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Complex processing of brewery waste for obtaining feed additives

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Abstract. One of the key directions in the development of the modern brewing industry in Ukraine is the rational utilisation of organic waste generated during beer and malt production. The article aimed to investigate the composition, physicochemical properties, and utilisation methods of the main brewing wastes, using Mykulynetsky Brewery as a case study. Quantitative and qualitative characteristics of solid (brewer's spent grain, malt sprouts, barley screenings, trub) and liquid (transport water suspensions of spent grain, protein sediment, residual yeast, lager sediments, wastewater) wastes were determined. It was established that brewer's spent grain accounts for up to 85% of all solid production residues and represents a valuable raw material for feed production due to its high content of protein, fibre, and minerals. Experimental studies were conducted on the processes of spent grain dewatering and drying, malt sprout and barley screenings grinding, and filtration of concentrated suspensions from the fermentation-brewing workshop. Optimal conditions for phase separation of suspensions were determined, yielding a concentrated protein

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fraction with 73% moisture content and a filtrate with a low concentration of suspended solids (0.1-0.45 g/dm³). A technology for the comprehensive processing of all major brewing wastes was proposed, resulting in two types of feed products: dewatered brewer's spent grain and granulated protein-vitamin feed containing 35% crude protein, 5-7% fibre, and 8-10% moisture. The developed technology also provides for the neutralisation of acidic and alkaline wastewater to standard parameters and their reuse in the production cycle. Practical implementation of the proposed technology significantly reduces environmental impact, decreases waste generation, increases resource efficiency of production, and creates a closed-loop system for the utilisation of secondary resources in the brewing industry

Keywords: brewing industry; waste utilisation; wastewater; feed products; technology; technical ecology

Introduction

One of the key challenges facing the modern brewing industry in Ukraine is the rational management of production waste of organic origin. During the production of beer and malt, a significant amount of solid and liquid waste is generated, which has high potential as secondary raw material. According to O. Servetnyk & O. Piven (2024), an average Ukrainian brewery produces up to 10-15 thousand tons of solid and several hundred thousand cubic meters of liquid residues annually. However, only a small portion of these materials is effectively utilised. This issue has become particularly relevant in the context of the ongoing full-scale war, when food security, the stability of the agro-industrial sector, and the preservation of environmental balance are of strategic importance for the country. The processing of brewing waste into high-quality protein-vitamin feed products for livestock and poultry can significantly strengthen the national feed base and reduce dependence on imported resources. The main types of waste generated by Ukrainian breweries include barley screenings, malt sprouts, brewer's spent grain, yeast residues, lager and protein sediments, as well as technical wastewater. These wastes contain valuable nutrients – proteins, fibre, carbohydrates, vitamins, and minerals – which make them promising for secondary use, particularly in feed production. In Ukraine, there is no single technological approach to the comprehensive processing of these wastes. Most enterprises are forced to store or dispose of them as ordinary waste, leading to the loss of potentially valuable resources and increased environmental pressure. Therefore, the development of an integrated technology for the processing of all major brewing wastes, aimed at using their components for feed production and environmental protection, remains an urgent scientific and practical task.

The rational utilisation of food industry waste, particularly that generated in brewing, has been the focus of active research within both the global and Ukrainian scientific and technical communities. Numerous studies, like those by S. Chattaraj *et al.* (2024a), A. Soceanu *et al.* (2024), emphasised the high nutritional value of brewing by-products, which contain significant amounts of proteins, fibre, amino acids, B-group vitamins, minerals (Ca, Mg, P, Fe), and enzymes. The main wastes generated during beer production include residues from barley and malt polishing (cleaning) prior to milling, brewer's spent grain, residual brewing yeast, hop trub, as well as protein sediment and solid residues formed after wort cooling and clarification. A significant amount of wastewater is generated during the washing and disinfection of production facilities, equipment, containers, and pipelines. As stated by M. Verhuelsdonk *et al*. (2021), brewing waste also includes defective labels, crown corks, and glass breakage. However, not all brewing industry wastes can be considered as secondary material resources suitable for the production of commercial products. The main types of brewery waste of practical interest due to their quantity and composition suitable for feed production include: solid wastes (brewer's spent grain, barley screenings, malt sprouts, and grain husks); highly concentrated liquid wastes (transport water from spent grain, protein sediment, residual yeast, and lager sediment). Because the main brewing wastes retain the nutritional components of the raw materials, their processing is of great importance to both the food and agricultural industries.

