains a variety of lipid-soluble compounds and phytochemicals, including tocopherols, phytosterols, and phytates. Among them, phytates have drawn significant attention due to their role in inhibiting colon cancer development (Suhag *et al* 2021).

**1.3. Oats by-products**

Oat bran, the outer layer of the oat grain (Avena sativa) that remains after removing the inedible hull, is a nutrient-dense by-product of oat milling. It is rich in dietary fiber, antioxidants, essential vitamins and minerals, making it a valuable component in the formulation of functional and health-promoting food products. Due to its balanced nutritional profile, oat bran is often considered more beneficial than conventional cereals, being higher in fiber and protein while lower in calories, despite having comparable fat and carbohydrate content (Paudel *et al* 2021). One of the most notable bioactive compounds in oat bran is beta-glucan, a water-soluble dietary fiber known for its viscous gel-forming property in the digestive tract. This characteristic aids in slowing digestion and glucose absorption, thereby helping to regulate blood sugar levels and enhance satiety (Mathews *et al* 2020). Moreover, beta-glucans are involved in reducing blood cholesterol by promoting the excretion of bile acids, which are rich in cholesterol, ultimately lowering the risk of cardiovascular disease. In addition to fiber, oat bran contains polyphenolic compounds with strong antioxidant activity. These phytochemicals protect the body against oxidative stress by neutralizing free radicals, which are implicated in the development of chronic conditions such as diabetes, cancer, and cardiovascular disorders (Sirotkin 2023). Furthermore, oat bran is a source of micronutrients including vitamin B6, niacin, folate, calcium, and trace minerals, which contribute to metabolic, cardiovascular, and bone health. While naturally gluten-free, oat bran may become contaminated with gluten during harvesting or processing. Therefore, individuals with gluten intolerance or celiac disease should opt for oat bran products specifically labeled as gluten-free to avoid potential cross-contamination (Shehzad *et al* 2023).

**1.4 Rye by-products**

Rye bran, a by-product of rye grain milling, is steadily gaining attention for its remarkable nutritional and health-boosting qualities. Once considered a milling residue, this fibrous outer layer of the rye grain is now recognized as a treasure trove of essential minerals like calcium, magnesium, iron, and zinc, along with a wealth of dietary fiber—particularly arabinoxylans and β-glucans (Dziki 2022). These fibers are known not only for improving digestion and blood sugar control but also for promoting a healthy gut microbiome and prolonging feelings of fullness, which can aid in weight management. Beyond fiber, rye bran is rich in beneficial compounds such as phenolic acids, lignans, and tocopherols—powerful antioxidants and anti-inflammatory agents that help reduce the risk of chronic illnesses like heart disease, diabetes, and hormone-related cancers. Although phytic acid in rye bran can hinder mineral absorption, modern techniques like fermentation and enzymatic treatment help to break down this compound and unlock the bran’s full nutritional potential. With such qualities, rye bran is no longer just a by-product—it is a promising ingredient in functional foods, nutraceuticals, and prebiotic products designed to support better health and wellness (Sharma et al 2025).

