УДК [664.696:635.658]

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ПЕРСПЕКТИВНІ СОРТИ СОЧЕВИЦІ ДЛЯ ВИРОБНИЦТВА СНЕКОВИХ ПРОДУКТІВ В УКРАЇНІ

Анотація

У статті представлено результати комплексного дослідження агрономічних і технологічних характеристик одинадцяти сортів харчової сочевиці, зареєстрованих у Державному реєстрі сортів рослин України, з метою визначення їхнього потенціалу для використання у виробництві снекової продукції на основі рослинної сировини. Враховуючи актуальність здорового харчування, попит на високобілкові та натуральні продукти, зростає інтерес до використання локальних бобових культур, зокрема сочевиці, як функціонального інгредієнта в технологіях виготовлення снеків. Проведено порівняння сортів за чотирма ключовими критеріями: урожайність, тривалість вегетаційного періоду, вміст білка та рівень посухостійкості. Дані отримано з архівів інформаційно-довідкової системи «Сорт» та офіційних джерел щодо сортових характеристик. У результаті встановлено суттєву різницю між сортами за всіма показниками. Найкращі значення за сукупністю досліджуваних параметрів продемонстрували сорти ЄС Максимум, Блонді та СНІМ 18, які мають найвищу врожайність (до 2,81 т/га), підвищений вміст білка (до 29,5 %), високу посухостійкість (8 балів) та короткий або помірний вегетаційний період. Такі характеристики є критично важливими для промислового використання сочевиці в технологіях екструзії або випікання, оскільки визначають економічну доцільність виробництва, стабільність текстури, вологоутримуючу здатність та харчову щільність кінцевих продуктів. Розглянуто взаємозв'язок між якістю сировини та властивостями готових снеків, на прикладі порівняння дешевих та преміальних зразків екструдованої продукції з кукурудзи, зернових і бобових. Це дозволило підкреслити важливість не лише сортових особливостей, а й подальшої технологічної обробки сировини. Також окреслено перспективи наступних етапів дослідження: вивчення нутрієнтного складу відібраних сортів, аналіз вмісту клітковини, мінералів (заліза, цинку), фолієвої кислоти та антипоживних речовин (фітатів, танінів), а також оцінка впливу пророщування, ферментації та екструзії на біодоступність поживних компонентів. Запропоновані результати створюють основу для розробки інноваційної технології виробництва снеків із сочевиці, адаптованої до умов українського ринку, що дозволить поєднати високу харчову цінність, стабільну якість та доступну собівартість.

Ключові слова: сочевиця, сорти, снекова продукція, антипоживні речовини, здорове харчування, технологія виробництва снеків.

Received 04.07.2025 **Revised 04.08.2025**
Reviewed 17.07.2025 **Approved 02.09.2025**

Cite as Vancouver Citation Style

Cherniakov V., Melnyk O. Promising lentil varieties for the production of snack products in Ukraine. Grain Products and Mixed Fodder's, 2025; 25 (3, 99): 21-26. **DOI https://doi.org/10.15673/gpmf.v25i3.3202**

Cite as State Standard of Ukraine 8302:2015

Promising lentil varieties for the production of snack products in Ukraine. / Cherniakov V., et al. // Grain Products and Mixed Fodder's. 2025. Vol. 25, Issue 3 (99). P. 21-26. **DOI https://doi.org/10.15673/gpmf.v25i3.3202**

UDC [663.4:664.9:637.5:641.1]
DOI https://doi.org/10.15673/gpmf.v25i3.3208

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ANALYSIS OF EXISTING TECHNOLOGIES FOR SECONDARY PROCESSING OF GRAIN RAW MATERIALS IN BEER PRODUCTION

