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## Nutritional potential and stabilization strategies of cereal bran: A comprehensive review

V. Meenakshi\*, Preeti Kittur\*\*, A. Kalaiselvan\*\*\*, J. Selvi\*\*\*\* and T. Siva Sakthi\*\*

\*Department of Horticulture, VOC Agricultural College and Research Institute, Killikulam, Vallanadu-628252, Tamil Nadu, India

\*\* Department of Food Science and Nutrition, Community Science College and Research Institute, Madurai-625104, Tamil Nadu, India

\*\*\* Department of Extension Education and Communication Management, Community Science College and Research Institute, Madurai-625104, Tamil Nadu, India

\*\*\*\* ICAR-Krishi Vigyan Kendra, Thirupathisaram-629901, Tamil Nadu, India

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## Abstract

The outer layer of cereal grains, known as bran, is a rich source of dietary fiber, antioxidants, and essential micronutrients. However, its quality and shelf-life can be compromised by the presence of active enzymes, such as lipase, which catalyze fat degradation, or by the inclusion of sensitive bioactive compounds. To preserve the nutritional value of bran and enhance its storage stability, various stabilization techniques aimed at enzyme inactivation have been developed. Heat treatments, including roasting, steaming, and microwave processing, have been extensively studied for their effectiveness in reducing enzymatic activity, thereby preventing rancidity, nutrient loss, and undesirable textural changes. Optimizing these processing conditions is critical to ensure effective stabilization without diminishing bran's health-promoting properties. Beyond its nutritional benefits, cereal bran has found novel applications across diverse fields, including functional foods, nutraceuticals, cosmetics, biofuel production, and biodegradable or edible packaging. This review examines the impact of enzyme inactivation methods on the compositional, functional, and antioxidant characteristics of bran while highlighting emerging applications, underscoring its potential as a value-added ingredient in sustainable food and non-food industrial systems.

## 1. Introduction

Cereals are a primary source of human food and animal feed, generating substantial by-products throughout the supply chain (Skendi *et al.*, 2020). Cereal bran is a nutrient-dense fraction of whole grains, providing not only protein with essential amino acids but also dietary fibre, essential fatty acids (notably linoleic acid), vitamins, minerals, and a wide range of bioactive phytochemicals. These bioactive compounds, including phenolic acids, flavonoids, and lignans, contribute to the antioxidant and anti-inflammatory properties of cereal bran, making it a valuable component for promoting metabolic and cardiovascular health (Das *et al.*, 2024; Nemes *et al.*, 2024). These components collectively position bran as a functional food ingredient with potential health-promoting properties. Bran, produced in large quantities as a by-product of cereal processing industries worldwide, particularly from wheat, rice, oats, and rye, is readily available for utilization. Its incorporation into food products enhances dietary fiber intake and provides bioactive compounds associated with health maintenance and the prevention of chronic diseases (Zhou *et al.*, 2025).

Bran lipids, although present in moderate quantities (typically 3-7% of bran), are nutritionally significant because they are rich in

essential fatty acids, particularly linoleic acid ( $\omega$ -6) and  $\alpha$ -linolenic acid ( $\omega$ -3). These fatty acids play an important role in cell membrane structure, inflammatory regulation, cardiovascular function, and metabolic health. In addition, bran lipids contain tocopherols (vitamin E), sterols, and alkylresorcinols, which exert antioxidant, anti-inflammatory, and cholesterol-lowering activities. The lipids located in the bran layer also interact with bran phenolic compounds to enhance bioavailability and free-radical scavenging capacity, making cereal bran a valuable functional food component (Yan *et al.*, 2024; Kobayashi *et al.*, 2025). In spite of its valuable nutrient profile and associated health-promoting properties, the direct application of cereal bran in food systems remains constrained by several technical challenges. The enzymatic activity within bran often causes the development of unpleasant sensory attributes, decreased shelf stability, and nutrient losses, most notably in lipid components. In parallel, antinutritional compounds, including phytic acid, tannins, and trypsin inhibitors, pose additional challenges by reducing mineral bioavailability, impairing protein digestion, and diminishing nutritional performance. Through complexation with essential nutrients, these compounds limit absorption and weaken the value of bran-fortified products (Zhou *et al.*, 2025). For cereal bran to be applied in food formulations rather than restricted to animal feed, it requires a process termed "stabilization", which inactivates lipolytic enzymes. This process is intended to avoid hydrolytic spoilage, commonly measured in rice bran through elevated lipase activity and free fatty acid formation. Enzymes such as lipoxygenase and peroxidase are also considered markers of cereal bran quality deterioration, though their influence is comparatively minor (Tuncel and Korkmaz, 2020).