**1.5 Barley by-products**

Barley by-products such as bran, husk, and spent grains are gaining recognition not just as agricultural residues but as valuable nutritional resources with significant benefits for human health. These by-products are especially rich in dietary fiber, primarily β-glucan, which has been extensively studied for its ability to reduce blood cholesterol levels and improve heart health by lowering low-density lipoprotein (LDL) cholesterol (Li *et al* 2022). Regular consumption of β-glucan from barley can also help regulate blood glucose, making it beneficial for managing and preventing type 2 diabetes. In addition to fiber, barley by-products are abundant in essential proteins, minerals such as magnesium, potassium, and iron, and vitamins, all of which contribute to overall nutritional balance and bodily functions. The presence of antioxidants, including phenolic acids and flavonoids, provides protection against oxidative stress, reducing inflammation and lowering the risk of chronic diseases such as cardiovascular disorders and certain cancers. Moreover, the bioactive compounds in barley bran have been linked to improved immune responses and potential anti-cancer properties due to their ability to modulate cellular pathways involved in tumor development. Certain varieties of barley, particularly hulless or naked barley grown in high-altitude regions, contain elevated levels of these health-promoting nutrients, enhancing their functional value (Raj *et al* 2023). Advances in food processing methods like fermentation and enzymatic treatment further improve the digestibility and nutrient availability of barley by-products by reducing anti-nutritional factors such as phytic acid, which otherwise inhibits mineral absorption. By incorporating barley by-products into the diet, individuals can benefit from improved cardiovascular health, better blood sugar control, enhanced antioxidant protection, and a reduced risk of metabolic and inflammatory diseases. These factors underscore the growing importance of barley by-products as key ingredients in functional foods and nutraceuticals aimed at promoting long-term human health (Manzoor *et al* 2022).

**1.6 Corn by-products**

Corn by-products, including corn bran, germ, and husks, have recently attracted considerable attention as rich sources of valuable bioactive compounds with significant health benefits for humans. These by-products are abundant in dietary fiber, essential fatty acids, proteins, vitamins (notably vitamin E and B-complex), minerals such as magnesium, zinc, and iron, and a wide range of phytochemicals like phenolic acids, flavonoids, and carotenoids. Advances in extraction technologies have enabled more efficient isolation and characterization of these compounds, revealing their strong antioxidant, anti-inflammatory, and cholesterol-lowering properties (Meena *et al* 2022). The dietary fiber in corn by-products supports digestive health by promoting regular bowel movements and enhancing gut barrier function, while also helping regulate blood glucose levels, which is crucial for preventing type 2 diabetes. Phenolic compounds found in corn bran and germ exhibit potent free radical scavenging activity, reducing oxidative stress and lowering the risk of chronic diseases such as cardiovascular disease and certain cancers. Additionally, carotenoids, especially lutein and zeaxanthin, contribute to eye health by protecting against age-related macular degeneration. The presence of essential fatty acids and vitamins further supports cardiovascular function and immune system strength. Recent bioprocessing methods, such as enzymatic treatments and fermentation, have improved the bioavailability of these nutrients by breaking down anti-nutritional factors like phytates, which otherwise hinder mineral absorption (Jiao *et al* 2022). Incorporating corn by-products into food formulations thus offers a sustainable way to enhance nutritional quality and provide multiple health benefits, making them valuable ingredients in the development of functional foods and nutraceuticals aimed at improving human health and preventing disease (Deepak *et al* 2022).

**1.7 Millet by-products**

Millet by-products, including bran, husk, and germ fractions generated during milling and processing, are increasingly recognized for their exceptional nutritional value and health-promoting potential. These by-products are rich sources of dietary fiber, essential amino acids, complex carbohydrates, phenolic compounds, and micronutrients like iron, calcium, magnesium, and zinc (Anagha 2023). Particularly, the high fiber content in millet bran supports digestive health, enhances satiety, and contributes to better weight management. The presence of antioxidants such as flavonoids and phenolic acids in millet residues helps in neutralizing oxidative stress, thus lowering the risk of chronic conditions like cardiovascular diseases, type 2 diabetes, and certain types of cancers. Moreover, the slow-digesting carbohydrates and low glycemic index associated with millet by-products are beneficial for glycemic control, making them especially suitable for diabetic individuals (Ajagekar *et al* 2023). Minerals found in millet husk and bran also play a vital role in bone health, blood formation, and immune function. Additionally, bioactive peptides derived from millet protein residues have shown potential in managing blood pressure and cholesterol levels. The nutraceutical potential of these by-products is further enhanced when subjected to processing methods such as fermentation or enzymatic hydrolysis, which increase nutrient bioavailability and reduce antinutritional factors. As consumers demand more functional and natural health-supportive ingredients, millet by-products stand out as sustainable, underutilized resources with immense promise for inclusion in high-fiber health foods, heart-healthy snacks, and therapeutic diets aimed at lifestyle disease prevention (Suri *et al* 2024).

