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BIOTECHNOLOGY APPLICATIONS OF WHEAT BRAN. REVIEW

Gabdulla F. Kurbanov, Artem O. Prichepa, Anatoly P. Nepomnyashchy, Ekaterina Yu. Ivanova, Natalia Yu. Sharova*

All-Russia Research Institute for Food Additives, Saint Petersburg, Russia

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wheat bran, hydrolyzation, biosynthesis, fermentation, secondary raw materials, waste products, biopolymer

ABSTRACT

The review presents the results of information research on the application of wheat bran, a by-product of wheat grain processing. The relevance of this topic is due to the difficulties of rationally using large-scale waste and its disposal without increasing the load on the ecosystem.The chemical composition of wheat bran is characterised, including the carbohydrate composition and the content of non-starch carbohydrates and proteins; a qualitative analysis of the components is provided. Special attention is given to the use of wheat bran in industry and as a substrate for the biosynthesis of useful metabolites. Wheat bran has significant biotechnological properties and is a valuable raw material for the development of new products and technologies. The review provides a comparative analysis of methods for the destruction of wheat bran, highlighting their advantages and disadvantages. Microbial destruction by enzyme preparations and microorganisms is relevant due to the promise of obtaining metabolites in demand as microingredients for feed and food purposes. The use of wheat bran in the production of functional foods is known; in animal husbandry, they are used as a feed additive. In biotechnology, wheat bran can serve as a substrate for the growth of various microorganisms used in the production of biotechnological preparations and enzymes, such as beneficial bacteria — probiotics. In the field of ecology, microbial communities using wheat bran are able to effectively degrade organic pollutants. Thus, the use of wheat bran in biotechnology opens up new horizons for the development of sustainable technological processes and improvement of product quality. Their biotechnological destruction is of interest as a method of converting waste into secondary raw material.

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БИОТЕХНОЛОГИЧЕСКОЕ ПРИМЕНЕНИЕ ПШЕНИЧНЫХ ОТРУБЕЙ. ОБЗОР

Курбанов Г. Ф., Причепа А. О., Непомнящий А. П., Иванова Е. Ю., Шарова Н. Ю.*

Всероссийский научно-исследовательский институт пищевых добавок, Санкт-Петербург, Россия

КЛЮЧЕВЫЕ СЛОВА:
пшеничные отруби, гидролиз, биосинтез, ферментация, вторичное сырье, отходы, биополимер

АННОТАЦИЯ

В обзоре представлены результаты информационных исследований по направлению применения отхода переработки зерна пшеницы — пшеничных отрубей. Актуальность рассмотрения данной темы обусловлена трудностями рационального использования крупномасштабного отхода и его реализации без увеличения нагрузки на экосистему. Дана характеристика химического состава пшеничных отрубей, включая углеводный состав, содержание некрахмальных углеводов, белков, проведен качественный анализ компонентов; уделено отдельное внимание использованию пшеничных отрубей в промышленности и в качестве субстрата для биосинтеза полезных метаболитов. Пшеничные отруби обладают значительными биотехнологическими свойствами и являются ценным исходным материалом для разработки новых продуктов и технологий. В обзоре дан сравнительный анализ способов деструкции пшеничных отрубей, отражены их преимущества и недостатки. Микробиологическая деструкция под действием ферментных препаратов и микроорганизмов актуальна в связи с перспективностью получения метаболитов, востребованных в качестве микроингредиентов кормового и пищевого назначения. Известно применение пшеничных отрубей в производстве функциональных продуктов питания; в сфере животноводства они используются в качестве добавки в корм. В биотехнологии: пшеничные отруби могут служить субстратом для роста различных микроорганизмов, которые используются в производстве биотехнологических препаратов и ферментов, например, полезных бактерий — пробиотиков. В области экологии: микробные сообщества, использующие пшеничные отруби, способны эффективно разлагать органические загрязняющие вещества. Таким образом, использование пшеничных отрубей в биотехнологиях открывает новые горизонты для разработки устойчивых технологических процессов и улучшения качества продуктов, а их биотехнологическая деструкция представляет интерес в качестве способа перевода отхода в форму вторичного сырья.

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1. Introduction

The majority of industrial products and energy carriers in the world are produced using fossil fuels. However, the reserves of such resources as oil and gas are gradually depleting, which necessitates the transition of the global economy to a new model based on renewable resources. In the new technological system, biorefineries will play a key role, providing environmentally sustainable conversion of biomass into various commercial products and energy [1].

Wheat bran (WB) represents one of the key by-products of the flour milling industry and is the most prevalent type of bran among cereal crops. The growth of the world's population leads to an increase in flour milling production volumes, which in turn increases the amount of WB.

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The high costs of WB transportation and their limited economic efficiency stimulate researchers to search for innovative and profitable methods of their utilization. According to various sources, WB is among the most common cereal crop residues (approximately 90 million tons per year [2]) due to the large market share obtained from wheat flour-based food products.

Wheat bran, like many other types of organic biomass obtained in the agricultural industry (such as stems, roots, sawdust, and wood waste), is increasingly being considered as a promising resource for further processing and utilization. This approach allows for the unlocking of their beneficial properties while simultaneously reducing the volumes of WB directed to landfilling or incineration.

Currently, WB primarily serves as animal feed (~90% of the total processed amount), while only a small portion (~10% of the total processed amount) is sold for culinary purposes or as dietary supplements [3]). However, WB contains a significant amount of carbohydrates and other macro- and microelements. In their natural state, they exhibit low biological availability, but additional processing procedures enable their consideration as a substrate for microbial cultivation [4]. Utilizing WB in this direction opens up a broad horizon for the production of numerous other compounds that can be applied both in the food industry and in other fields.