Due to its high moisture content (up to 88%), wet spent grain has limited storage stability; therefore, various stabilisation and processing technologies have been developed (Terefe, 2022). The main methods include drying, ensiling, and preservation. According to L. Nyhan *et al*. (2023), S. Chattaraj *et al*. (2024b), dried brewer's spent grain is used in animal feed, baking, and as an additive to biogas substrates. Other brewing by-products also have processing potential. Malt sprouts contain proteins, B-group vitamins, and enzymes, enabling their use in feed production, baking, microbiological media, and enzyme preparation manufacturing. Protein sediment can be hydrolysed to obtain protein hydrolysates used in brewing and compound feed production (Karlsen & Skov, 2022). Under modern conditions, integrated processing of brewing waste – combining several technological approaches – has gained special importance, as it minimises the loss of valuable substances and yields value-added products. Studies by M. Pires Maria *et al*. (2023), G. Wei *et al*. (2024) demonstrated the effectiveness of such methods: drying and granulation of spent grain and yeast, biogas or ethanol production from brewing residues, and the use of protein sediment in feed concentrate manufacturing.

Thus, literature analysis shows that brewing waste represents a promising biotechnological raw material. Its rational utilisation contributes to reducing environmental impacts, increasing production efficiency, and creating new types of feed and food products. Despite the wide range of existing methods for the utilisation of malt and beer production waste, there is still no systemic, integrated technology for complete processing of secondary brewing resources. Existing solutions are often complex, multi-stage, and costly. The most promising direction is the production of protein-vitamin feed products based on all major brewing wastes. The purpose of the study was to develop a comprehensive technology for processing solid and liquid wastes of the Ukrainian brewing industry to obtain feed products and reduce environmental impact. To achieve this goal, the following objectives were set: to investigate the processes of processing solid and liquid brewing waste and study the possibilities of cleaning and reusing industrial wastewater; to develop a technology for obtaining a feed product; to develop a technology for the complex processing of brewing waste.

Materials and Methods

The main object of the study was solid and liquid waste generated during the beer production process at Mykulynetsky Brewery LLC, the production facilities of which are located in the town of Mykulyntsi, Ternopil region, Ukraine. The research period was January-September 2025. The research was conducted on the basis of the laboratories of the Odesa National University of Technology.

Methods of processing the main brewing waste. Beer grains were processed by dehydration and drying to a humidity of 10%. Dehydration was aimed at removing excess liquid, improving transportability and extending the shelf life of the product. In order to study the process of beer grains dehydration and choosing the optimal method in laboratory conditions, static and dynamic methods of its processing on polyethylene and metal meshes were tested. To ensure static dehydration conditions, the raw grain was placed in an even layer on a stationary filter material (according to the principle of a Nutsche filter). A metal mesh with square holes measuring 1.5 x 1.5 mm or a polyethylene mesh with rectangular holes measuring 0.5 x 1.5 mm was used as the filter elements. The process lasted for 2 hours, while the formed filtrate was collected in a receiving container (Fig. 1).

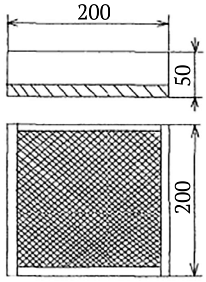

Figure 1. Dewatering of beer grains under stationary conditions
Note: materials: (1) metal mesh with square holes measuring 1.5 × 1.5 mm; (2) polyethylene mesh with rectangular holes measuring 0.5 × 1.5 mm
Source: authors' drawing

During the dynamic process, a cylindrical drum with the following main dimensions was made from the above-mentioned filter materials: diameter = 145 mm, length = 175 mm. The drum was equipped with a central axis for connection to the drive, which ensured its rotation around the axis at a speed of 0.35 rpm (Fig. 2). The moisture content of the material was determined after 1 and 2 hours during the dehydration process.

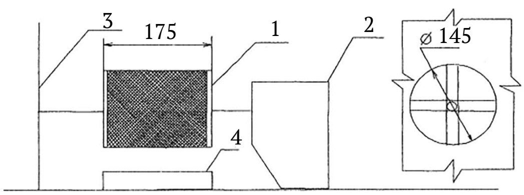

Figure 2. Dewatering of beer grains under dynamic conditions
Note: 1 – drum made of metal mesh with square holes measuring 1.5 × 1.5 mm; 2 – electric drive; 3 – tripod with holder; 4 – receiving tank
Source: authors' drawing

Drying of dehydrated grains. In laboratory conditions, hot air drying was carried out in a SESH-3M (Ukraine) drying cabinet (220 V, 50 Hz, 1,200 W) with the ability to regulate the temperature. To ensure uniform heating of the entire volume of material, it was periodically stirred. The drying temperature did not exceed +60°C, according to Y. Bulii *et al*. (2022), which did not impair the quality of the product.