**2. Cereal by-products nutritional composition that support microbial growth**

The cereal processing industry generates a substantial amount of by-products such as bran, germ, husk, and brewer’s spent grain. Far from being mere waste, these by-products are packed with nutrients—complex carbohydrates, proteins, dietary fibers, and essential minerals—that provide an ideal environment for microbial growth. Their rich organic profile serves as a low-cost and sustainable substrate for cultivating a wide range of beneficial microorganisms. Industrially, these by-products are increasingly being valorized through microbial fermentation to produce functional foods, bioactive compounds, organic acids, enzymes, bioethanol, and probiotics (Iram *et al* 2023). Lactic acid bacteria, yeasts, and fungi thrive on the polysaccharides, peptides, and fermentable sugars found in cereal residues, making them excellent raw materials for biotechnological applications. For instance, wheat bran and maize fiber have been used to cultivate *Lactobacillus*, *Saccharomyces*, and other probiotic strains that enhance food quality, shelf life, and health benefits (Galanakis 2022).

Furthermore, their application spans across food, pharmaceutical, and agricultural sectors—where they support the development of prebiotics, biofertilizers, and natural additives. With growing interest in circular bioeconomy and sustainable food systems, cereal by-products are no longer discarded but harnessed for their untapped potential to support microbial ecosystems, reduce production costs, and promote green innovation (Fărcaș *et al* 2022).

**2.1. Comparative analysis of microbial growth in cereal bran-based and conventional culture media**

With the growing emphasis on sustainable and cost-effective agricultural practices, there has been increasing interest in replacing expensive synthetic media used for biofertilizer production with more affordable and eco-friendly alternatives. Traditionally, plant growth-promoting rhizobacteria (PGPR) such as *Azospirillum*, *Azotobacter* and *Rhizobium* have been cultivated using synthetic or semi-synthetic media like Dobereiner medium, Jensen’s medium and Yeast Extract Mannitol (YEM) medium. These media are effective but often require costly ingredients, specialized conditions, and high investments, which hinder their widespread commercial use (Gupta *et al* 2024)

In recent years, agro-industrial by-products, particularly cereal brans from wheat and rice milling, have emerged as promising substitutes due to their abundance, low-cost and rich nutritional profile. Cereal brans, although traditionally used as animal feed, are now being explored as substrates for microbial culture due to their ability to support the growth of beneficial microbes (Gupta 2023; Riseh *et al* 2024).

For instance, Lade *et al* (2015) reported successful microbial detoxification using a 5% wheat bran-based medium under submerged conditions. More notably, a study employing a simple mixture of wheat or rice bran with distilled water in a 1:2 ratio demonstrated substantial microbial proliferation—achieving 10.68 Log CFU/ml for *Azotobacter chroococcum*, 12.63 Log CFU/ml for *Bacillus subtilis* and 12.71 Log CFU/ml for *Pseudomonas* spp. within just three days of incubation (Kumari and Rani 2024). These results are not only comparable to but in some cases exceed growth achieved in conventional synthetic media.

Such findings highlight the potential of bran-based formulations to replace costly synthetic alternatives without compromising microbial viability or performance. Additionally, unlike traditional solid carrier-based biofertilizers, which often face challenges such as limited shelf life and low cell densities, bran-based liquid formulations offer enhanced cell viability, ease of handling, and extended storage stability (Kumari and Rani 2024).