2. Objects and methods

The literature analysis was conducted using scientific search systems, namely PubMed and ScienceDirect. The literature search was performed using the following keywords: wheat bran, application of wheat bran, bioconversion of wheat bran.

Within the framework of this work, 107 scientific sources in English and Russian were analyzed.

Inclusion criteria:

- Published scientific articles.
- Publication period: 1985–2025.
- Publications from Scopus and WOS databases.
- Articles from official websites of specialized institutions: WHO (World Health Organization).

Exclusion criteria:

- Publications issued before 1985.
- Publications not included in the Scopus and WOS databases.
- The article's focus is on the use of wheat bran in industry, as well as the use of wheat bran as the main substrate source in microbial fermentation processes.

3. Wheat bran

Wheat (Triticum aestivum L.) is one of the most important cereal crops cultures, and refined wheat flour is widely used for cooking in almost every household. Wheat bran represents a by-product of the flour milling industry. The term "bran" denotes a complex fibrous structure that includes insoluble compounds such as xylans, lignin, cellulose, and hemicellulose, as well as soluble polysaccharides like galactans and fructans. Additionally, bran is rich in essential minerals such as iron, zinc, manganese, magnesium, and phosphorus [5]. Wheat bran contains both water-soluble (1.5–4%) and water-insoluble (35–48.4%) dietary fibers [6].

In the food industry, cereal crops are typically processed into flour, yielding a product output within the range of 70–80% of the initial grain weight, which depends on the crop variety, growing conditions, and the specifics of the milling process [7]. In this process, approximately 25% of the grain weight constitutes bran, the main by-product resulting from hulling and milling. Wheat bran represents the outer layers of wheat grain and consists of various tissues, including pericarp (fruit coat), testa (seed coat), hyaline layer, and aleurone layer, the latter belonging to the endosperm. Bran is characterized by histological and chemical heterogeneity, and the choice of methods for their processing to extract valuable components depends on the specific target tissue [8].

According to WHO report [9], the amount of wheat produced as of 2024 was projected to be approximately 780 million tons, accounting for slightly more than 27% of the total cereal production. If all the wheat were to be ground into flour, it would result in approximately 190 million tons of wheat bran alone. Such quantities of wheat bran require attention, as although they are a by-product, they represent a resource that can be utilized in production chains. The structure of a wheat grain is shown in Figure 1.

4. Chemical composition of wheat bran

The data on the composition of wheat bran, expressed as a percentage of dry matter, are presented in Table 1 [3].

Table 1. **Chemical composition of wheat bran (Dry matter basis, mass%) [3]**
Таблица 1. **Химический состав пшеничных отрубей в пересчете на сухое вещество (масса,%) [3]**

Proteins	Fat	Carbo-hydrates	Ash	Total dietary fibres	Crude fibres
14.4	2.3	64.0	1.9	12.1	2.9

Chemical composition of wheat bran is influenced by various factors, including the region of production and the type of wheat [10]. The second, equally important factor, includes the conditions and depth of grain processing. As a result, the content of various components may vary. This is due to the fact that different processing methods can remove different layers of bran, which will change the final composition [11]. At the same time, wheat bran can undergo further processing in various ways, which leads to an increase in the extracted substances [12].

When describing the chemical composition of wheat bran, it is possible to identify major components, the presence of which is mandatory, but may vary depending on various factors.

4.1. Carbohydrates in wheat bran

The carbohydrates in wheat bran include cellulose (30–50%), hemicellulose (15–35%), and lignin (10–25%) [13].

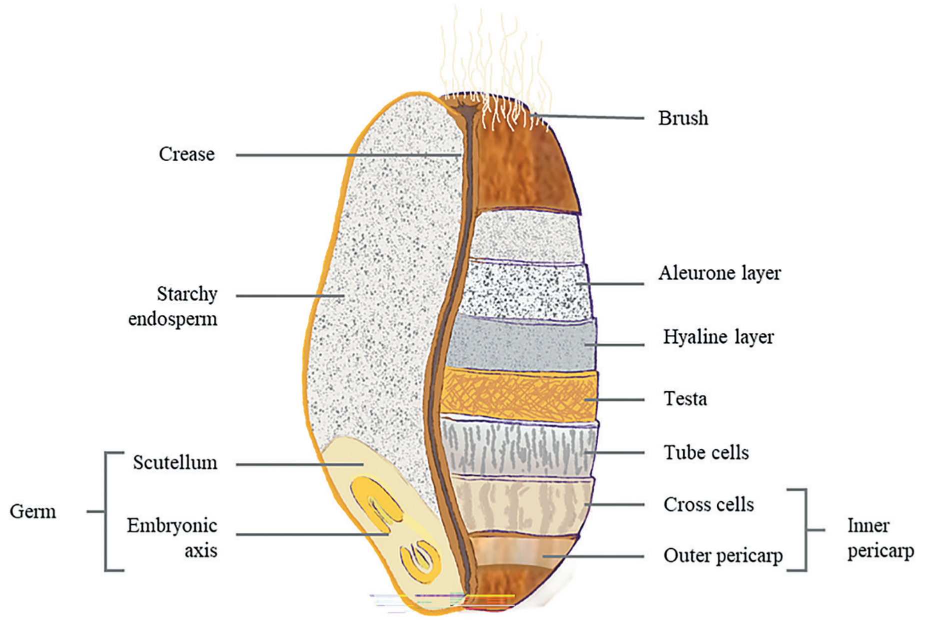

Figure 1. **Schematic representation of wheat grain. The prototype of the image was an article [3]**
Рисунок 1. **Схематическое изображение пшеничного зерна. Прототипом изображения служила статья [3]**

Starch is a branched polysaccharide composed of amylose and amylopectin. The difference between these two components lies in the chemical bonds between glucose monomers. Amylose predominantly contains α-(1→4) bonds, resulting in a linear structure, while amylopectin has more frequent α-(1→6) bonds, leading to a more branched structure. Starch extracted from wheat bran shows a higher amylose content compared to starch from wheat grain [14]. This chemical characteristic of wheat bran is of interest because the addition of starch with a high amylose content improves the properties of food products. For example, such products have a reduced glycemic response due to lower starch digestibility [15].