Abstract

The article reviews and systematizes the main modern technologies for the secondary processing of grain residues generated during beer production. The main attention is paid to brewer's grains as the most massive by-product of brewing. Traditional and innovative approaches to its storage, stabilization, drying, fermentation, bioprocessing, and use in various sectors, including feed production, food industry, bioenergy, and biotechnology, are analyzed. It is shown that the most common use of brewer's grains is in the production of animal feed due to the high content of crude protein, fiber, minerals, and essential amino acids. The article discusses in detail the technologies for drying brewer's grains, which allow to increase their *shelf life, prevent microbiological spoilage and ensure convenient transportation. The methods of fermentation and bioprocessing of brewer's grains using microorganisms, enzyme preparations and heat treatment are presented, which contribute to increasing their bioavailability and digestibility in feed. The latest technological solutions used in the EU, the USA, Canada and China, including extrusion, microwave processing, ultrasonic disintegration and combined methods, are separately characterized. The technologies for using brewer's grains as a raw material for the production of biogas, bioethanol, enzymes and dietary fiber are also considered. The paper emphasizes the potential for implementing a circular economy in the brewing industry. The paper emphasizes the potential of implementing a circular economy in the brewing industry, where the recycling of grain raw materials can help reduce waste, reduce the burden on the environment and generate additional economic benefits. The expediency of an in-depth study of local technological practices of brewer's grains processing in Ukrainian craft and industrial breweries, taking into account their technical capabilities, climatic conditions and market demand, is substantiated. Comparative data for wet and dried brewer's grains per 100 g of weight are presented, which demonstrate a significant concentration of proteins (up to 30%), fiber (up to 50%) and micronutrients in the dried product. Potential areas of secondary use of brewer's grains in the food, feed, bioenergy, and chemical industries, in particular as a source of natural proteins, dietary fiber, fermentation substrates, and fertilizers, are revealed. Particular attention is paid to the possibilities of adapting foreign experience to Ukrainian realities, given the limited capacity of craft production. The expediency of introducing technologies for drying and storing brewer's grains to extend their service life is emphasized. The article summarizes the main scientific approaches and offers practical recommendations for producers in order to increase the economic efficiency and innovation of the Ukrainian brewing sector.*

Keywords: brewer's grains, secondary processing, grain raw materials, brewing by-products, feed, biotechnology, dietary fiber, bioenergy.

Introduction

Brewer's grains are one of the most significant by-products of the brewing industry, which produces millions of tons of this resource worldwide every year [2]. They are formed during the beer brewing process after malting and extraction of soluble components from grain, leaving behind a residue rich in organic and inorganic substances. In the context of modern food security and circular economy challenges, the use of by-products from the agricultural and food industries is becoming particularly important [2]. Brewer's grains are a rich source of protein (20–24%), fiber, polysaccharides, phenols, and other bioactive compounds. They are commonly used as feed for cattle, but innovative technologies are currently being developed for its processing for food and feed applications in order to increase its added value.

In the context of modern challenges related to reducing food waste and the need to ensure sustainable food production, brewers' grains are becoming particularly relevant. The global community is increasingly implementing a "zero waste" approach and developing the concept of sustainable food, in which every resource must be used as efficiently as possible [3]. Due to its chemical composition, brewers' grains fit perfectly into this paradigm. It contains high-value proteins, dietary fiber (primarily insoluble fiber), minerals (calcium, magnesium, phosphorus), polysaccharides, antioxidants, phenolic compounds, and other biologically active substances that determine its high nutritional and functional value [3].

In this regard, interest in the use of brewers' grains as an ingredient in the food industry has been growing in recent years. It is already being successfully integrated into the recipes of various food products: bakery products, snacks, meat products, meat substitutes, protein bars, functional beverages, etc. Such use not only reduces food waste but also contributes to the creation of innovative products that meet modern requirements for healthy nutrition and consumer expectations for environmentally friendly and functional products.

In the US and European countries, technologies for the deep processing of brewers' grains are being actively implemented, which allow improving their organoleptic properties, reducing moisture content, separating individual fractions, or enriching them with useful components. Some companies specialize in developing new food products with the addition of brewers' grains, offering consumers healthy and environmentally friendly alternatives to traditional products. In this way, brewers' grains are transformed from waste into a valuable food resource.

Analysis of recent studies and publications

Fig. 1 shows a description and diagram of the beer production process [2], which results in the formation of beer grains.

The first stage is malting, which involves soaking the grains and the process of sprouting them (1). The sprouted grains are crushed and dried in an oven to inhibit further growth and maintain enzymatic activity (2).

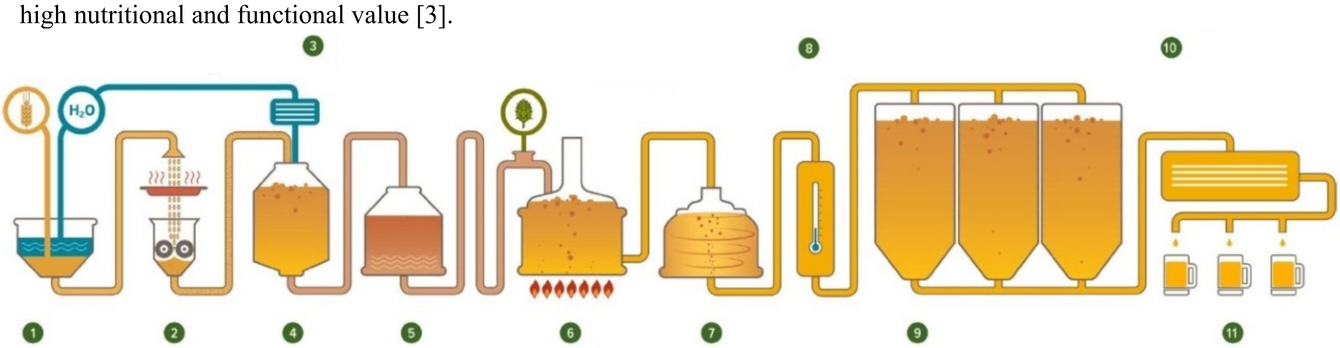

Fig. 1. Beer production diagram [2]