**2.2. Rice by products**

Rice bran, a nutrient-rich by-product from cereal milling, serves as an excellent substrate that supports microbial growth across various industries due to its high content of dietary fiber, essential minerals (zinc, iron, calcium, sodium, potassium), and macronutrients (protein, fat, carbohydrates) (Hanis-Syazwani *et al* 2018). In the food sector, rice bran flour is commonly incorporated into bakery products such as bread, cookies, muffins, and cakes to improve their nutritional quality and texture. Incorporation rates up to 20% have been shown to enhance mineral content and fiber levels while influencing dough rheology and loaf volume because of gluten dilution (Lai and Lin 2007). Rice bran also acts as a beneficial medium for microbial fermentation. Sourdough cultures containing *Lactobacillus plantarum* and *Saccharomyces cerevisiae* enhance the sensory qualities, shelf life, and nutritional value of bakery products, increasing protein bioavailability and antioxidant potential (Bultum *et al* 2020; Christ-Ribeiro *et al* 2021; Da Rocha Lemos Mendes *et al* 2021). Sensory studies confirm the consumer acceptability of fermented rice bran-enriched gluten-free baked goods.

Beyond food production, cereal bran by-products play a pivotal role in supporting beneficial microbes in agricultural biofertilizers. A recent study demonstrated that cereal bran based low-cost liquid medium significantly enhanced the growth, multifunctional traits and shelf life of a consortium biofertilizer containing *Azotobacter chroococcum*, *Bacillus subtilis*, and *Pseudomonas* species (Kumari and Rani 2024). This highlights the utility of cereal bran as a sustainable and nutrient-rich carrier for microbial inoculants, supporting eco-friendly agricultural practices. In a study conducted by Liu *et al* (2024) concluded that biochar derived from rice husk (RHBC) significantly enhances the bioremediation of petroleum-contaminated soil by accelerating the degradation of total petroleum hydrocarbons and key n-alkanes compared to natural attenuation and raw rice husk. RHBC shortens the biodegradation half-life, boosts soil enzyme activity, and stimulates the growth of petroleum-degrading bacteria, making it an effective biostimulator for improving petroleum hydrocarbon cleanup in contaminated soils.

Moreover, rice bran’s fiber and prebiotic components create an ideal environment for microbial proliferation in probiotic beverages and various fermentation-based biotechnological processes, including enzyme and organic acid production (Spaggiari *et al* 2021). These features make cereal by-products valuable not only in the food industry but also in fermentation and agriculture, demonstrating their multifunctional potential as microbial growth substrates.

**2.3 Wheat by products**

Because wheat bran is a well-known excellent source of dietary fiber, it is mostly used to increase the fiber level of processed foods. When manufacturing bread, a variety of nutritional fiber sources are utilized, such as bran, whole meal flour, pulse hulls, wheat fiber, maize, and oats. Products like whole grain flour or steamed bread enhanced with wheat bran are now readily available in Asian shops. Many items, such as banana chocolate, nut, and spice cakes, employ wheat bran as an added fiber source. Bread enriched with up to 10% fermented wheat bran is one example of a highly acceptable product made using fermented coarse wheat bran, varying percentages of wheat bran (0–20%) incorporation was utilized to create brown flour with added minerals (Butt *et al* 2004). You can make high-fiber phulkas or chapatis with 5% wheat bran without compromising their sensory qualities. Numerous studies have investigated the use of cereals and their by-products as cost-effective substrates for formulating low-cost media to support the growth of various microorganisms. Saman *et al* (2011) reported that *Lactobacillus plantarum* NCIMB 8826 reached a viable cell density of 10.41 Log CFU/ml when cultured in a liquid medium formulated from brown rice and its bran. During the investigation of rice bran as an alternative to nitrogen source, Narh *et al* (2018), observed maximum cellulose yield by *Acetobacter xylinum* in 1:3 ratio of D-mannitol with rice bran showing 100% increase over the 1:2 ratio of same formulation showing bacterial cellulose yield proportional to the amount of rice bran added. In a separate study, Saguibo *et al* (2022) formulated a low-cost alternative medium (LCAM) for lactic acid bacteria (LAB) using agro-waste components such as coconut water, rice bran extract, baker’s yeast extract, salts, and table sugar. Two optimized formulations—LCAM A (1% baker’s yeast extract, 58% coconut water, 35% rice bran extract, and 1% sugar) and LCAM B (60% coconut water and 35% rice bran extract)—supported LAB growth of 8.91 and 8.88 Log CFU/ml, respectively, while also promoting significant metabolite production. Remarkably, these media were 7.4–7.6 times more economical than the cheapest available commercial medium. Similarly, Aloo *et al* (2022) reported that bagasse supported the highest growth of *Klebsiella grimontii* (MPUS7) at 5.331 Log CFU/g under refrigerated storage, and *Citrobacter freundii* (LUTT5) under both storage conditions (4.094 Log CFU/g). Additionally, wheat bran was found to be the most supportive substrate for *K. grimontii* MPUS7 at room temperature (25 ± 2°C), achieving a viable count of 3.721 Log CFU/g. Admasu *et al* (2024) investigated that the supplementing wheat flour with varying levels of wheat bran improved the nutritional content particularly dietary fiber while maintaining acceptable dough and bread quality.