Mature wheat grains contain two types of starch granules: Type A (diameter > 9.9 μm) and Type B (diameter < 9.9 μm) [16]. In general, wheat grain starch contains 70–80% Type A granules and no more than 30% Type B granules by weight [17]. In one study, when comparing starch extracted from wheat bran with starch obtained from regular wheat, it was noted that the former has an increased content of Type B granules [14].

The size of starch granules is significant during enzyme processing, particularly with alpha-amylase. Smaller particles exhibit a higher hydrolysis rate due to their larger surface area and greater enzyme accessibility [18].

4.2. Non-starch carbohydrates in wheat bran

The main components of wheat bran are non-starch polysaccharides, such as heteroxylans, mixed-linked β-glucans, and cellulose. These components account for approximately 46% of the total volume of industrial wheat bran [19].

Cellulose is undeniably considered the most abundant organic substance on the planet. Its annual growth is equal to $1{,}5 \times 10^{12}$ tons, which allows it to be considered an inexhaustible source of raw materials [20]. Its molecular structure consists of numerous glucose residues linked by β-(1→4) glycosidic bonds. Cellulose forms long chains that are tightly packed together. This is ensured by intramolecular and intermolecular interactions of the molecule's atoms [21]. The interaction between the surface of crystalline cellulose molecules occurs through: hydrogen bonds, electrostatic attraction between layers, dispersion forces [22]. This multilayer structure is crucial for biotechnology. On the one hand, the complex, highly ordered, and densely packed fibrillar architecture of cellulose complicates its hydrolysis [23]. On the other hand, it has found application in various fields of nanotechnology, such as the production of functional membranes.

Hemi-cellulose is a widely distributed polysaccharide that can occupy up to one-third of the dry plant biomass. It represents a collective term for heterogeneous polysaccharides, whose monomers most often have a β-(1→4) linkage. These polysaccharides have a common feature: they are embedded between cellulose microfibrils and bind it through adhesion mechanisms [24]. In general, hemi-cellulose consists of pentoses (xylose, arabinose) and hexoses (glucose, galactose, mannose), as well as uronic acids. The composition may vary depending on the plant species [25]. Arabinoxylan is a key structural component of wheat bran cell walls, accounting for 10.9% to 26.0% of their total content on a dry matter basis [1]. It consists of a backbone of β-(1–4)-linked D-xylose pyranosyl units, to which α-L-arabinofuranose substituents are attached at positions (O)-2 and/or (O)-3 of xylose residues. Some arabinose residues are further linked by an ether bond at position (O)-5 to ferulic acid [26]. Ferulic acid-substituted residues play a significant role in gel properties due to their ability to interact with each other through the formation of ferulic acid dimers [27]. This polymer exhibits several structural forms: linear, branched, and H-shaped [28]. Substituents in the arabinoxylan structure play an important role in cellulose binding within the cell wall. Low-substituted arabinoxylan binds more easily to cellulose, thereby promoting fiber bonding. Conversely, under-substituted arabinoxylan binds less effectively to cellulose fibrils and is more readily extractable by water [29].

Lignin is predominantly deposited in the cell walls of secondarily thickened cells, rendering them rigid and impermeable. This compound provides protection to cell wall polysaccharides against microbial attack [30]. Lignin exhibits a complex and variable molecular structure, composed of three covalently linked subunits: guaiacyl, syringyl, and p-hydroxyphenyl [31]. The application of lignin in food products presents multiple areas of interest. Primarily, it demonstrates potent free radical scavenging capacity [32,33]. Additionally, lignin provides protection against UV radiation and inhibits foodborne pathogens [34]. Notably, a study has confirmed that lignin effectively suppresses the growth of *Staphylococcus aureus* ATCC25923 and *Salmonella enterica ATCC*13076 [35].

4.3. Wheat bran proteins

From the perspective of the food industry, wheat bran is of significant interest as a source of vegetable protein. Overall, the total protein content is considerably higher compared to wheat grain. This is due to the uneven distribution of protein within the grain, with the highest concentration found in the subaleurone and aleurone layers [36,37]. It is evident that wheat bran possesses high potential as raw material for the production of various protein products and preparations. These substances can find extensive application in agriculture for feed fortification. Similarly, they can be considered as inexpensive raw material for the preparation of food products with elevated protein content. For instance, one study involved the production of protein concentrate using alkaline extraction, followed by enrichment of bread and pasta [38]. Another research yielded protein isolates obtained through the treatment of wheat bran with lactic acid bacteria [39].

4.4. Qualitative analysis of wheat bran proteins

One of the key components of wheat bran is the aleurone layer. Proteomic analysis of this layer has been conducted by several researchers. To date, it is known that the qualitative composition of proteins is influenced by numerous factors. The aleurone layer contains a large amount of storage proteins belonging to the globular type. Their quantity varies significantly depending on the wheat variety. For example, in tetraploid wheat variety Mexicali, their content was about 35%, while in soft wheat variety Babbler it was approximately 74.9% [40]. In one experiment, using the Osborne protein extraction method, the following data were obtained: total protein content 12.086%, water-soluble albumins (2.43%), salt-soluble globulins (1.93%), alcohol-soluble prolamins (2.47%), and acid-soluble glutelins (5.25%) [41].