The operations performed in a brewery usually begin in a mash tun, where crushed malt grains (i.e. malt) are combined with hot water (3) to maximize enzyme activity and sugar extraction (4). After mashing, the brewer's grains are removed from the wort by filtration (5). Since most of the starch is converted to sugar, the starch content in the grains is reduced, but it still contains fiber and valuable nutrients, including vitamins and proteins. The collected wort is transferred to a boiling tun, where it is brought to a boil (6). Hops are added for bitterness, aroma, and as a natural preservative. After boiling, the wort must be quickly cooled to a temperature that promotes yeast fermentation (7, 8). The cooled wort is transferred to a fermentation vessel and mixed with yeast to initiate fermentation; the fermentable carbohydrates are consumed by the yeast, converting them to alcohol and carbon dioxide [2]. After primary fermentation, the beer is conditioned (9). The final beer product is filtered after it has achieved the desired taste and clarity (10) and is then bottled (11).

Beer grains are the solid residues of malted barley and other grains used in brewing, from which sugar was extracted during mashing, contributing to the taste and body of the beer. Beer grains account for approximately 85% of the total amount of all brewing by-products. After the mashing process, the insoluble part of the barley grain is mixed with the soluble (liquid) wort. The wort, which will be fermented into beer, is filtered through the grains.

It is known [3] that spent grain is one of the most voluminous types of waste in the world in terms of mass. As is known [3-5], the production of 1 hectoliter of beer generates about 20 kg of spent grain (moisture content 75-80%). This means that even small craft breweries (with a production volume of 500–1,000 hl/year) generate up to 10–20 tons of beer spent grain annually, which creates potential for the processing or commercial use of spent grain in many industries, particularly in the food and agricultural industries [3-5]. Average annual global beer production is estimated at approximately 39 million tons, with about 3.4 million tons produced in the Europe an Union, 2 million tons of which are produced in Germany alone [3-5]. For every 100 liters of beer brewed, about 20 kg of wet spent grain remains as a by-product [3-5].

Proper storage conditions are crucial for the use of grain, as high levels of moisture, polysaccharides, and proteins can lead to rapid spoilage, posing a potential health risk [7]. Many craft breweries lack the necessary infrastructure and equipment to safely store grain for long periods of time, with animal feed production remaining the most common method of processing.

It is stated [1] that one of the most common and simplest uses of grain waste from beer production in Ukraine is its processing into feed for cattle. However, most of this valuable product is still simply thrown away.

Beer grains are rich in nutrients, making them an economically efficient source of nutrients for feed formulations for cattle and other farm animals.

Table 1 shows the nutrient content in 100 grams of barley malt before the mashing process.

The data in Table 1 shows that barley malt is a source of protein (10.28 g/100 g of malt), carbohydrates (71.2 g/100 g of malt), and dietary fiber (7.1 g/100 g of malt).

During the beer production process, some substances are transferred from the malt to the wort,

Table 1 – Chemical composition of barley malt (mg)/100 g before mashing

№	Component	Amount	Daily requirement	% of daily requirement met
1	kcal	361	2200	16.41
2	Proteins, g	10.28	62	16.58
3	Carbohydrates, g	71.2	288	24.72
4	Fats, g	1.84	67	2.74
5	Mono- and disaccharides, g	0.8	100	0.8
6	Saturated fatty acids, g	0.386	15	2.57
7	Ash, g	1.37	-	-
8	Water, g	8.21	2000	0.41
9	Fiber, g	7.1	20	35.5
10	Sodium, mg	11	2300	0.48
11	Potassium, mg	224	2500	8.96
12	Phosphorus, mg	303	800	37.87
13	Magnesium, mg	97	400	24.25
14	Calcium, mg	37	1250	2.96
15	Copper, mg	0.27	1	27
16	Manganese, mg	1.193	2	59.65
17	Selenium, mcg	37.7	70	50.85
18	Zinc, mg	2.06	12	17.16
19	Iron, mg	4,71	10	47.1
20	B1, mg	0.309	1.7	18.17
21	B2, mg	0.308	2	15.4
22	B6, mg	0.655	2	32.75
23	B5, mg	0.577	5	11.54
24	B9, mcg	38	400	9.5
25	C, mg	0.6	90	0.66
26	E, mg	0.57	15	3.8
27	K, mcg	2.2	120	1.83
28	PP, mg	5.636	20	28.18
29	A, mcg	1	900	0.11
30	Beta-carotene, mg	0.011	5	0.22

while others remain in the spent grain.