**2.4 Oats by products**

Oat by-products, including oat bran and oat straw, are nutrient-rich materials that can be effectively utilized through microbial biotechnology to produce valuable compounds. Oat bran contains approximately 5.5% β-glucans, which make up 16% of its total dietary fiber (Verni *et al* 2019), while oat straw consists of 27–35% cellulose, 20–37% hemicellulose, and 10–19% lignin (Soni *et al* 2019). Oats also provide proteins, and fermentation processes enhance their solubility and bioavailability. For example, sourdough fermentation of oat bran has been shown to double protein solubility. Oat bran contains 58 g/kg of lipids, with oleic acid (44.09–46.68%) and linoleic acid (32.54–32.88%) as the predominant fatty acids (Joyce *et al* 2019). Fermentation with yeast strains such as *Saccharomyces cerevisiae*, *Pseudozyma spp.*, *Rhodotorula glutinis*, and *Kluyveromyces marxianus* has been used to increase folate content in oat bran (Verni *et al* 2019), while *Candida milleri* has been shown to double the solubility of protein and β-glucans. Additionally, *Candida spp.* has been utilized to convert xylose, a sugar in oat straw, into xylitol, a sugar alcohol with significant industrial applications. Lactic acid bacteria, such as *Lactobacillus rhamnosus*, enhance folate production and promote the growth of beneficial gut microbiota (Joyce *et al* 2019). Solid-state fermentation with *Mucor spp.* strains can produce polyunsaturated fatty acids like γ-linolenic acid and β-carotene (Verni *et al* 2019). These microbial processes enhance the bioavailability of minerals, vitamins, and proteins, providing health benefits such as cholesterol reduction, short-chain fatty acid production (e.g., propionate and butyrate), and folate fortification. Moreover, xylitol can be produced from the hemicellulose fraction of oat straw. The microbial valorization of oat by-products has a wide range of applications in the food industry (e.g., in baked goods and cholesterol-lowering dairy products), animal feed, and the pharmaceutical and cosmetic industries. This approach offers a sustainable solution to waste management and contributes to the circular bioeconomy by transforming low-cost agricultural residues into high-value products (Fărcaș *et al* 2022).

**2.5 Rye by product**

Rye bran, a nutrient-dense cereal by-product, offers a rich source of dietary fibers, minerals, phenolic compounds, and bioactive substances that collectively create an ideal environment for microbial growth and diverse industrial applications. Its unique nutritional profile not only enhances the functional properties of food products but also supports the proliferation of beneficial microorganisms in fermentation and bioprocessing (Németh 2021). For example, rye bran has been successfully used to enrich bakery products by replacing portions of wheat flour, boosting mineral content (Ca, P, K, Fe, Mg, Zn) and dietary fiber while increasing antioxidant capacity through elevated phenolic compounds. This makes rye bran a valuable ingredient for functional food development and a substrate conducive to microbial activity, such as fermentation by *Lactobacillus* and yeast strains (El-Mahis *et al* 2023).