Wheat bran contains a wide variety of proteins, with the functions of some still unknown at present. Among the identified proteins, those performing protective functions can be distinguished. These include inhibitors of α-amylase and proteases, which are capable of protecting the endosperm from enzymatic degradation. At the same time, β-amylase was found, capable of hydrolyzing starch to maltose [42]. Its activity is likely limited by its existence in a bound state. Experiments conducted with barley grains show that β-amylase becomes active when the grain is exposed to proteases, which release it and restore its activity [43]. The presence of β-amylase inhibitors in the endosperm and aleurone layer is also noted [44]. Currently, it is known that amylase and trypsin inhibitor proteins are among the allergens, which are also thermostable [45]. Among the proteins, three more storage globulins were discovered: globulin-1, globulin-3A, and Gsp-1 [42]. An investigation of the amino acid composition of wheat bran revealed a high content of asparagine [46]. Proteomic analysis of proteins revealed that most proteins are involved in metabolic pathways and stress protection [42].

5. The use of wheat bran in industry

Summary information on the examples of bran application in various forms in industrial fields is presented in Table 2. The main areas of wheat bran usage in industrial applications are also shown in Figure 2.

Currently, wheat bran is primarily used as a feed additive, while its application in the food industry remains limited. Only a small portion of wheat bran is used in food products on a commercial scale. Given the significant volumes of accumulated bran biomass and the low cost of products made from them, the flour milling industry is actively seeking new directions for their high-value application. Bran serves as a valuable ingredient, especially in the diet of ruminants, contributing to balanced nutrition and providing several benefits for the health of the animals' digestive system, carbohydrate absorption, and mineral requirements [3]. Additionally, bran can be used in combination with other waste products for feed purposes. For example, in combination with sugar beet waste [47]. Such feed combinations have a positive impact on protein content and transform human-edible products obtained from cows, increasing energy and protein content by 6.8 and 5.3 times, respectively.

In the food industry, bran is added to bakery products to increase fiber content and alter the texture of the products. In this case, bran can be added to dough to modify its properties. Their addition affects the baking process and bread quality, including structural, functional, and sensory characteristics [48]. Furthermore, wheat bran can be presented in the form of powder or capsules, serving as a food additive to increase fiber intake [3].

Wheat bran can serve as a valuable source of various biologically active components, including carbohydrates [14] proteins and amino acids [49], and oils [50]. Additionally, wheat bran is rich in other compounds such as phenolic substances, B vitamins, and minerals, which opens up opportunities for their use in the production of nutraceuticals and functional food products [1].

Enzyme-treated wheat bran serves as a source of starch. Furthermore, starch extracted from wheat bran can be hydrolyzed into glucose, which then serves as raw material for fermentation processes that allow the production of lactic acid, succinic acid, ethanol, and/or butanol [51].

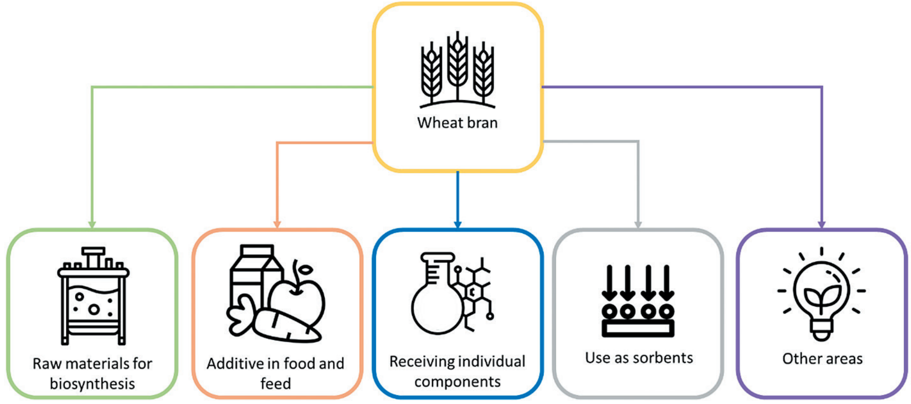

Figure 2. **Schematic representation of the main areas of wheat bran application**
Рисунок 2. **Схематическое изображение основных областей применения пшеничных отрубей**

Table 2. **Overview of wheat bran applications**
Таблица 2. **Обзор областей применения пшеничных отрубей**

Area	Content \ form of wheat bran	Application \ product	Source
Feed industry	Wheat bran and beet pulp mixture	Feed for dairy cows	[47]
Food industry and nutraceuticals	Wheat bran powder/flour	High-fiber bakery products	[48]
	Wheat bran powder, tablets and capsules	Dietary supplement to increase fiber intake	[3]
	Wheat bran subjected to hydrolysis and extraction	Wheat bran starch	[14]
	Wheat bran subjected to hydrolysis and extraction	Acetone, butanol, ethanol	[51,85]
	Wheat bran subjected to protein extraction	Proteins	[53]
	Wheat bran subjected to autolysis by proteolytic enzymes	Branched amino acids	[49]
	Wheat bran	Wheat oil	[50]
	Wheat bran subjected to alcohol extraction and $Ba(OH)_2$ extraction	Arabinoxylan	[55,56]
	Wheat bran subjected to ethanol precipitation and enzymatic treatment	Beta-glucans	[57]
	Wheat bran subjected to pressure-assisted alkaline extraction	Ferulic acid for vanillin production	[59]
Chemical industry	Acid degradation of xylose or glucose from wheat bran	Furfural production	[1]
Agricultural industry	Organic waste from cereal bran	Improve soil structure and water retention due to high N, P, and K content	[68,86]
Sorbents	Organic waste from cereal bran	Dye absorbent	[60–62]
		Absorbent for organic chlorine compounds and benzene aqueous solutions	[63]
		Removal of Cr(VI), Pb(II), and Cd(II) from wastewater	[64–67]
Energy storage	Chemical industry Agricultural industry	Removal of Pt(IV) from wastewater	[69,70]
		Supercapacitors and energy storage devices	[71]
	Sorbents	Strain sensors	[72,73]
	Unprocessed wheat bran	Biogas production	[74–78]
Construction and buildings	Organic waste from cereal bran	Reinforcement, insulating filler, lightweight and sustainable buildings. Cement binder	[79]
Medicine and cosmetology	Molecule derived from wheat bran	Antimicrobial peptide	[80]
	Molecules derived from wheat bran	Antioxidant peptides	[81]
	Wheat bran extract	Wound healing extracts	[82]
Textile industry	Processed wheat bran	Tanning agents	[83,84]