Substances that pass from malt to wort:

1. Sugar (mainly maltose): enzymes break down the starch in malt grains into fermentable sugars, primarily maltose, which are necessary for the fermentation process carried out by yeast.

2. Proteins: Proteins from malt contribute to the formation of beer and its taste. Some proteins also contribute to the formation of foam or beer head.

3. Enzymes: Enzymes, including amylase and protease, help convert starch into sugar and break down proteins into smaller peptides and amino acids.

4. Amino acids: Amino acids are the building blocks of proteins and play an important role in yeast metabolism during fermentation. They also contribute to the flavor profile of beer.

5. Minerals: Various minerals, such as calcium, magnesium, and trace elements, are extracted from malt and affect the overall taste and stability of beer.

6. Flavor compounds: Compounds such as phenols and esters, which contribute to the aroma and flavor of beer, are partially derived from malt and are influenced by mashing and fermentation processes.

Substances remaining in spent grain:

1. Fiber: Indigestible plant material, including cellulose and hemicellulose, remains in spent grain. This fiber is not fermentable and provides bulk.

2. Unfermented carbohydrates: complex carbohydrates that have not been converted to sugar during mashing remain in the spent grain.

3. Protein residues: proteins that have not been completely broken down during mashing and filtration remain in the spent grain.

4. Lignin: Lignin, a complex organic polymer, is a structural component of plant cell walls and remains in the spent grain.

5. Microminerals: Some minerals and trace elements remain in the spent grain after the mashing process.

It is important to note that the exact composition of substances in wort and spent grain may vary depending on the specific beer recipe, malt type, and brewing technologies used.

Table 2 shows a comparison of the chemical composition of wet and dry beer grains.

Table 2 – Chemical composition of wet and dry beer grains after the mashing process g (mg)/100 g [16-20]

№	Component	Moist grain (average moisture content 75–80%)	Dry grain (0% moisture content)
1	Dry residue, g	20,0–25,0	100,0
2	Protein (crude), g	4,5–7,5	19,0–30,0
3	Fiber (total), g	10,0–14,0	40,0–50,0
4	Fats (ether extracts), g	1,5–2,5	6,0–10,0
5	Non-nitrogenous extracts (NNE), g	1,5–3,0	5,0–10,0
6	Ash (minerals total), g	0,5–1,2	2,0–5,0
7	Lignin, g	2,0–4,0	10,0–15,0
8	Energy value, kcal	~3,5–5,0	~15,0–17,0
9	Leucine, g	~1,5	~7,8
10	Isoleucine, g	~0,9	~4,5
11	Lysine, g	~0,8	~3,8
12	Methionine, g	~0,3	~1,5
13	Valine, g	~1,0	~5,2
14	Threonine, g	~0,7	~3,8
15	Phenylalanine, g	~1,0	~5,0
16	Arginine, g	~1,1	~5,4
17	Potassium (K), mg	250,0–400,0	1000,0–2000,0
18	Phosphorus (P), mg	150,0–225,0	600,0–900,0
19	Calcium (Ca), mg	40,0–50,0	150,0–200,0
20	Magnesium (Mg), mg	50,0–75,0	200,0–300,0
21	Iron (Fe), mg	0,7–1,5	3,0–6,0
22	Zinc (Zn), mg	0,5–1,0	2,0–5,0
23	Manganese (Mn), mg	0,3–0,6	1,5–3,0
24	Sodium (Na), mg	< 10,0	< 50,0
25	Vitamin B1 (thiamine), mg	0,15–0,25	0,60–1,00
26	Vitamin B2 (riboflavin), mg	0,08–0,15	0,30–0,60
27	Vitamin B3 (niacin), mg	2,0–3,5	8,0–14,0
28	Vitamin B6 (pyridoxine), mg	0,2–0,4	0,8–1,6
29	Folic acid (B9), mcg	30,0–60,0	120,0–240,0
30	Vitamin E, mg	0,5–1,0	2,0–4,0
31	Vitamin A (retinol equiv), mcg	< 10,0	< 40,0

The chemical composition of spent grain may vary depending on the quality of barley or other cereals used in beer production, as well as other factors such as harvest time, malt germination conditions, and the quality of unsweetened raw materials. The data in Table 2 show that spent grain is a concentrate of biologically active compounds that can be used in various industries, from animal husbandry to the food industry. Its nutritional value is based on proteins, fiber, lipids, minerals, and vitamins, mainly B vitamins. Since wet spent grain contains up to 75–80% water, all the main nutrients are present in significantly lower concentrations than in dry spent grain.