Beyond food applications, rye bran serves as an effective raw material for producing fermentable sugars via hydrolysis, which can then be converted into bioethanol. Enzymatic treatments combining xylanase and ferulic acid esterase have enhanced the release of phenolic acids from rye bran, improving bioaccessibility and benefiting microbial fermentation processes. This enzymatic bioprocessing not only optimizes microbial growth but also facilitates the production of bioactive-enriched food ingredients (Saleh *et al* 2019).

Rye bran also acts as a substrate for microbial enzyme production. Specific microorganisms, like *Streptomyces fulvissimus*, thrive on rye bran to generate industrially important enzymes such as cellulase, amylase, and xylanase, which aid in breaking down lignocellulosic biomass for sustainable biofuel generation. The high arabinoxylan content in rye bran makes it particularly suitable for such enzyme production, offering an economical and eco-friendly alternative to conventional methods (Kołodziejczyk *et al* 2020). In agriculture, bioactive compounds extracted from rye bran have demonstrated protective effects against fungal diseases in crops, illustrating its potential as a natural biopesticide substrate that supports microbial antagonists. Moreover, rye bran-derived water-extractable arabinoxylans improve dough quality and yeast viability during frozen storage, enhancing bread volume and texture—highlighting rye bran’s role in supporting fermentative microbes and food quality. Additionally, rye bran is utilized as a binder in pellet fuel production, improving pellet durability and calorific value, thereby extending its industrial relevance beyond nutrition and microbial fermentation (Kulichová *et al* 2019).

Overall, rye bran exemplifies how cereal by-products, due to their rich nutritional and biochemical composition, effectively support microbial growth across multiple sectors, including food processing, biofuel production, enzyme manufacture, and sustainable agriculture, while simultaneously valorizing milling by-products and contributing to circular bioeconomy strategies.

**2.6 Barley by products**

Barley by-products such as barley bran, spent grains, husks, and malt rootlets are important residues produced during the processing of barley for various purposes, including food, feed, and brewing. These by-products are rich in nutrients like complex carbohydrates (including starch, cellulose, and hemicellulose), proteins, fats, vitamins, and minerals, making them excellent, cost-effective substrates for supporting microbial growth and enzyme production. In the field of microbial biotechnology, they are widely used in both submerged fermentation (SmF) and solid-state fermentation (SSF) to cultivate diverse microorganisms such as bacteria (e.g., *Bacillus* species), fungi (e.g., *Aspergillus* and *Trichoderma* species), and yeasts (Feng *et al* 2024). The balanced nutrient profile of these materials enhances microbial activity and leads to the production of key industrial enzymes like amylases, cellulases, xylanases, proteases, and lipases, which are used across sectors such as food, textiles, biofuels, animal feed, and paper manufacturing. Utilizing barley by-products in fermentation not only lowers production expenses but also helps mitigate environmental issues associated with agro-waste disposal (Nigam 2017). Their widespread availability, biodegradability, and sustainability make them promising eco-friendly alternatives to conventional fermentation media in microbial and enzyme-based industries. In a study by Takeuchi *et al* (2024), the substitution of wheat with waxy barley bran flour for high-function noodle production was found to support the development of nutrient-enriched and sustainable food products, with minimal compromise on quality. Ikuomola *et al* (2017) evaluated cookies made by replacing wheat flour with 5–50% malted barley bran. They observed enhanced nutritional content, particularly protein, ash, and fiber. The 5–10% inclusion level yielded the best sensory qualities, improving crispiness and color. In Japan, increasing demand for waxy barley has led to concerns over barley bran waste. Replacing wheat flour with 10% Inner Bran Layer Powder (IBLP) improved bread volume, softness, and texture. Higher levels (30–50%) of IBLP enhanced beta-glucan and antioxidant content (Furuichi *et al* 2024). In a controlled trial, crackers formulated with 40% barley flour enriched with β‑glucan were included in a dietary intervention. While acute glycemic and lipidemic effects were modest, the study highlighted the potential of barley-enriched crackers as functional foods by Chatziharalambous *et al* (2024).