Wheat bran, containing 13–18% protein, represents a promising source for protein extraction. The main components of bran proteins are albumins and globulins, characterized by a more balanced amino acid composition. Compared to endosperm proteins, bran proteins feature higher contents of lysine, arginine, alanine, asparagine, and glycine, as well as lower levels of glutamine, proline, phenylalanine, and sulfur-containing amino acids. Due to these characteristics, bran proteins have higher biological and nutritional value [52,53]. Autolysis of wheat bran using proteolytic enzymes can be utilized to produce a mixture of amino acids, which can subsequently be incorporated into other products [49].

Wheat oil is another product that can be obtained through extraction from wheat bran. Wheat oil contains high amounts of fatty acids in the form of oleic and linoleic acids, as well as carotenoids. This product can be used in cosmetology [54].

Arabinoxylans are the main structural component of wheat bran cell walls and can be extracted using various methods, although their commercial application is challenging [55,56]. More interestingly, arabinoxylan can be decomposed into arabinose and xylose, followed by xylitol production. Xylitol is a sweetener that can be used by diabetics and is also utilized in toothpaste formulations [1].

Beta-glucans present in wheat bran can be obtained through extraction using 70% ethanol, followed by treatment with alpha-amylase under high temperature conditions. Beta-glucans can be used as dietary supplements for individuals with diabetes or heart diseases [57].

Ferulic acid is the main phenolic compound that can be extracted from wheat bran. It is claimed that ferulic acid possesses antioxidant, antimicrobial, and anti-inflammatory activities, thus having high potential for application in the food, medical, and cosmetic industries. The simplest method for extracting ferulic acid from wheat bran involves extraction with anhydrous ethanol followed by centrifugation [58,59].

Furfural and 5-HMF are by-products and toxic products of wheat bran processing, but they can also be produced through the acidic degradation of xylitol or glucose and subsequently used as solvents in various applications [1]

Although cereal bran is primarily processed in the feed and food industries, economic development opens up new technical and engineering possibilities for their broader use.

Wheat bran, due to its relatively high content of proteins, potassium, and phosphorus, can be used as a fertilizer for growing cultivated plants. There is also evidence that wheat bran can be used as a sorbent, particularly absorbing malachite green and methylene blue [60–62]. Additionally, wheat bran can act as a sorbent for certain chlorine-containing compounds [63] and for ions of heavy metals such as platinum, lead, chromium, and cadmium [64–87]. Furthermore, it is possible to produce charcoal from wheat bran, which can also adsorb various air pollutants [68].

The carbon from wheat bran can also be utilized in green energy, particularly for creating components used in electronics, such as capacitors or carbon anodes [69,70] and even sensors [71].

Due to its high content of fermentable carbohydrates, such as starch and cellulose, bran is potentially excellent raw material for biorefineries, where biogas and valuable chemical compounds can be produced from it [72,73].

Another interesting area of application for wheat bran is construction. Wheat bran is a cheap, porous, and lightweight material that can also be disposed of through biodegradation. Currently, heat-insulating panels, biocomposites, and other building elements are being developed. When combined with other natural materials such as clay, it is possible to develop a cheap option for temporary housing or structures required during construction [74–78].

In addition to research on obtaining already known molecules, more fundamental developments are being carried out, including the search for unique proteins and peptides. It has been shown that wheat bran contains compounds that potentially have antibacterial effects. For example, the peptide WBp-1 has demonstrated antibacterial properties against *Listeria monocytogenes* by damaging the bacterial cell wall [79]. In another study, bioactive peptides obtained from wheat bran were investigated. A total of 91 bioactive peptides were found, with some exhibiting antioxidant activity against H_2O_2-induced oxidative stress in HepG2 cells. Two peptides (DLDW and DLGL) may be the most promising antioxidant peptides due to their higher binding affinity to Keap1 [80]. All described molecules have potential applications in medical or cosmetic purposes. Wheat bran extracts are also being developed for medical purposes. For example, cold aqueous and methanolic extracts of wheat bran are potentially beneficial for promoting the healing of burn wounds. This development requires further research but shows promise in cases where traditional measures are not effective enough or formulations with one or more active substances are too expensive [81].

Another interesting application of wheat bran is the production of carbon material (CM), which can be used in the leather industry. CM from bran is an interesting inexpensive and environmentally friendly tanning agent. CM potentially represents a step forward in the further use of wheat bran waste in sustainable leather manufacturing [82].

Wheat bran contains a large amount of polysaccharides that have potentially significant applications. For example, it has been shown that wheat bran contains antifreeze polysaccharides. Such polysaccharides can be used both for producing dough more resistant to crystallization and for preserving other food products, or even applied in other industries [83,84].

Wheat bran undoubtedly deserves attention as it is economically affordable raw material that may contain solutions to many non-trivial issues. Apart from the already described applications requiring pure or chemically treated wheat bran, it is worth considering wheat bran as a substrate for microbial cultivation.