Grinding of grain waste. The particle size composition of malt production waste was determined by sieving. For this purpose, a laboratory set of sieves with hole sizes from 2 to 0.5 mm was used. Grinding of dry malt production waste (barley bran and sprouts) was carried out using a laboratory mill OLISLAB 2100 (Olis, Ukraine), and the grinding efficiency was assessed by the particle size composition of the grinding products (Tertyshny *et al*., 2022). The flour production process included the preparation of raw materials, grinding and sorting of the resulting product. Given that the separate grinding of the product, previously sorted into fractions of a certain size, contributes to a more complete use of the grain, the barley screenings and malt sprouts were pre-sifted through sieves with opening sizes of 2.0; 1.0 and 0.5 mm. The grinding of fractions larger than 0.5 mm of dry malt waste was carried out in a laboratory mill for 3 minutes.

Separation of highly concentrated liquid waste. In order to isolate protein-containing substances from highly concentrated liquid waste of the fermentation and brewing plant, their phase separation was carried out by filtration on a laboratory installation (Fig. 3).

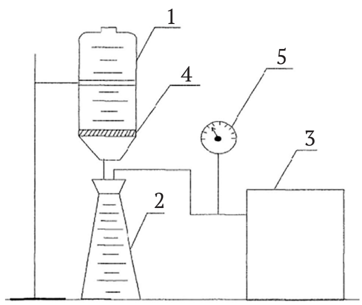

Figure 3. Laboratory setup for phase separation of highly concentrated liquid wastes
Note: 1 – filtering cylinder (volume – 2,000 mL, diameter – 80 mm); 2 – receiving conical flask (volume – 1,000 mL); 3 – vacuum pump: model VN-46 (Ukraine), Q = 45 l/min, P = 5 · 10-3 mm Hg, n = 500 rpm, m = 40 kg; 4 – filter: cotton belting (article 2073, Ukraine), BECO KD 7 filter cardboard (Eaton Filtration LLC, Germany); 5 – OBV1-100 vacuum gauge (model VT-100, Ukraine)
Source: authors' drawing

As filter materials, cardboard intended for filtering beer and cotton belting were used alternately. The pressure difference on the filter partition was created using a VN-46 vacuum pump, which provided a vacuum of up to 0.9 kgf/cm^2. Vacuum (rarefaction) was measured using a VT-100 vacuum gauge, the scale of which was graduated to -1 kgf/cm^2. Table 1 shows the parameters of the suspension filtration processes.

Table 1. *Parameters of the suspension filtration process of the fermentation and brewing plant*

Filtering material	Suspension volume, m^3	Sediment layer height (Hoc), m	Mass of solid particles (mth), kg	Sediment humidity, %	Filtrate volume (Vf), m^3	Concentration of suspended solids in the filtrate, g/dm^3
Belting	190×10^{-4}	2×10^{-3}	5.92×10^{-3}	73	174×10^{-3}	0.45
Cardboard	190×10^{-4}	2×10^{-3}	6.9×10^{-3}	73	174×10^{-3}	0.1

Note: the concentration of suspended solids in the mixture before filtration is 8.2 g/dm^3
Source: compiled by the authors

Purification of spent alkaline solution. In order to study the possibility of purifying the spent alkaline solution of the bottle washing machine from suspended substances and reusing it in beer bottling technology, it was filtered on a laboratory filter (Fig. 4). To purify and reuse the spent alkaline solution, laboratory tests were conducted using filtration through layers of activated carbon and sand of various grain sizes (0.7-3 mm).

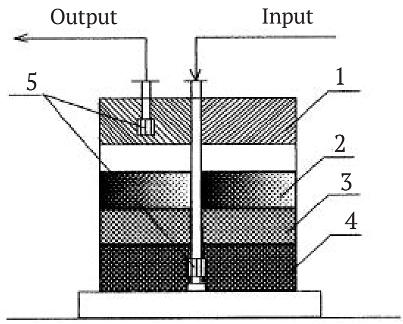

Figure 4. Laboratory filter for cleaning spent alkaline solution of bottle washing machine
Note: D = 100 mm; H = 800 mm; 1 – expanded polystyrene (0.8-2.5 mm); 2 – activated carbon AG-3 (1.0-2.8 mm); 3 – crushed quartz (0.7-1.2 mm); 4 – crushed quartz (2.0-3.5 mm); 5 – slotted nozzles
Source: authors' drawing

The principle of operation of the installation is the passage of liquid through a layer of bulk material. The filter materials for loading the installation consisted of four bulk layers. The choice of these materials and their arrangement in layers (from fine to coarse) is typical for multilayer filters. Crushed quartz (two fractions) provides mechanical filtration and acts as a supporting layer due to its high mechanical strength and insolubility. Activated carbon AG-3 is added to adsorb organic contaminants, colour, odour and chlorine, which is critical in the purification of technological solutions. Expanded polystyrene is used as a lightweight filter material that helps in the removal of suspended solids. Slotted nozzles in the laboratory filter provide a large contact area between the phases, creating optimal conditions for filtration.