## Corresponding author: Dr. V. Meenakshi

Associate Professor Department of Horticulture, VOC Agricultural College and Research Institute, Killikulam, Vallanadu-628252, Tamil Nadu, India

E-mail: [Meenakshi.v@tnau.ac.in](mailto:Meenakshi.v@tnau.ac.in)

Tel.: +91-8012587005

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## 2. Nutrition composition of cereal bran

In 2020, global cereal grain production was 2.1 billion metric tons, comprising wheat, rice, maize, millet, barley, and oats. Milling of these cereals produces bran as a by-product, which accounts for roughly 10-20% of the grain weight depending on the cereal type and degree of milling. With the world population projected to approach 9.7 billion by 2050, the growing demand for sustainable food resources highlights the importance of valorizing cereal bran as a functional and nutritional ingredient rather than treating it merely as a milling residue (Hadidi *et al.*, 2023). Cereal grains such as wheat, rice, maize, barley, and oats exhibit a cross-sectional structure made up of distinct anatomical layers, each contributing uniquely to grain development, nutrient storage, and nutritional value (Khalid *et al.*, 2023). In recognition of its health-promoting potential, nutritional guidelines worldwide encourage higher intake of whole grains and bran-derived foods as part of a balanced diet (Mathews and Chu, 2019). Cereal bran consists of a complex mixture of macronutrients and bioactive compounds. Among these, dietary fibers, both soluble and insoluble, form a dominant component, providing well-established benefits for gastrointestinal function. Proteins with essential amino acids and a lipid fraction containing health-promoting oils further enhance its nutritional value (Fărca' *et al.*, 2021). Rice bran oil, is particularly notable for its tocopherols, tocotrienols, phytosterols and  $\gamma$ -oryzanol (Tufail *et al.*, 2024).

Cereal bran is also an important source of phenolic acids, including derivatives of hydroxybenzoic acid and hydroxycinnamic acid, which are recognized as important contributors to the reported protective effect of whole-grain consumption against chronic diseases (Martín-Diana *et al.*, 2021). Importantly, the nutritional profile of bran differs across cereals. Rice is the most important cereal crop and a staple food for more than half of the world's population. A significant by-product of rice milling, rice bran makes up 8% to 10% of the weight of rice. Crude fiber (8%-10%), protein (14%-16%), fat (12%-23%), carbohydrates, vitamins, minerals, important unsaturated fatty acids, and phenolics are all abundant in it (Tan *et al.*, 2023). The affordability and hypoallergenic nature of rice bran make it a valuable plant-based resource for producing essential amino acids and proteins. Rice bran is recognized for its oil content and lipid-soluble bioactive. Furthermore, rice bran oil is composed of approximately 47% monounsaturated, 33% polyunsaturated, and 20% saturated fatty acids and it is enriched with vitamin E (including tocopherols and tocotrienols), vitamin K, and  $\gamma$ -oryzanol, which contribute to its nutritional and functional significance (Tan *et al.*, 2023). Quick oil extraction immediately following the milling of the rice can also prevent the development of hydrolytic rancidity. But in reality, rice milling and rice bran oil extraction are not done in that order, and the interval between the two processes leads to an excess of free fatty acid (more than 20%).

It has been regarded as one of the most valuable and healthiest edible oils. Research indicated that around 90% of rice bran is lost annually, despite the possibility of creating 8 million tons of rice bran oil globally (Wang *et al.*, 2017). Wheat bran is particularly high in insoluble fiber and minerals (Solmaz *et al.*, 2025). Corn bran is rich in phenolic acids, with ferulic acid being the most abundant, followed by vanillic, caffeic, and other acids (Fărca' *et al.*, 2022). Additionally, corn bran is rich in anthocyanins, making them valuable food pigments (Tlais *et al.*, 2020). Wheat bran contains 12% moisture, 13% protein,

3.5-3.9% fat, and 56% carbohydrates and provides fiber and bioactives such as polyphenols and  $\beta$ -glucans that support gut and metabolic health (Viuda-Martos *et al.*, 2019; Deroover *et al.*, 2019). Oat bran contains 60% starch, 5-9% lipids, and 2.3-8.5% fiber, particularly soluble  $\beta$ -glucans that improve cholesterol and glycemic control (Paudel *et al.*, 2021). Rye bran provides 14-21% dietary fiber, especially arabinoxylans, along with phenolic acids contributing to antioxidant and anti-inflammatory activity (P. N. P. V. and Joye, 2020). Maize bran contains 9-23% starch, 10-13% protein, and 2-3% lipids and is rich in heteroxylan fibers and phenolics that support digestive health and functional food applications (Hussain *et al.*, 2024). Effective utilization of cereal bran can reduce waste, enhance nutritional value in foods, and support sustainability, but stabilization is essential. Naturally occurring enzymes such as lipase and lipoxygenase can cause rancidity, making it critical to preserve bioactive compounds while preventing degradation during storage and processing.