**2.7 Corn by products**Corn by-products such as corn steep liquor (CSL), corn bran, corn gluten meal, corn fiber, and distillers dried grains with solubles (DDGS) are important agro-industrial residues produced during maize processing through wet and dry milling. These by-products are abundant in nutrients including carbohydrates, proteins, amino acids, organic acids, B-complex vitamins, and minerals, making them highly effective and economical substrates for microbial growth and enzyme production. CSL, a by-product from the corn steeping process, is particularly rich in nitrogen and growth-stimulating compounds, making it widely used in fermentation media to support the cultivation of various microorganisms like bacteria (e.g., *Bacillus* spp.), fungi (e.g., *Aspergillus*, *Penicillium*), and yeasts (e.g., *Saccharomyces cerevisiae*). Corn bran and fiber, which contain high levels of cellulose, hemicellulose, and lignin, are ideal substrates for solid-state fermentation using cellulolytic and xylanolytic microbes (Taiwo 2024). These microorganisms are capable of producing a variety of industrially valuable enzymes, including cellulases, xylanases, amylases, proteases, and phytases, which find applications in industries such as food, animal feed, bioethanol production, and waste treatment. In addition, corn gluten meal, due to its high protein content, is effective for supporting the production of protease enzymes. Utilizing corn by-products in microbial biotechnology not only boosts enzyme productivity but also helps in recycling agricultural waste, reducing production costs, and advancing sustainable and circular bioeconomy approaches in industrial processes (Guillaume *et al* 2019).

**2.8 Millets by products**

Millet by-products such as husks, bran, and spent grains, which are generated during milling and processing, are often overlooked agro-industrial residues with great potential as substrates for microbial cultivation and enzyme production. These residues are rich in complex carbohydrates like cellulose, hemicellulose, and resistant starch, as well as significant amounts of proteins, dietary fibers, phenolic compounds, and essential minerals. Due to this nutrient richness, they are well-suited for use in both submerged fermentation (SmF) and solid-state fermentation (SSF) processes to grow various microorganisms, including bacteria such as *Bacillus* species, fungi like *Aspergillus* and *Trichoderma*, and yeasts such as *Saccharomyces cerevisiae (*Adebiyi 2018). These microbes utilize the complex polysaccharides and nutrients in millet by-products to produce important industrial enzymes including cellulases (for cellulose breakdown), xylanases (for hemicellulose degradation), amylases (for starch hydrolysis), proteases (for protein digestion), and phytases (which free phosphorus from phytate). These enzymes have extensive applications in industries such as food and beverage processing, animal nutrition, textile manufacturing, paper production, and biofuel generation (Mudau *et al* 2022). Moreover, fermenting millet residues with microbes can enhance their bioactive qualities by boosting antioxidant capacity and possibly improving antimicrobial properties, thereby increasing their value as functional food or feed ingredients. The use of millet by-products for microbial enzyme production offers a cost-effective alternative to traditional substrates, promotes sustainable waste recycling, minimizes environmental pollution, and supports a circular bioeconomy by transforming agricultural waste into valuable bioproducts (Verni *et al* 2019).

**3. Conclusion**

Cereal by-products are no longer agro-industrial residues but represent a rich, sustainable resource with high nutritional value. Their ability to support microbial growth makes them an attractive alternative to conventional culture media for use in diverse industrial applications, including food, pharmaceuticals, agriculture and biofuels. The valorization of these by-products promotes human health, reduces environmental waste, and supports green innovation. To realize their full potential, future research should focus on optimizing fermentation processes, standardizing substrate formulations, and overcoming challenges related to compositional variability. Overall, leveraging the nutritional and functional benefits of cereal by-products contributes significantly to a more sustainable and resilient bioeconomy.

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**Authors contributions**

This work was carried out in contribution among all the authors. All authors read and approved the final manuscript.

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