Granulation and evaluation of granule quality. In laboratory conditions, a press granulator of the OPG 150 brand (Ukraine) was used to obtain beer grains granules (Fig. 5), a granulator with the following technological characteristics and modes: drive with a power of 1.5 kW; flat matrix; number of pressing rollers – 2 pcs, matrix diameter – 4.7 mm; mass fraction of moisture of the mixture fed for granulation – 16...18%; matrix heating temperature – +90 ± 5°C; temperature of granules at the exit of the press – +70 ± 3°C. The obtained granules with a length of 5-15 mm were dried in a SESH-3M cabinet dryer at a temperature not higher than +60°C for 15-45 minutes.

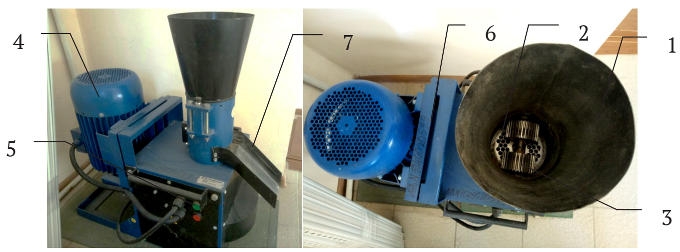

Figure 5. Press granulator OPG-150
Note: 1 – receiving hopper; 2 – matrix; 3 – pressing rollers; 4 – engine; 5 – control panel; 6 – housing; 7 – pellet tray
Source: authors' photo

Methods of physical and chemical analysis. During the experiments to study the composition and properties of brewing waste and their processing products, mainly methods of physical and chemical analysis were used. The study of the chemical composition of malting waste and beer grains was based on methods intended for the analysis of compound feeds and raw materials for compound feeds, in particular: method for determining moisture content (DSTU ISO 6496:2005, 2006); method for determining the content of nitrogen and crude protein (DSTU 7169:2010, 2011); method for determining crude fibre (DSTU 8844:2019, 2020). During the study of the composition of liquid brewery waste, the following main indicators were determined: COD (chemical oxygen demand) – dichromate method; BOD_5 (biological oxygen demand for 5 days) – iodometric method; concentration of suspended solids – gravimetric method (Hryn *et al.*, 2019). The viscosity (coefficient of internal friction) of the liquid phase of the suspensions was determined using a capillary viscometer.

After cooling the granules, three single samples were selected, from which a general sample was formed. Then the average sample was selected for analysis. The sizes (diameter and length) of the granules were measured using a calliper. The volumetric mass was determined using a litre funnel with a falling load and laboratory scales of the 2nd accuracy class according to DSTU 8024:2015 (2017). The angle of natural slope was determined according to the degrees applied to the side surface of a special device by R. Zenkov by pouring the product from a funnel according to DSTU 8024:2015 (2017). The flowability of the granules is characterised by the speed of the product flowing out through a hole of a certain diameter according to DSTU 8482:2015 (2017). Granule friability was determined by shaking the granules in a device for one hour and measuring the mass before and after shaking in accordance with DSTU 8482:2015 (2017).

Processing of research results. The reliability of the results of the analysis of the composition of feed products was determined by the Student criterion (Danilov, 2019) (1):

$$t = Mean\ X/m, \tag{1}$$

where t – the reliability of the results; *Mean X* – the arithmetic mean of a series of indicators; m – the error of the arithmetic mean. The arithmetic Mean X was calculated by the formula (2):

$$Mean\ X = \sum X_i/n, \tag{2}$$

where Xi – individual variants of the series; n – the number of values in the series.

The error of the arithmetic mean was determined by the formula (3):

$$m = \frac{\sigma}{\sqrt{n}}, \tag{3}$$

where σ – the standard deviation, which was calculated as follows (4):

$$\sigma = \sqrt{\frac{\Sigma(Xi - Mean\ X)^2}{n-1}}. \tag{4}$$

The obtained value of the reliability of the results t (according to formula 1) was compared with the standard values of the Student's t-test. If $t > t_{table}$, a conclusion was made about the reliability of the results with the appropriate level of probability. The reliability of the detected differences between the averages was calculated by the Student's t-test. Statistical processing of the obtained data was carried out using the MS Excel 2019 package using generally accepted algorithms.