The protein content in dry offal reaches 19–30g/100 g, which makes it possible to use offal as a source of vegetable protein for the food industry.

Fiber accounts for up to 50% of dry matter, mainly of the insoluble type (cellulose, hemicellulose, lignin), which can be used to improve the functioning of the digestive system in both humans and animals.

The amino acid profile, especially the high content of leucine, valine, arginine, and phenylalanine, indicates its value for the formulation of feed or functional foods.

The significant content of minerals (K, P, Mg, Ca) and B vitamins makes spent grain a potential source of micronutrients and cofactors in dietary nutrition.

Thus, the drying process not only extends the shelf life of spent grain, but also makes it suitable for technological standardization as a feed or food ingredient.

To assess the technological potential of brewer's grains, it is advisable to compare its main components with other agro-industrial wastes. As can be seen from Table 3, brewer's grains exceed bran, soybean hulls, and corn cobs in terms of protein, fat, and fiber content. This makes it a versatile substrate for both feed and the food industry.

According to Table 2, brewers' grains are a lignocellulosic material rich in proteins, fiber (20–70%), minerals, and vitamins [3]. According to [33], brewers' grains contain up to 30% crude protein, 50% fiber, 10% fat, and significant amounts of minerals and B vitamins in dry matter [33]. The high content of structured fiber (hemicellulose, cellulose, lignin) gives brewers' grains potential as a feed additive with prebiotic properties.

The significant variability in the composition of spent grain, even within a single brewery, was confirmed in a study [35], indicating the need to standardize parameters for its industrial use [35]. Processing into feed proteins, organic acids, enzymes, or fertilizer additives is considered particularly promising [34].

To preserve the quality of the grain and extend its storage life, it is important to reduce excess moisture by drying [4, 5]. The moisture content of dried grain should not exceed 10% [4, 5]. The drying process not only prevents spoilage but also reduces the volume of grain, improving its storage and transportation conditions [4, 5]. As is known [5, 6], grain can be stored for up to three months by adding substances such as lactic acid, potassium sorbate, or acids such as acetic, formic, or benzoic acid.

In modern studies of secondary processing of beer grains, several key technological blocks are distinguished — stabilization, hydrolysis, fermentation, extrusion — which contain specific schemes for the production of functional products.

Table 4 shows a comparison of beer grain processing technologies.

The table shows a wide range of modern technologies for recycling beer grains, the conditions for their implementation, productivity, and technical and

Table 3 - Comparison of the main components of brewers' grains with other agro-industrial wastes %

№	Indicator / Raw material	Brewer's grains	Wheat bran	Corn cobs	Soybean hulls
1	Protein (%)	19–30	15–17	4–6	10–12
2	Fiber (%)	40–50	10–12	25–35	45–55
3	Fat (%)	6–10	4–6	1–2	<1
4	Ash (%)	2–5	4–6	2–3	5–7
5	NFE (sugars, starch, %)	5–10	35–40	50–60	5–8
6	Energy value, kcal/kg	~15,0	~12,0	~10,0	~11,0

Table 4 - Comparison of beer grain processing technologies

№	Technology	Conditions	Products / Output	Characteristics of the method
1	Convection drying	+50–70 °C, 6–48 hours	Dry beer grain (<10% moisture content) (researchgate.net)	Long, energy-intensive
2	Pulsed fluidized bed	+70–90 °C, 0.5–0.7 m/s air	Fast drying, better functional properties of proteins	More efficient than conventional drying
3	Air-microwave and vacuum drying	250 W, +54 °C, 1.1 mbar	High sensory appeal of the dry product	High capital costs
4	Alkali combined with Viscozyme L	NaOH 1 M, +50 °C, 60 min	≈50% protein extract	Alternative to acid hydrolysis
5	ZA / acid + enzyme combination	72% H_2SO_4, +120 °C, 17 min	Xylose (~22 g/l) → xylitol 0.7 g/g	High return on added value
6	Enzymatic and acid/alkaline	Asp. niger enzyme cocktail	Glucose 18 g/l, xylose 6 g/l	No pre-treatment of raw materials required
7	Extrusion	15.8% moisture, 164 rpm, +122 °C	↑ soluble fiber 67%	Versatile for food and feed products
8	Extrusion and solid phase technology	F. oxysporum after extrusion	Maximum yield of arabinoxylans, antioxidant compounds	Synergistic effect, but more difficult to implement
9	Solid phase (Neurospora crassa)	61.5% moisture, bioreactor	Ethanol 74 g/kg dry matter	Bioenergy potential

economic characteristics. All methods can be divided into three groups:

1.Drying technologies (items 1–3):
Convection drying (No. 1) is traditional, but very energy-intensive and time-consuming. It is suitable for small-scale production without intensive technological load.