6. The use of wheat bran as a substrate for biosynthesis

Wheat bran is a complex multicomponent system. Due to its composition, wheat bran can be used in fermentation to produce various products, but often require preliminary treatment with enzyme preparations, certain chemical compounds, temperature exposure with or without water, or step-by-step processing with the addition of different microorganisms. The goal of hydrolysis in this multicomponent system is most often polysaccharides, dietary fibers, and proteins, although lipids can also be a target. Depending on the objectives, thermal hydrolysis, hydrothermal hydrolysis, enzymatic hydrolysis, chemical hydrolysis, and microbiological hydrolysis methods can be used.

Thermal hydrolysis is represented by prolonged temperature exposure and is primarily associated with the degradation of insoluble dietary fibers and proteins, while also leading to an increase in the amount of water-soluble dietary components [87]. Most often, thermal hydrolysis is used as a preliminary treatment.

Hydrothermal hydrolysis is a prolonged temperature exposure of wheat bran in a solvent. The processes of thermal hydrolysis are valid for it, and there are also known particular cases: hydrothermal hydrolysis reduces the amount of hydrocarbon molecules such as phytane and, due to temperature exposure, leads to the degradation of proteins and certain peptides such as glutathione, which results in an increase in the number of disulfide bonds [88].

Chemical methods make it possible to extract many components, but chemical hydrolysis methods for biosynthesis are a preliminary stage, most often quite specific. Wheat bran can be treated with compounds such as sulfuric acid, iron (III) chloride.

Different strains of microorganisms have varying effects on the nutritional and functional properties of fermented wheat bran, which primarily depends on the microorganism itself and fermentation conditions.

Treatment with microbial starters or enzyme preparations leads to the degradation of the wheat bran structure, destruction of the cell wall, and protein breakdown, while biologically active and bioavailable components of primary interest, such as peptides, amino acids, and other nitrogenous compounds with physiological functions, are formed during fermentation by the main fermentation culture.

The scheme of the main methods of wheat bran treatment is presented in Figure 3.

Mycelial fungi (*Aspergillus, Trichoderma, Mucor* and *Rhizopus*), yeasts (*Saccharomyces* and *Candida*) and bacteria (*Lactobacillus* and *Bacillus*) are commonly used in the biotransformation of wheat bran to degrade cell wall fibers, thereby improving the availability and digestibility of nutrients. Yeast and lactic acid bacteria are well-established starters frequently used to enhance the nutritional and structural characteristics of wheat bran [4].

One of the simplest examples of using food bran as a substrate is the saccharification of wheat bran for bioethanol production. This process can be carried out by numerous microorganisms or microbial consortia, including those of the genera *Aspergillus*, *Penicillium*, *Rhizopus*, *Mucor* and *Trichoderma*. The highest content of soluble carbohydrates (198.8 mg/g) was obtained by the strain *P. chrysogenum* F.00814 after 3–5 days of pretreatment. Subsequently, ethanol biosynthesis was conducted using strains *S. cerevisiae Levuline Fb* and *K. marxianus* NCAIM Y.00959 and *Z. mobilis subsp. mobilis* B.01327T. The maximum ethanol content was 7.6% (v/v), obtained after 7 days of fermentation with wort containing 20% (w/v) initial reducing sugar, initiated by mixed cultures (*S. cerevisiae* and *K. marxianus*), with the addition of *Z. mobilis subsp. mobilis* B.01327T after two days [89].

For vitamin B12 production, wheat bran was pre-fermented using *Levilactobacillus brevis* and *Lactiplantibacillus plantarum*, along with a strain of *Saccharomyces cerevisiae* yeast, followed by the addition of *Propionibacterium freudenreichii*. Through 24 hours of treatment with the starter culture, a vitamin B12 yield of 55 ± 3.4 ng/mL was achieved, which is approximately 6 times higher than that obtained in the fermentation process without pre-fermentation [90,91].

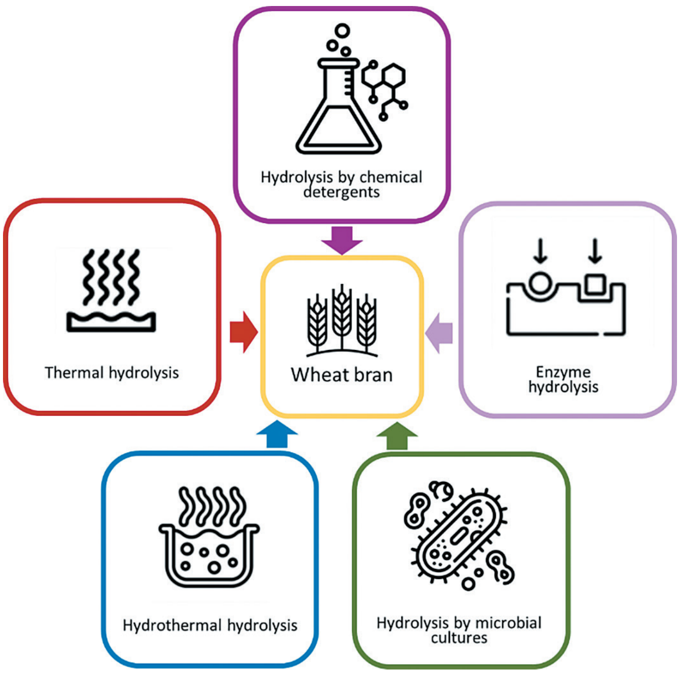

Figure 3. **Schematic representation of the methods of hydrolysis of wheat bran**