## 3. Techniques for cereal bran stabilization

Enzymatic activity in cereal bran is a major factor contributing to the development of undesirable sensory characteristics, reduced storage stability, and nutrient degradation, particularly within lipid fractions (Soe *et al.*, 2018). In addition to enzymatic rancidity, other factors also play significant roles in bran deterioration. Moisture content is very important because high water activity speeds up hydrolytic rancidity by making lipase activity higher and making it easier for microbes to grow. Microbial contamination compounds this instability by producing metabolites such as organic acids and volatile compounds that impair flavor and quality, while microbial enzymes can act in concert with native bran enzymes to further intensify lipid oxidation (Zhou *et al.*, 2025). Moreover, phenolic compounds exert a dual influence on stability, although many function as antioxidants that inhibit lipid peroxidation (Chen *et al.*, 2019), some phenolic compounds can undergo oxidative transformations, leading to the formation of quinones and other reactive intermediates that, under adverse storage conditions, may accelerate rancidity. Evidence from studies on phenolic-rich agro-food matrices shows that flavan-3-ols and catechol acids are especially susceptible to auto-oxidation, which diminishes their antioxidant potential over time, particularly in alkaline or oxygen-rich environments. Such behavior underscores the dual role of phenolics, where they may shift from functioning as antioxidants to exhibiting pro-oxidant activity depending on storage conditions (Pasquet *et al.*, 2024).

Mitigating the instability of cereal bran is fundamental to enhancing its incorporation into food systems and advancing the valorization of agro-industrial by-products. Stabilization interventions are employed to inactivate endogenous enzymes, limit microbial proliferation, and reduce oxidative degradation, thereby extending shelf life while safeguarding or augmenting the nutritional and functional properties of bran (Tlais *et al.*, 2020).

Several stabilization techniques have been investigated for cereal bran, including thermal processes such as extrusion, hot air drying, autoclaving, infrared heating, roasting, toasting, steaming, and parboiling, along with a range of non-thermal alternatives. While thermal methods are effective, they often compromise heat-sensitive bioactive compounds and may lead to undesirable physicochemical changes (Figure 1, Table 1). This limitation has driven growing interest in green, non-thermal technologies that emphasize energy efficiency

and nutrient preservation, reflecting the food industry's shift toward more sustainable and health-conscious practices (Irakli *et al.*, 2020).

Notably, approaches such as microwave heating, ohmic heating, cold plasma treatment, ultrahigh pressure processing, electron beam irradiation, and enzymatic stabilization have emerged as promising solutions (Liu *et al.*, 2021; Lavanya *et al.*, 2019). These methods extend shelf life, safeguard bioactive integrity, and reduce waste, while also offering energy-efficient and environmentally responsible alternatives to conventional stabilization. In doing so, they support the valorization of agro-industrial by-products like cereal bran and expand opportunities for their incorporation into functional food applications.

### 3.1 Conventional stabilization techniques

#### 3.1.1 Acid treatment

Acid treatment stabilizes cereal bran by reducing its pH with suitable acids, thereby suppressing lipase activity. Stabilization is often carried out using acids such as hydrochloric acid, acetic acid, and propanoic acid. Akhter (2015) reported that hydrochloric acid at 30 ml/kg was the most effective among tested acids for suppressing lipase activity and limiting FFA formation in rice bran, while phosphoric acid, acetic acid, and sodium metabisulphite were less effective. This simple spray-mix chemical stabilization method is suitable for mills without steaming equipment or electricity. Since rice bran lipase is most active at pH 7.5-8.0 (Das *et al.*, 2024), pH adjustment can inhibit rancidity. Treatment with a 2% acetic - propionic acid solution has been shown to reduce lipid oxidation and preserve quality during storage, offering a safer stabilization method for rice bran intended for oil extraction (Gopinger *et al.*, 2015).