Pulse fluidized bed drying (No. 2) reduces drying time and better preserves biologically active substances, in particular proteins. It is considered more promising, although it requires specialized equipment.

Air-microwave and vacuum drying (No. 3) produces the highest quality product in terms of organoleptic properties and stability, but requires significant capital expenditure, which limits its availability to small businesses.

Drying efficiency increases with the use of the latest technologies, but the economic feasibility of their implementation depends on the scale of production.

2. Extraction-hydrolysis and enzymatic methods (items 4–6):

Alkaline with Viscozyme L (No. 4) is a simple alternative to acid hydrolysis, allowing up to 50% protein extract to be obtained, which is suitable for use in the food or feed industry.

The acid-enzyme combination (No. 5) provides a high yield of xylose, which is then fermented into xylitol, a product with high added value. This method is commercially attractive, especially in the pharmaceutical and dietary segments.

The A. niger enzyme cocktail (No. 6) avoids the aggressive chemical hydrolysis stage. It is an environmentally friendly and gentle method, but with a moderate yield of glucose and xylose.

Enzymatic methods are becoming key in the production of food ingredients and sugars from brewers' grains, especially when environmental purity of the process is required.

3. Biotechnological and combined solutions (items 7–9):

Extrusion (No. 7) is a universal approach for both the food and feed industries. Its advantages include an increase in soluble fiber (up to +67%), preservation of bioactive substances, and the ability to create products with improved texture.

Extrusion + SSF (solid-state fermentation) (No. 8) provides the highest yield of antioxidant and functional substances (arabinooligans), but requires complex technological integration and careful control of fermentation processes.

Pure SSF with Neurospora crassa (No. 9) is promising for the production of bioethanol — up to 74 g/kg. This opens up an energy direction for the reuse of brewer's grains, especially in farms or biogas plants.

Combined methods provide the highest biotechnological efficiency but require more complex logistics and investment in equipment.

All of the technologies considered have their own area of applicability depending on the target product:

1.If the goal is food additives and compound feed, extrusion, fermentation, and enzymatic extraction are most appropriate.

2.To obtain high value-added nutrients — proteins, xylitol, antioxidants — it is better to use hydrolysis-enzymatic schemes.

3. In the context of the circular economy and energy recovery, bioenergy and combined fermentation technologies are promising.

The choice of technology should be based on a balance between economic feasibility, the level of technological equipment of the enterprise, the target market, and the expected product quality. In the future, hybrid integrated approaches will have the greatest effect, allowing the processing of brewery grains to be combined with other agricultural waste and creating closed production cycles.

Scientists in China have investigated the potential of using spent grains as a raw material for the production of biofuel, which serves as an alternative to fossil fuels [10]. The process involves preliminary acid treatment followed by the production of bioethanol through fermentation using various microorganisms, including Pichia stipitis and Kluyveromyces marxianus [10], Neurospora crassa and Fusarium oxysporum [11], as well as Scheffersomyces stipitis and E. coli [12]. The data obtained indicate that biogas production alone is not economically viable; however, integrating the process into a biorefinery that produces additional products will increase its economic feasibility [9, 13, 14].

Studies have shown [15] that brewers' grains are an excellent source for the extraction of phenolic compounds, which can be obtained using traditional extraction methods or advanced technologies such as ultrasonic and microwave extraction [15]. Phenolic compounds, known for their antioxidant properties, have attracted considerable interest due to their beneficial effects on human health [15]. In addition, protein extraction from beer grains has been effectively achieved using hydrothermal pretreatment at +60°C in combination with the use of protease enzymes [16,17]. Scientists [16,17] extracted polyphenols using ultrasound, and enzymes as the final product obtained a protein hydrolysate, where glutamic acid and proline predominated.