Рисунок 3. **Схематическое изображение способов гидролиза пшеничных отрубей**

Table 3. **Application of wheat bran for cultivation**

Таблица 3. **Применение пшеничных отрубей для культивирования**

Producer	Product	Source
Strains of *Aspergillus, Trichoderma, Mucor, Rhizopus, Saccharomyces, Candida, Lactobacillus, Bacillus*	Bioconversion before obtaining other products	[4]
Strains of *Aspergillus, Penicillium, Rhizopus, Mucor and Trichoderma*	Bioconversion before ethanol production	[89]
Propionibacterium freudenreichii	Vitamin B12	[90,91]
E. coli BL21	Acetic acid	[92]
P. acidilactici ZPA026	Feed with adsorbent	[94]
Pichia stipitis (NCIM 3497)	Xylitol	[95]
Fusarium graminearum Ec220	Xylanases	[99]
T. reesei NCIM 1186 N. crassa	Cellulases	[96]
Aspergillus sojae	Polygalacturonase	[100,101]
Aspergillus niger NRRL 3112	β-glucosidase	[97]
Aspergillus flavus	Carboxymethyl cellulase	[98]
P. pastoris GS115	Xylans and xylooligosaccharides	[93]
Aspergillus niger / Lactobacillus fermentum JN248	Ferulic acid	[102,103]
Clostridium beijerinckii ATCC55025	Acetone, butanol, ethanol	[104]
Aspergillus terreus CICC40205	Itaconic acid	[105]
S. diastaticus ATCC13007	Ethanol	[106]
Rhodosporidium toruloides DSM 4444	Carotenoids	[107]

The use of recombinant strains for product generation using wheat bran is also known. A complex approach was used for acetic acid production with *Escherichia coli*. Acetylxylan esterase from *Phingobacterium soilsilvae Em02* was integrated into *E. coli*. Before recombinant *E. coli* cultivation, wheat bran was treated with amylase and papain. Combined with acetylxylan esterase catalysis, this pathway yielded 0.39 g of acetic acid per 1 g of wheat bran, equivalent to a conversion rate of 39% [92].

An additional example of recombinant strain utilization involves the production of xylanase A from *Bacillus amyloliquefaciens*, which was expressed in *Pichia pastoris GS115* under the AOX1 promoter. The resulting endo-active xylanase exhibited transglycosylase activity and was capable of hydrolyzing insoluble xylan from wheat bran, as well as beech and birch xylan. Wheat bran was processed using this xylanase to obtain xylooligosaccharides and xylans from wheat bran [93].

An interesting approach also involves the use of fermented wheat bran as a nutritional feed. *Lactobacillus* was utilized for the preliminary treatment of wheat bran, followed by the addition of *Pediococcus acidilactici ZPA026* culture. The processed bran was subsequently used as pig feed. Feeding pigs with fermented wheat bran reduced the concentration of heavy metals in pig feces, thus revealing fermented wheat bran as a feed with sorbent properties [94].

Another notable method is the production of xylitol through fermentation using *Pichia stipitis*, achieving a yield of 6.134 g/L, whereas chemical treatment with sulfuric acid resulted in a yield of 1.42 g/L [95].

Furthermore, wheat bran can be utilized as raw material for enzyme production from microorganisms. Cultivation of *T. reesei* NCIM 1186 and *N. crassa* NCIM 1021, without preliminary treatment with enzymes or other cultures, was employed for cellulase production [96].

Partial replacement of the carbon source with wheat bran can also increase the yield of produced enzymes. For instance, when using wheat bran for β-glucosidase production, substituting the carbon source with wheat bran and additionally adding glycerol allowed obtaining an enzyme activity of 9.3 U/mL of medium through the cultivation of *Aspergillus niger* NRRL 3112, compared to 5.6 U/mL in the medium without co-substrate [97]. The use of wheat bran as a co-substrate also led to an increase in the expression of thermostable carboxymethyl cellulase during *Aspergillus flavus* cultivation, which can be used for the production of commercial carboxymethyl cellulase [98].

Wheat bran can be used as a nutrient medium for selecting enzyme producers. For example, *Fusarium graminearum Ec220* was used in the presence of carboxymethyl cellulase to produce xylanase with low cellulase activity [99]. *Aspergillus sojae* ATCC20235, which was cultivated in the presence of wheat bran, was used to produce polygalacturonase with increased activity [100,101].

Using *Aspergillus niger*, it is possible to produce ferulic acid without the use of other microorganisms or enzyme preparations. The efficiency of ferulic acid synthesis was 358.72 µg per 1 g of decarboxylated wheat bran [102]. Similarly, the bacterium *Lactobacillus fermentum JN248* was used to produce ferulic acid, yielding 10.24 mg per 1 g of decarboxylated wheat bran [103].

Sulfuric acid-treated wheat bran hydrolysate can be used to produce acetone, butanol, and ethanol. When cultivating *Clostridium beijerinckii* ATCC55025, the yields of acetone, butanol, and ethanol were 2.2, 8.8, and 0.8 g/L, respectively [104]. Also, on a medium with wheat bran hydrolysate obtained by sulfuric acid treatment, *Aspergillus terreus* CICC40205 can be cultivated to produce itaconic acid. The itaconic acid titer using this mutant strain was 49.65 g/L [105].

Another method for ethanol production is the cultivation of *S. diastaticus* ATCC13007 on wheat bran hydrolysate obtained in the presence of alpha-amylase, cellulase, beta-glucosidase, cellobiase, hemicellulase, and xylanase. The yield ranged from 8.9 to 11.4 g/L of the nutrient medium[106].

Equally interesting is the production of carotenoids through fermentation using *Rhodosporidium toruloides* DSM 4444. Through chemical hydrolysis in the presence of $FeCl_3$ and microwave exposure, followed by enzymatic hydrolysis, it is possible to achieve carotenoid yields of up to 14.8 mg/g, as well as lipid yields of up to 5.2 g/L [107].