#### 3.1.2 Dry and moisture heating

Heat treatment is an effective method for maintaining the nutritional quality of rice bran while simultaneously inactivating both microbial growth and lipase. Dry heating, a conventional method, employs hot air to reduce moisture and lipase activity (Zhou *et al.*, 2025). In large-scale industrial applications, dry heating demands precise control of temperature, uniform heat distribution, processing time, and energy efficiency (Wang *et al.*, 2017). A study used dry-heat treatments at 120°C (88-233 min) and 130°C (50-86 min) and found that lipase activity decreased markedly (and free fatty acid rise slowed) after storage (Rashid *et al.*, 2022). Stabilization of rice bran through steam treatment occurs as the elevated temperature effectively inactivates lipase. Compared to dry heating, moist-heat methods offer the advantages of faster, more uniform heating and greater enzyme inactivation efficiency. The application of superheated steam to milled oats has been shown to completely suppress lipase activity, thereby extending the storage stability of rice bran.

#### 3.1.3 Extrusion

Bran stabilization can also be achieved through extrusion cooking, which integrates both thermal and mechanical processing. During extrusion, the combined action of heat, pressure, and shear inactivates enzymes that trigger rancidity, while simultaneously enhancing the sensory qualities and nutritional profile of bran or bran-enriched formulations (Sule *et al.*, 2024).

In a recent study, rice bran was stabilized by extrusion, which improved its color and other physicochemical characteristics. The

amount of dietary fiber increased, which benefits potential functionality, while the levels of lipids, vitamins B2, B3, and B5 and folic acid remained statistically unchanged. Additionally, the levels of protein, vitamin E, and phytic acid in stabilized rice bran are significantly lower than those in raw rice bran. It might be simpler to use the extruded bran as an ingredient in a range of food kinds due to its improved nutritional characteristics (Rafe and Sadeghian, 2017). Rashid *et al.* (2022) examined the influence of extrusion at varying temperatures (15°C, 25°C, and 40°C) during a 60-day storage period. Their findings indicated that extrusion treatment modified lipase activity as well as other enzymatic processes, which in turn affected the stability of rice bran. The study also reported substantial alterations in lipid oxidation, fatty acid composition, protein properties, and overall enzymatic activity, underscoring the role of extrusion in enhancing bran stabilization.

#### 3.1.4 Cold temperature treatment

Cold storage methods, including refrigeration (0-5°C) and freezing (below -18°C), are among the most accessible techniques for delaying rancidity in cereal bran. Lower temperatures significantly diminish the catalytic activity of lipase and lipoxygenase, consequently decelerating the formation of free fatty acids and oxidative reactions. This, in turn, aids in preserving the nutritional integrity and sensory attributes of bran during storage (Dubey, 2019). However, such treatments do not achieve permanent enzyme inactivation but rather temporarily suppress activity. Consequently, once the bran is exposed again to ambient conditions, rancidity progresses rapidly. Freezing can prolong stability more effectively than refrigeration, yet its high energy demand and limited scalability restrict its widespread adoption for industrial scale, long-term preservation (Das *et al.*, 2024).

#### 3.1.5 Biological method

Enzymatic treatment, also known as biological stabilization, is a method of rice bran preservation that targets the deactivation of lipase through protease action (Yu *et al.*, 2020). Enzymatic treatments have emerged as a promising strategy for bran stabilization, as they either deactivate undesirable enzymes or induce structural modifications that enhance stability and bioactive compound retention. Among these, the application of immobilized papain, a proteolytic enzyme, has shown notable potential (Zhou *et al.*, 2025). This method preserves the nutrients in rice bran while selectively targeting the enzyme function in mild reaction conditions without leaving behind any limiting reagent residue. Enzymatic treatments enhance bran quality by degrading antinutritional factors, improving mineral bioavailability, and preserving sensitive bioactives. Their precision, gentle conditions, and compatibility with other methods position them as a sustainable approach to bran stabilization. This method has the benefits of being lowcost and simple to utilize (Das *et al.*, 2024).

### 3.2 Non-conventional stabilization techniques

#### 3.2.1 Ohmic heating

Ohmic heating functions by generating heat as alternating current flows through a conductive material. The electric field produced during this process can modify molecular arrangements, enhance interchain interactions, and potentially deactivate lipase by detaching its metal-containing prosthetic groups. A 10 kg/batch ohmic heating system was developed to stabilize rice bran by hydrating and heating

the bran through electric current. The ohmically treated rice bran exhibited markedly slower lipid hydrolysis during storage, with free fatty acid levels reaching only 4.77% after 75 days compared to 41.84% in untreated bran. Peroxide and acid values remained low (4.7 meq/kg and 9.34%, respectively), demonstrating that ohmic heating effectively maintains rice bran quality and inhibits rancidity during storage (Dhingra *et al.*, 2012).