Results and Discussion

Composition and physico-chemical properties of the main brewing wastes and priority directions for their processing. Solid wastes – barley screenings, malt sprouts, trub, and brewer's spent grain – are generated during the malting and brewing processes. The main component of these wastes is brewer's spent grain (maximum up to 8,600 tons per year) with a moisture content of 87%, protein content of 5.2%, and fibre content of 18% (Table 2). After dewatering (to 80%), it is used as feed for cattle. The highest protein content was found in malt sprouts (23%), which makes their use as feedstock reasonable. The crude fibre content in solid wastes ranged from 10% to 18%.

Table 2. *Composition and quantity of solid wastes from Mykulynetskyi Brewery for 2024*

Type of waste	Place of formation	Quantity, t/day	Quantity, t/year	Main indicators	Value, %
Brewer's spent grain	Lauter tuns of the brewhouse	24.0	8,000	Moisture Protein Fibre	87 5.2 18
Barley screenings	Sorting equipment of the malt house	0.17	57.3	Moisture Protein Fibre	10 15 11
Malt sprouts	Rootlet removal machine of the malt house	0.18	60.1	Moisture Protein Fibre	11 23 15
Barley trub	Steeping section of the malt house	0.1	18.2	Moisture Protein Fibre	29 10 10

Note: the daily quantity of wastes was calculated assuming 330-340 working days per year
Source: compiled by the authors according to the production balance sheet at the enterprise

Liquid wastes, or wastewater, are generated at virtually all stages of the production process. Depending on the degree of contamination, they can be divided into highly concentrated and low-concentrated types; according to the pH reaction of the medium, they are classified as acidic, alkaline, or neutral. The highest content of organic substances was observed in the wastewater from the fermentation and brewhouse departments (Table 2), which includes transport water from the spent grain, protein sediment, residual yeast, and lager sediments. The COD and BOD_5 values for these waters were 3-45 g O_2/dm^3 and 2-10 g O_2/dm^3, respectively – dozens of times higher than the permissible discharge standards for pollutants. The content of suspended solids in these wastewaters also exceeded the norms, ranging from 5 to 30 g/dm^3. All suspensions from the fermentation and brewhouse departments had an acidic reaction, with pH values between 4.5 and 5.5. In contrast, alkaline effluents from the bottling department exhibit pH levels exceeding the allowable limit – particularly the alkaline disinfectant solution from the bottle-washing machine, which is up to five units above the norm. Meanwhile, rinsing waters from the malt house and water treatment facilities are considered conditionally clean (Table 3).

Table 3. *Characteristics of liquid brewing wastes from Mykulynetskyi Brewery*

Type of waste	Place of formation	Quantity, m^3/day	Quantity, m^3/year	Indicators	Value	Exceedance of approved discharge standards
Transport water from spent grain	Spent grain dewatering section of the brewhouse	74	24,420	COD BOD_5 Suspended solids pH	3-8 g O_2/ $dm^3$2-4.5 g $O_2/dm^3$4-6 g/ $dm^3$4.5-5.0	1.5-4 × 1.5-3.5 × 5.7-8.5 × 1-1.5 units
Protein sediment	Whirlpool of the brewhouse	6	1,980	COD BOD_5 Suspended solids pH	18-30 g O_2/ $dm^3$6-10 g O_2/ $dm^3$8-15 g/ $dm^3$5.0-5.5	9.2-15.4 × 4.6-7.7 × 11.4-21 × 0.5-1 unit

Table 3. Continued

Type of waste	Place of formation	Quantity, m^3/day	Quantity, m^3/year	Indicators	Value	Exceedance of approved discharge standards
Residual yeast	Fermentation tanks	6	1,980	COD BOD_5 Suspended solids pH	21-45 g O_2/dm^3 4-10 g O_2/dm^3 5-30 g/dm^3 4.5-5.5	10-23× 3.0-7.7× 7-14× 0.5-1.5 units
Lager sediments	Fermentation tanks	6	1,980	COD BOD_5 Suspended solids pH	21-45 g O_2/dm^3 4-10 g O_2/dm^3 5-30 g/dm^3 4.0-5.5	10-23× 3.0-7.7× 7-14× 0.5-2 units
Alkaline disinfectant solution from bottle washer	Bottle-washing machine in the bottling department (discharge once every 6 days, V = 40 m^3)	–	–	Suspended solids pH	0.8 g/dm^3 14	1.1× 5 units
Rinsing water from bottle washer	Bottle-washing machine in the bottling department	59	19,470	pH	11.0-11.5	2-2.5 units
Barley rinsing water	Steeping vessel of the malt house	60	19,800	COD BOD_5 Suspended solids pH	1 g O_2/dm^3 0.2 g O_2/dm^3 – 6.0-7.0	None None None None
Rinsing water from water treatment department	Water treatment filters	90	29,700	COD BOD_5 Suspended solids pH	0.4 g O_2/dm^3 0.006 g O_2/dm^3 0.05 g/dm^3 7.0-8.0	None None None None

Note: the daily quantity of wastes was calculated assuming 330-340 working days per year
Source: compiled by the authors according to the production balance sheet at the enterprise

Based on the study of the composition and physicochemical properties of the main wastes from Mykulynetskyi Brewery, three priority directions for their processing were identified: (1) dewatering and drying of brewer's spent grain for further use in animal husbandry or as secondary raw material; (2) utilisation of protein compounds contained in concentrated liquid wastes as components of feed additives; (3) neutralisation of alkaline wastewater generated in the bottling department to achieve standard quality parameters.