7. Conclusion

Based on the results of conducted information research, analysis of scientific publications, and comparison of experimental data obtained by researchers from different scientific groups, it has been concluded that the search for applications of wheat bran is relevant both in established industries and in more innovative fields. The chemical composition of wheat bran has been described, and various industries and forms of processing wheat bran for their application have been considered. In addition to the known use as feed additives, the processing of wheat bran potentially allows their use as a cheap building material or adsorbent, while chemical treatment enables the extraction of various individual components. One of the promising solutions for the processing of wheat bran is the production of various products through bioconversion. Wheat bran represents a cheap substrate, although it is limited by the presence of a large number of complex and insoluble compounds. Pre-hydrolyzed wheat bran becomes a more accessible source of carbon and energy, which allows it to be used for the cultivation of various microorganisms or their consortia, thus revealing its potential as a substrate for the production of a wide range of biologically active molecules. Thus, the combination of various hydrolysis methods opens up opportunities for the biosynthesis of certain hard-to-access enzymes, sugars, vitamins, and simple organic acids. This approach significantly expands the potential practical applications of wheat bran in modern industry, highlighting its versatility and economic feasibility in various technological processes.

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AUTHOR INFORMATION	СВЕДЕНИЯ ОБ АВТОРАХ
Affiliation	**Принадлежность к организации**
Gabdulla F. Kurbanov, Research Assistant, Laboratory of Biotechnology and Bioengineering, All-Russia Research Institute for Food Additives 55, Liteiny pr., 190000, St. Petersburg, Russia Tel.: +7–937–164–45–66 E-mail: tatanka.sn@gmail.com ORCID: https://orcid.org/0000-0002-3958-7326	**Курбанов Габдулла Фаритович** — лаборант-исследователь, лаборатория биотехнологий и биоинженерии, Всероссийский научно-исследовательский институт пищевых добавок 190000, Санкт-Петербург, Литейный пр., 55 Тел.: +7–937–164–45–66 Email: tatanka.sn@gmail.com ORCID: https://orcid.org/0000-0002-3958-7326
Artem O. Prichepa, Research Assistant, Laboratory of Biotechnology and Bioengineering, All-Russia Research Institute for Food Additives 55, Liteiny pr., 190000, St. Petersburg, Russia Тел.: +7–931–588–40–14 E-mail: prichepa.a@yandex.ru ORCID: https://orcid.org/0000-0002-1037-5629	**Причепа Артем Олегович** — лаборант-исследователь, лаборатория биотехнологий и биоинженерии, Всероссийский научно-исследовательский институт пищевых добавок 190000, Санкт-Петербург, Литейный пр., 55 Тел.: +7–931–588–40–14 E-mail: prichepa.a@yandex.ru ORCID: https://orcid.org/0000-0002-1037-5629
Anatoliy P. Nepomnyashiy, Junior Researcher, Laboratory of Biotechnology and Bioengineering, All-Russia Research Institute for Food Additives 55, Liteiny pr., 190000, St. Petersburg, Russia Tel.: +7–929–116–25–29 E-mail: nepomnyashiy.95@mail.ru ORCID: https://orcid.org/0000-0003-0088-2704	**Непомнящий Анатолий Павлович** — младший научный сотрудник, лаборатория биотехнологий и биоинженерии, Всероссийский научно-исследовательский институт пищевых добавок 190000, Санкт-Петербург, Литейный пр., 55 Тел.:+7–929–116–25–29 e-mail: nepomnyashiy.95@mail.ru ORCID: https://orcid.org/0000-0003-0088-2704
Ekaterina Yr. Ivanova, Research Assistant, Laboratory of Biotechnology and Bioengineering, All-Russia Research Institute for Food Additives 55, Liteiny pr., 190000, St. Petersburg, Russia Tel.: +7–905–999–07–15 E-mail: e_iva.nova@mail.ru ORCID: https://orcid.org/0009-0002-0793-2719	**Иванова Екатерина Юрьевна** — лаборант-исследователь, лаборатория биотехнологий и биоинженерии, Всероссийский научно-исследовательский институт пищевых добавок 190000, Санкт-Петербург, Литейный пр., 55 Тел.: +7–905–999–07–15 E-mail: e_iva.nova@mail.ru ORCID: https://orcid.org/0009-0002-0793-2719
Natalya Yu. Sharova, Doctor of Technical Sciences, Professor of the Russian Academy of Sciences, Deputy Director for Research, All-Russia Research Institute for Food Additives 55, Liteiny pr., 190000, St. Petersburg, Russia Тел.: +7–900–624–11–09 E-mail: n.sharova@fncps.ru ORCID: http://orcid.org/ 0000-0002-4208-9299 * corresponding author	**Шарова Наталья Юрьевна** — доктор технических наук, профессор РАН, заместитель директора по научной работе, Всероссийский научно-исследовательский институт пищевых добавок 190000, Санкт-Петербург, Литейный пр., 55 Тел.: +7–900–624–11–09 E-mail: n.sharova@fncps.ru ORCID: http://orcid.org/ 0000-0002-4208-9299 * автор для контактов
Contribution	**Критерии авторства**
Gabdulla F. Kurbanov: conducting information research, creating drawings and tables. **Artyom O. Prichepa**: conducting information research, creating tables. **Ekaterina Yr. Ivanova**: conducting information research. **Anatoliy P. Nepomnyashiy**: conducting information research, creating drawings. **Natalya Yu. Sharova**: systematization of information data results, editing the article.	**Курбанов Г. Ф.**: проведение информационных исследований, создание рисунков и таблиц. **Причепа А. О.**: проведение информационных исследований, создание таблиц. **Иванова Е. Ю.**: проведение информационных исследований. **Непомнящий А. П.**: проведение информационных исследований, создание рисунков. **Шарова Н. Ю.**: систематизация результатов информационных данных, редактирование статьи.
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