### 3.2.2 Microwave heating

Microwave heating is based on ultrahigh-frequency electromagnetic waves that have a significant penetration strength. The initial moisture level during the heating process is an important factor in the microwave stabilization of rice bran and should be properly regulated to optimize the treatment process. Microwave heating, which also has beneficial antibacterial and insecticidal effects in addition to inactivating enzymes, has no influence on the nutritional value and functional properties of rice bran (Patil *et al.*, 2016).

Patil *et al.* (2016) conducted various treatments at a microwave power density of 2 W/g for 2, 4, and 6 min, as well as 4W/g for 2 min. A recent study by him found that rice bran stabilized by parboiling and microwaving had a much lower fiber content than bran that had not been treated. This can be the result of heat degradation of the fiber during the process. These results suggest that microwave heating is a rapid and practical way to stabilize rice bran. To sum up, microwave heating provides homogenous heating, high thermal conversion rates, low thermal inertia, and time savings. Preeti *et al.* (2025) reported that microwave treatment effectively stabilized foxtail millet bran, achieving complete lipase inactivation, enhanced oil yield, and improved protein content while reducing moisture, ash, and fiber. Solmaz *et al.* (2025) reported that microwave stabilization effectively preserved the bioactive compounds in cereal bran and increased its soluble dietary fiber content. When incorporated into cookies, the microwave-stabilized bran improved nutritional quality, enhancing protein, phenolic content, antioxidant activity, and mineral levels without negatively affecting texture, demonstrating its suitability for developing functional, health-focused bakery products.

### 3.2.3 Ultrasound

According to Mohammadi *et al.* (2020), ultrasound treatment alone can reduce microbial load and enhance the release of antioxidant compounds in rice bran; however, it is generally insufficient to fully inactivate endogenous lipases responsible for initiating lipolytic and hydrolytic rancidity. Ultrasound generates cavitation effects that disrupt cellular structures and improve mass transfer, thereby facilitating the removal of lipase activating conditions. Yet, because lipase remains partly active, ultrasound is most effective when applied in combination with complementary stabilization approaches such as acidic washing, mild heat treatment, or pre-washing to remove surface oil. When ultrasound is integrated with these measures, the rate of free fatty acid (FFA) formation and the increase in peroxide value (PV) during storage are significantly reduced compared with untreated bran. Thus, combined ultrasound-based stabilization slows both hydrolytic and oxidative rancidity, improving rice bran storage stability while maintaining desirable nutritional and functional qualities (Estivi *et al.*, 2022; Mohammadi *et al.*, 2020).

### 3.2.4 High-pressure processing (HPP)

High-pressure processing inactivates enzymes through pressure-induced denaturation and has been reported to improve rice bran

storage stability while better preserving unsaturated lipids and phytochemicals relative to some thermal treatments. HPP presents promising non-thermal (or mild) alternatives that preserve functional compounds (Zhou *et al.*, 2025). Grau-Fuentes *et al.* (2024) utilized stabilization method where rice bran is subjected to pressures typically between 300-600 MPa. The pressure denatures lipase and lipoxygenase enzymes in rice bran by altering their tertiary and quaternary protein structures, thereby reducing hydrolytic rancidity. This allows storage without rapid increases in free fatty acids (FFA), which normally cause rancid odor and bitterness. Compared with heat-based stabilization (toasting/extrusion), HPP is particularly effective in preserving heat-sensitive bioactives, including  $\gamma$ -oryzanol, tocopherols, tocotrienols, and phenolic acids. Additionally, when rice bran is processed under controlled moisture levels, HPP improves protein solubility, emulsifying capacity, and dietary fibre hydration properties, enhancing its value as a functional ingredient.

High-pressure processing (HPP) significantly stabilizes rice bran by reducing lipase activity (62-73%) and slowing free fatty acid formation, thereby delaying rancidity, while retaining higher levels of  $\gamma$ -oryzanol (90-95%) and vitamin E compounds (85-92%) compared with dryheat stabilization. Additionally, HPP enhances protein solubility (18-31%) and increases the extractability of bound phenolics, making rice bran nutritionally and technologically more functional (Li *et al.*, 2022).