Dewatering and drying of brewer's spent grain. Processing of brewer's spent grain was carried out by dewatering and drying it to a moisture content of 10%. The purpose of dewatering was to remove excess liquid, improve transportability, and extend storage life. Experiments were performed using static and dynamic methods on polyethylene and metal meshes (Table 4).

Table 4. *Dewatering of raw spent grain*

Filtering material	Time, h	Amount of raw spent grain, kg	Moisture of raw spent grain, %	Moisture of dewatered spent grain, %
On polyethylene mesh				
Static	2	0.3	87.7	86.4
Dynamic	2	0.3	87.7	80.0
On metal mesh				
Static	1 2	0.3	87.7	82.7 82.0
Dynamic	1 2	0.3	87.7	80.2 75.2

Source: compiled by the authors

The most effective method was dynamic dewatering on a metal mesh, where the moisture content decreased from 87.7% to 75.2%. Under dynamic conditions, a rotating drum ensures continuous mixing of the material, while the metal mesh allows better liquid drainage due to larger openings and a reduced risk of clogging. Dynamic dewatering also offers several advantages: shorter processing time; lower final moisture content; improved storage stability; enhanced efficiency of subsequent drying. The resulting product (dehydrated pellets), with a moisture content of 10%, had a loose, granular consistency, suitable for use as a feed component. The disadvantage of this method is the aspiration loss of fine particles during drying in an amount of up to 8%.

Processing of malt production wastes (barley screenings and malt sprouts). Processing of malt production wastes – barley screenings and malt sprouts – was carried out to study the possibility of producing flour-based materials from them. The fractional composition of these wastes is presented in Table 5.

Table 5. *Fractional composition of malt production wastes*

Type of waste	Fractional composition, %			
	> 2 mm	2-1 mm	1-0.5 mm	< 0.5 mm
Barley screenings (moisture 10%)	86.7	9.0	1.0	3.2
Malt sprouts (moisture 8%)	12.0	41.1	4.8	42.1

Note: production of flour from barley trub is economically impractical due to its high moisture content (about 30%), which would require an additional drying stage
Source: compiled by the authors

As shown in Table 5, malt sprouts contain 13.6 times more fine fraction (<0.5 mm) than barley screenings, which indicates lower energy consumption required for their grinding. The grinding efficiency was evaluated based on the granulometric composition of the resulting products (Table 6), determined by sieving through a mesh with square openings of 0.5 mm.

Table 6. *Granulometric composition of ground malt production wastes*

Type of waste	Proportion of obtained products, %	
	Flour (< 0.5 mm)	Screenings (> 0.5 mm)
Barley screenings	86.9	13.0
Malt sprouts	95.9	4.0

Source: compiled by the authors

The obtained results indicate a high efficiency of grinding dry malt production wastes. The yield of the fine fraction (<0.5 mm) was 86.9% for barley screenings and 95.9% for malt sprouts. The resulting flour had a homogeneous structure: flour from malt sprouts exhibited a yellowish-straw tint, while that from barley screenings was white. The moisture content of the products was 8.8% and 9.15%, respectively.

Processing of highly concentrated liquid brewing wastes. The purpose of processing highly concentrated liquid wastes from brewing production – represented by the suspensions of the fermentation and brewhouse departments (Table 2) – is the utilisation of protein substances. For this purpose, it is advisable to separate the suspensions of transport water from spent grain, protein sediment, residual yeast, and lager sediments into solid and liquid phases. The study showed that filtration of suspensions through cardboard proceeds slightly slower than through cotton belting, due to a 1.03 times higher hydraulic resistance. However, cardboard provides a much cleaner filtrate: the concentration of suspended solids in it is 4.5 times lower, and the transparency is significantly higher. The mass of the sediment formed on the cardboard was 1 g greater than that formed on the belting cloth (Table 6). Thus, the use of cardboard for phase separation of concentrated liquid wastes is more efficient, providing clear separation into a filtrate with a low content of suspended solids and a thickened protein product with a moisture content of about 73%, which can be used as a component of feed additives. The tests on cleaning the spent alkaline solution from the bottle-washing machine demonstrated high purification efficiency (Table 7). The quality of the treated alkaline solution (28-112 mg/dm³ of suspended solids) allows its reuse in the bottle-washing machine. Process water should be additionally purified from suspended solids to meet the standard limit of 900 mg/dm³ established for Mykulynetskyi Brewery.