Beer grain, with its high moisture content and rich chemical and nutritional profile, has proven to be an excellent substrate for microbial cultivation [7]. In addition, the sweetener xylitol can be obtained from spent grain hydrolysate along with the production of lactic acid. Lactic acid has become the focus of intensive research due to its diverse applications in various industries, including pharmaceutical, chemical, food, textile, and leather [16, 17]. Traditionally, lactic acid is produced by fermenting sugars such as glucose, fructose, sucrose, and lactose, as well as starch, which accounts for 90% of global production, while chemical synthesis accounts for the remaining 10% [16, 17]. Given the low selling price, scientists [18] have tried to find new, cheaper raw materials from which lactic acid can be obtained. One way to reduce production costs is to use lignocellulose and starchy by-products. Spent grain can also be used as a carrier to immobilize yeast during fermentation, thus replacing commercial carriers [18]. It has a high yeast binding capacity (430 mg/g dry matter), has no negative effect on the fermentation process, and the taste of beer is easily applied and can be restored by washing in an alkali solution. Pullulan can also be

Table 5 - Nutritional value of compound feed with the addition of brewers' grains for different types of animals

№	Types of animals	Characteristics of use
1	Cattle	High digestibility, promotes the development of rumen microflora, a source of effective fiber. Up to 20–30% in the diet.
2	Pigs	Limited use (up to 10–15%), requires additional protein and energy balance. Often used after enzyme treatment.
3	Poultry	Up to 5–10% in compound feed for laying hens and turkeys. Used as a source of fiber and micronutrients.
4	Rabbits, sheep	Inclusion of up to 15–20% without significant reduction in growth.
5	Fish (aquaculture)	After fermentation — as a source of protein. Can replace up to 30–40% of fish meal (under certain processing conditions).

extracted from spent grain. Pullulan and its derivatives are used in the food, pharmaceutical, and electrical industries due to their ability to form fibers and films that are insoluble in oil and impermeable to oxygen. Pullulan can be obtained from spent grain using Aureobasidium pullulans.

Brewer's grains contain a variety of nutrients that are beneficial to the human diet, including vitamins, fiber, and minerals [28]. As noted by scientists [24], enriching durum wheat flour with brewers grains significantly improves the nutritional profile of the flour, increasing the fiber content by 135%, β-glucan by 85%, and total antioxidant capacity by 19% compared to standard durum wheat flour. Adding 10% brewers' grains to pasta recipes improves the organoleptic and technological properties of the finished products [24].

In bread production, the addition of brewers' grains flour not only increases the fiber content but also improves water absorption, improving the texture and volume of bread [25]. Similarly, its inclusion in cookies has a positive effect on the quality of the finished product, but a negative effect on appearance and aroma has been noted [26].

It is also known [27] that brewers' grains are used as an additive to meat products, such as sausage products, to increase the fiber content and reduce the fat content in the finished product [27]. Similarly, adding brewers' grains to snacks increases their fiber and protein content on the one hand, but on the other hand negatively affects the taste of the finished product, especially when the grain content exceeds 30% [28, 29].

Unfavorable sensory characteristics when adding brewers' grains to food products, including changes in color and texture [30], can be minimized by adding corn starch and whey protein isolate [31]. Another approach to solving these issues involves pre-treatment in an autoclave, which depolymerizes the structure of the grain, improving its appearance and shelf life. This process allows a higher percentage of spent grain to be used in food products [30]. In general, the acceptable limit for spent grain content in food products is about 20%, with 10–15% spent grain being most acceptable for maintaining optimal sensory characteristics [32].

Due to its rich chemical composition, brewers' grains are a valuable feed ingredient for various types of farm animals. In the feed industry, it is used in three main forms: wet (direct feeding on farms, shelf life — up to 48 hours without preservatives); silage (mixed with pomace, straw, grass, corn grits); dry (dried spent grain as a component of compound feed recipes).

Dry spent grain has the best storage and transportability characteristics, and also allows it to be standardized as a feed additive or included in premix formulas.

Table 5 shows the nutritional value of compound feed with the addition of brewers' grains for different types of animals.

A number of studies [36] have shown that brewers' grains can successfully replace part of soybean meal or grains in compound feed formulas. To ensure better digestibility and absorption, brewers' grains are often pre-treated, as shown in Table 4.

Such methods make it possible to increase the concentration of digestible protein (up to 30–40%), reduce the content of anti-nutritional factors, and improve the taste properties of the feed.

The advantages of using brewers' grains in compound feed are the low cost of raw materials, the enrichment of compound feed with fiber, proteins, and minerals, and the positive effect on digestion and growth of animals.

It is known [36] that farms attached to breweries in Ukraine and Poland use spent grain to feed cattle (wet or silage). In Germany and the Netherlands, automated drying units and granulators are widely used to convert spent grain into high-protein feed additives.

In India and China, fermented spent grain is actively used in the production of fish feed, which reduces the cost of importing protein components.

Spent grain is a promising, inexpensive, and nutritious raw material for the feed industry. It can partially or completely replace traditional ingredients, reducing the cost of feed and increasing its biological value. The optimal use of brewers' grains requires appropriate processing (fermentation, drying), but in the long term contributes to the formation of a safe, sustainable, and cost-effective livestock system.