## 3.3 Stabilization of bran with the combination of various methods

Cereal bran stabilization can be optimized through the integration of multiple methods, such as hurdle technology, which combines different processing techniques to maximize effectiveness. Hurdle technology involves the coordinated use of heat, pressure, and mechanical treatments to improve nutritional retention, ensure safety, and enhance overall quality. In general, the combined application of stabilization methods yields superior outcomes compared to individual approaches.

In the study by Aluthge *et al.* (2023), rice bran was stabilized through a combined process involving steaming at  $100 \pm 2^\circ\text{C}$  for 30 min and microwaving at 900 W for 3 min, with moisture adjusted to 21%. The control sample initially recorded an oil yield of 16.37%, whereas the combined treatment produced a higher yield of 22.26%. After 50 days, oil yield in the control declined to 11.16%, while the treated sample maintained a comparatively higher yield of 18.47%. Throughout storage, the combined treatment consistently outperformed the control in preserving oil yield. IR heating combined with other treatments achieves simultaneous drying and effective stabilization for rice bran and provides a more effective way for the utilization of rice bran without affecting the quality of rice bran oil (Wang *et al.*, 2017). The findings demonstrated that ferulic acid exhibited the greatest rise in the chemical profile after many treatments of fermentation and complex enzyme hydrolysis, whereas pretreatment of rice bran with alpha-amylase resulted in improved total phenolics and flavonoids. It is hypothesized that lactic acid bacteria create more phenolic esterase and carbohydrase, which hydrolyze the ester bond between phenolics and cell wall components to liberate more phenolic chemicals. In the meantime, the complex enzymes (glucoamylase, cellulase, and protease) that are applied break down macromolecules into smaller ones in order to facilitate

bacterial fermentation and soften the structure of cell walls, which in turn promotes the production of free phenolic acids (Liu *et al.*, 2016)

#### 4. Novel applications and benefits of cereal bran

Cereal bran, a by-product of milling processes, has gained significant attention for its potential applications across various industries. In the food sector, cereal bran is utilized to enhance the nutritional profile of products, particularly through its high fiber content. Research indicates that incorporating cereal bran into bakery products can improve dietary fiber intake and contribute to health benefits such as improved gut health and reduced risk of chronic diseases (Galanakis, 2022). Beyond food applications, cereal bran is being explored for its use in biotechnology. Studies have shown that cereal bran can serve as a substrate for microbial fermentation processes, leading to the production of valuable bioactive compounds and enzymes (Arzami *et al.*, 2021). Furthermore, the environmental impact of cereal bran is being addressed through its valorization. Innovative approaches are being developed to convert cereal bran into biofuels and other sustainable materials, contributing to waste reduction and resource efficiency (Aït-Kaddour *et al.*, 2024).

Cereal brans, including those from rice, wheat, oats, and millet, are rich in bioactive compounds such as phenolic acids, flavonoids,  $\beta$ -glucans, dietary fiber, tocopherols, tocotrienols, and  $\gamma$ -oryzanol. These constituents confer multiple health benefits, including antioxidant, anti-inflammatory, hypocholesterolemic, anticancer, and antidiabetic effects, making bran a valuable functional food ingredient and nutraceutical (Gul *et al.*, 2025). Studies have shown that incorporating cereal bran into diets can enhance gut health, improve glycemic control, and reduce the risk of chronic diseases such as cardiovascular diseases and type 2 diabetes. Moreover, advancements in processing techniques, including stabilization and enzymatic

treatments, have improved the bioavailability of these bioactive compounds, increasing the therapeutic potential of cereal bran in functional food applications (Sapwarobol *et al.*, 2021).

The adoption of eco-friendly extraction techniques such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), pulsed electric field (PEF), and membrane separation technology (MST) offers a sustainable approach for recovering bioactive compounds from plant-based residues and agro-industrial by-products (Aït-Kaddour *et al.*, 2024). Ultrasound-assisted extraction (UAE) has been widely employed for the recovery of polysaccharides from wheat and oat brans, offering high efficiency and reduced processing time (Martins *et al.*, 2023). Similarly, microwave-assisted extraction (MAE), which relies on non-ionizing microwave radiation to rapidly heat solvents through their interaction with polar molecules in plant matrices, facilitates the efficient extraction of bioactive compounds (Alvi *et al.*, 2022; Bitwell *et al.*, 2023). In addition, enzyme-assisted extraction (EAE) has been effectively utilized to enhance the release of phenolic compounds, particularly flavonoids and anthocyanidins, from wheat bran, thereby improving both yield and functionality (Streimikyte *et al.*, 2022). Green extraction techniques offer eco-friendly recovery of bioactive compounds from plant by-products, reducing waste and environmental impact. They support circular economy goals by generating functional ingredients for food, pharmaceutical, and cosmetic applications (Aït-Kaddour *et al.*, 2024). Cereal bran utilization remains limited by inefficient processing, high extraction costs, limited evidence on bioavailability, and low awareness, though animal feed still dominates its use. However, applications in food (especially rice bran oil and bakery products), nutraceuticals, cosmetics, protein hydrolysates, and biorefinery processes are gradually expanding (Kittur *et al.*, 2024).