Table 7. *Treatment of spent alkaline solution*

Mode	Concentration of suspended solids, mg/dm³		Purification efficiency, %	Filter parameters
	before	after		
Filtration	360	112	69	$S_f = 0.008$ m² Vss = 8 dm³

Source: compiled by the authors

Production of feed products from brewing wastes. The dewatered brewer's spent grain is used separately as feed for cattle. Other wastes – spent grain filtrate, protein sediment, residual yeast, lager sediments, barley screenings, and malt sprouts – are processed into a protein-vitamin feed product. A conceptual flowchart of the feed production process was developed, which is presented in Figure 6. The annual yield of feed products will depend on the starting raw materials, daily productivity of the plant, and the number of working days per year. 30-35% of the malt mass goes into waste and by-products. The average balance of the enterprise consists of: brewer's grains – 75-80%, contact water (organic loads) – 15-20%, yeast – 3-5%, sediments and other losses – 1-2%. On average, when processing 1 ton of barley malt, the yield of by-products is: brewer's grains (moisture) 280-320 kg, brewer's yeast (moisture) 35-45 kg, protein sediments 6-10 kg, extract losses 15-25 kg, fermentation CO_2 28-35 kg, wastewater 3.5-5.0 m³.

According to the developed scheme, highly concentrated wastewater from the fermentation and brewing plant was separated by filtration, obtaining a concentrated protein product (moisture content up to 73%) and filtrate. Solid waste from malt production was crushed and sieved through a 0.5 × 0.5 mm sieve; the fine fraction (flour) was added to the feed product, and the coarse fraction was crushed again. The concentrated protein product and flour were mixed until the moisture content ≤18% was reached, after which the mixture was granulated. The resulting dried product, with a moisture content of about 10%, became loose, and the granules acquired significant hardness. The characteristics of the feed product obtained from brewery waste, according to the main indicators, are presented in Table 8 and Table 9.

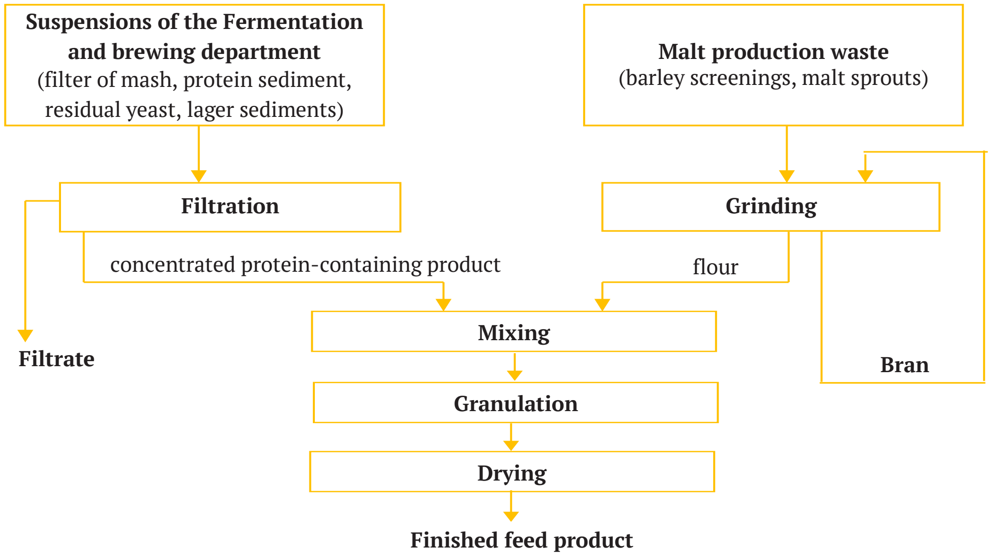

Figure 6. Flow chart of feed product production based on brewing waste

Source: developed by the authors

Table 8. *Chemical composition of the feed product based on brewing waste*

Indicator	Value, %
Moisture	8-10
Crude protein	35
Crude fibre	5-7
Crude fat	4
Ash	10

Source: compiled by the authors

Table 9. *Physical properties of granulated feed product based on brewery waste*

Indicator	Value, %
Moisture	8-10
Granule diameter, mm	7.7
Granule length, mm	7.7-11.5
Bulk weight, g/dm^3	400-420
Angle of natural slope, deg.	50-55
Flowability, cm/s	12-15
Fragility, %	4.6-5.0