Conclusions

This review provides a comprehensive analysis of ways to further process brewers' grains in both the food industry and agriculture. A comprehensive analysis of modern technologies for the secondary processing of brewers' grains, the main by-product of brewing, was carried out. Traditional and innovative methods of raw material processing, in particular drying, fermentation, hydrolysis, extrusion, and biological treatment, were considered. The prospects for using brewers' grains as a functional ingredient in the food industry (production of flour products, protein supplements, antioxidants), as well as a high-protein and fibrous component of compound feed for animals, poultry, and fish, were demonstrated. It is concluded that the introduction of beer grain processing technologies contributes to the creation of resource-saving production systems, reduction of food waste, and development of a circular economy in the agro-industrial sector.

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УДК [663.4:664.9:637.5:641.1]

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АНАЛІЗ ІСНУЮЧИХ ТЕХНОЛОГІЙ ВТОРИННОЇ ПЕРЕРОБКИ ЗЕРНОВОЇ СИРОВИНИ ПРИ ВИРОБНИЦТВІ ПИВА

Анотація

У статті розглянуто та систематизовано основні сучасні технології вторинної переробки зернових залишків, що утворюються під час виробництва пива. Основна увага приділяється пивній дробині, як найбільш масовому побічному продукту пивоваріння. Проаналізовано традиційні та інноваційні підходи до її зберігання, стабілізації, сушіння, ферментації, біообробки та використання в різних секторах — зокрема в комбікормовому виробництві, харчовій промисловості, біоенергетиці та біотехнологіях. Показано, що найбільш поширеним напрямом використання пивної дробини є виробництво кормів для тварин завдяки високому вмісту сирого протеїну, клітковини, мінеральних речовин та незамінних амінокислот. Детально розглянуто технології сушіння пивної дробини, які дозволяють збільшити термін її зберігання, запобігти мікробіологічному псуванню та забезпечити зручність транспортування. Представлено методи ферментації та біо-обробки пивної дробини з використанням мікроорганізмів, ферментних препаратів та термічної обробки, які сприяють підвищенню її біодоступності та засвоюваності в кормах. Окремо охарактеризовано новітні технологічні рішення, що застосовуються в країнах ЄС, США, Канаді та Китаї, серед яких — екструзія, мікрохвильова обробка, ультразвукова дезінтеграція та комбіновані методи. Також розглянуто технології використання пивної дробини як сировини для виробництва біогазу, біоетанолу, ензимів і харчових волокон. У роботі підкреслено потенціал впровадження циркулярної економіки в пивоварній промисловості, де вторинна переробка зернової сировини може сприяти зменшенню обсягів відходів, зниженню навантаження на навколишнє середовище та отриманню додаткової економічної вигоди. Обґрунтовано доцільність поглибленого вивчення локальних технологічних практик переробки пивної дробини в умовах українських крафтових і промислових пивоварень, з урахуванням їхніх технічних можливостей, кліматичних умов та ринкового попиту. Наведено порівняльні дані для вологої та висушеної дробини на 100 г маси, які демонструють значну концентрацію білків (до 30%), клітковини (до 50%) та мікронутрієнтів у висушеному продукті. Розкрито потенційні напрями вторинного використання пивної дробини у харчовій, кормовій, біоенергетичній та хімічній промисловості, зокрема як джерела натуральних білків, харчових волокон, субстратів для ферментації та добрив. Особливу увагу приділено можливостям адаптації закордонного досвіду до українських реалій, враховуючи обмежені потужності крафтових виробництв. Акцентовано на доцільності впровадження технологій сушіння та зберігання пивної дробини для подовження терміну її використання. Стаття узагальнює основні наукові підходи та пропонує практичні рекомендації для виробників з метою підвищення економічної ефективності та інноваційності пивоварного сектору України.

Ключові слова: пивна дробина, вторинна переробка, зернова сировина, побічні продукти пивоваріння, комбікорм, біотехнології, харчові волокна, біоенергетика.

Received 04.07.2025 **Revised 15.08.2025**
Reviewed 17.07.2025 **Approved 02.09.2025**

Cite as Vancouver Citation Style

Telezhenko L., Dubyna A. Analysis of existing technologies for secondary processing of grain raw materials in beer production. Grain Products and Mixed Fodder's, 2025; 25 (3, 99): 26-34. DOI https://doi.org/10.15673/gpmf.v25i3.3208

Cite as State Standard of Ukraine 8302:2015

Analysis of existing technologies for secondary processing of grain raw materials in beer production. / Telezhenko L. et al.// Grain Products and Mixed Fodder's. 2025. Vol. 25, Issue 3 (99). P. 26-34. DOI https://doi.org/10.15673/gpmf.v25i3.3208