**Table 1: Effect of different stabilization methods on nutrient composition of bran**

S.No.	Stabilization technique	Approach	Inference	References
<b>I. Thermal treatment</b>				
1	Microwave	950W 6 min, 78°C	Decrease: Moisture, minerals, carbohydrates Increase: Total lipids, proteins, energy, fatty acids (palmitic, stearic, oleic, linoleic)	Faria <i>et al.</i> , 2012
2	Roasting	80°C, 6 min	Decrease: Moisture, palmitic acid, stearic acid Increase: Oleic acid, linoleic acid, total lipids, proteins, energy	Faria <i>et al.</i> , 2012
3	Autoclave	120°C, 180 min	Increase: Moisture (12.25%), crude fiber (7.61%) No significant change: Fat (18.98%), protein (15.75%), ash (7.38%) Decrease: Carbohydrates (45.63%)	Nusrat <i>et al.</i> , 2019
4	Steaming	120° C, 60 min	Decrease: Moisture (9.97%), fat (10.31%) Increase: Protein (17.45%), crude fiber (13.69%), carbohydrates (54.86%) No significant change: Ash (7.41%)	Nusrat <i>et al.</i> , 2019
5	Microwave	heating 150° C, 3 min (Power 800 w, frequency 2450 MHz)	Decrease: Moisture (4.89%), protein (13.98%), ash (6.59%), crude fiber (7.96%), Increase: Fat (21.07%), carbohydrates (53.47%)	Nusrat <i>et al.</i> , 2019
6	Ohmic heating		Decrease: Lipid oxidation, free fatty acid (FFA) formation Increase: Phenolic compounds, $\alpha$ -tocopherol, $\gamma$ -oryzanol, antioxidant activity	Dung 2014

II. Non-thermal treatment				
1	Enzymatic treatment	Immobilized papain	Lipase activity: Decreased 78% nutrient degradation: <5% Significance: Offers a milder alternative to thermal stabilization	Zhou <i>et al.</i> , 2025
		Protease (papain) hydrolysis	Lipase inactivation: 79% antioxidants: Increased (phenolics, $\gamma$ -oryzanol) Storage stability: Improved	Laokuldilok and Rattanathanan, 2014
2	Chemical treatment	Sodium metabisulfite and hydrochloric acid	Reduction observed in: lipid oxidation and lipid acidity	Gopinger <i>et al.</i> , 2015
		Hydrochloric acid, phosphoric acid, Sodium metabisulphite, and acetic acid treatments	Effective: Hydrochloric acid successfully inhibited lipase activity and limited FFA accumulation. Ineffective: Phosphoric acid, acetic acid, and sodium metabisulfite failed to prevent FFA increase.	Akhter, 2015
III. Combined stabilization treatment				
1	Microwave and steaming	Steaming - 100 $\pm$ 2°C for 30 min and Microwave - 900 W for 3 min	Lowest FFA: ~2.95% (50 days) Lowest PV: ~0.518 mEq/kg Antioxidants retained: Phenolics, $\gamma$ -oryzanol (highest)	Aluthge <i>et al.</i> , 2023
2	Radiofrequency and microwave	RF heating (27.12 MHz) and Microwave heating (2.45 GHz)	Significant reduction in FFA and PV Higher antioxidant activity and total phenols RF slightly superior to MW in nutrient retention	Sood <i>et al.</i> , 2024
3	Infrared and vacuum	999 W of infrared power and 650 mm Hg of vacuum strength	Shelf life extended: ~130 days at 30°C FFA rise strongly suppressed Bioactives preserved: Tocols, $\gamma$ -oryzanol	Kreungngern <i>et al.</i> , 2021

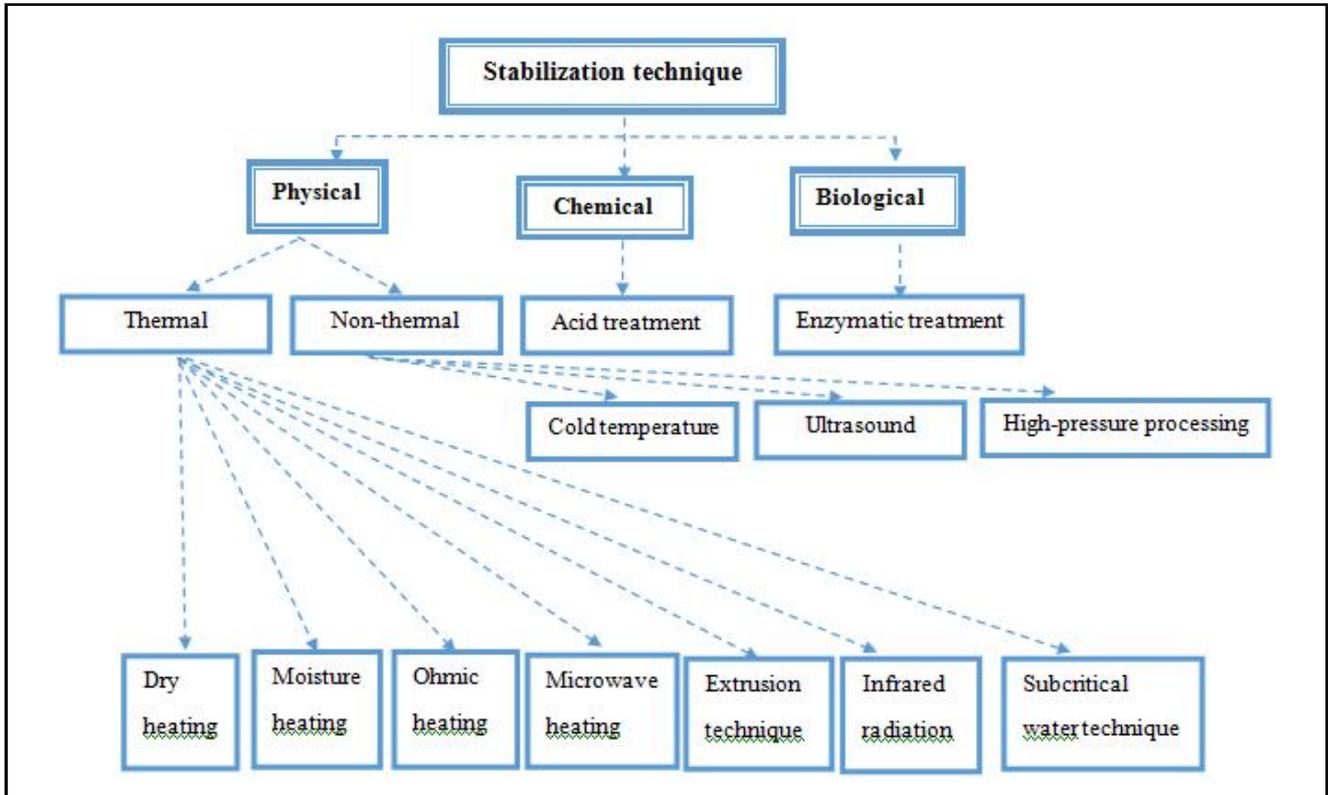


Figure 1: Classification of stabilization techniques.

## 5. Conclusion

By employing a combination of physical, chemical, and biological methods, it is possible to stabilize bran effectively, thereby enhancing its shelf life while retaining its health benefits. This is crucial for its use in food products and functional ingredients. Continuous research and technological advancements in bran stabilization can further optimize these methods for better efficiency and cost-effectiveness. Further research into innovative stabilization techniques and their application to various bran types can lead to more sustainable and efficient methods for bran preservation. As the demand for bran as a functional ingredient and dietary supplement continues to grow, advancing stabilization technology will be key to ensuring the long-term availability and quality of bran-based products. Thus, effective bran stabilization not only benefits the food industry by increasing product shelf life but also contributes to reducing food waste and enhancing the nutritional value of bran as a functional food ingredient. Cereal brans are versatile by-products used in functional foods, nutraceuticals, cosmetics, biofuel production and edible packaging. They enhance nutritional and functional value while promoting sustainability by valorizing agro-industrial waste.

## Conflict of interest

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

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