Source: compiled by the authors

The developed scheme (Fig. 6) enabled the utilisation of all main wastes generated during malt and beer production to create a novel feed product with a high crude protein content of 35%. The developed granulated protein-vitamin feed product can be incorporated into animal diets at varying inclusion rates depending on species and production goals. Based on its high crude protein content and nutritional composition, recommended inclusion rates are: 10-25% in cattle feed formulations (up to 50% in protein concentrates for cattle), 10-11% for swine diets, and up to 800 g/t for poultry feed. These inclusion levels ensure optimal nutritional balance whilst maintaining feed palatability and digestibility. This achievement aligns with the growing recognition of brewery by-products as valuable resources rather than waste materials. S. Mussatto *et al.* (2006) emphasised that brewer's spent grain (BSG), which constitutes approximately 85% of total brewing by-products, contains around 20% protein and 70% fibre on a dry basis, making it an attractive raw material for various applications beyond traditional animal feeding. The protein content achieved in the present study (35%) represents a significant improvement over untreated BSG, demonstrating the effectiveness of the comprehensive processing approach. The practical application of brewery waste in feed formulations has been extensively documented. F. Karlsen & P. Skov (2022) highlighted that BSG's relatively high protein content, low market price, and stable annual availability position it as a promising protein source for aquaculture feeds, though they noted that appropriate refinement methods are essential to remove anti-nutritional factors such as lignin and fibre. This observation supports the necessity of the processing technology developed in the current study, which incorporates dewatering, drying, and granulation steps to enhance digestibility and nutritional value.

Recent advances in bioprocessing have demonstrated even greater potential for protein enrichment in brewery wastes. C. Eliopoulos *et al.* (2022) reported that solid-state fermentation of BSG using *Pleurotus ostreatus* resulted in a 49.49% increase in protein content and a ten-fold increase in β-glucans, whilst simultaneously reducing cellulose by 11.42%. Although the present study did not employ fermentation, the achieved protein concentration of 35% through mechanical and physical processing methods represents a cost-effective alternative that can be readily implemented at industrial scale without requiring specialised microbial cultivation. The versatility of brewery waste extends beyond animal feed applications. A. Chetrariu & A. Dabija (2023) reviewed the incorporation of spent grain into various food products, including bakery goods, pasta, and plant-based alternatives, noting that such applications align with circular economy principles by reducing waste and promoting sustainable development. Whilst the current study focused primarily on feed production, the developed processing technology – particularly the grinding and granulation steps – could potentially be adapted for food industry applications, thereby expanding the market opportunities for brewery waste valorisation.

The comprehensive approach presented in this study addresses several practical challenges identified in previous research. The granulated form of the final product overcomes the perishability issues associated with high-moisture BSG, as noted by F. Karlsen & P. Skov (2022), whilst the incorporation of multiple waste streams (spent grain, malt sprouts, barley screenings, protein sediment, and yeast residues) maximises resource utilisation. This integrated processing strategy not only produces a nutritionally enhanced feed product but also contributes to environmental sustainability by reducing the overall waste burden of brewing operations, thereby supporting the transition towards a circular bio-economy in the brewing industry.

Neutralisation of wastewater. According to the pH value, the wastewater of the enterprise is divided into: acidic (pH 4.0-5.5) – suspensions from the fermentation and brewing shop; alkaline (pH 11-14) – disinfectant solutions and washing waters from the finished product bottling shop; neutral (pH about 7) – washing waters from the malt and water treatment shops (Table 3). Acidic wastewater of the enterprise, after phase separation of the suspensions from the fermentation and brewing shop, is represented by a filtrate containing a small amount of suspended solids – from 0.1 to 0.45 g/dm^3 – and has a pH of 4.0-5.5 (Table 6). The alkaline wastewater from the finished product bottling shop exceeds the established discharge limits for Mykulynetskyi Brewery in two indicators: pH – by up to 5 units, and suspended solids – by 1.1 times (Table 3). Neutralisation of the alkaline wastewater from the bottling shop can be carried out using the filtrate obtained during the processing of suspensions from the fermentation and brewing shop. As previously noted, the washing waters from the malt and water treatment shops do not exceed the established discharge limits for pollutants in any indicator (Table 2). Therefore, they can be used as diluting solutions. Thus, the neutralisation of acidic and alkaline wastewater followed by dilution with conditionally clean washing waters from the malt and water treatment shops makes it possible to ensure compliance with all discharge standards for pollutants (Hryn *et al.*, 2019) established for Mykulynetskyi Brewery into the municipal sewage system.

Technology for integrated processing of solid and liquid brewing waste. Based on the generalisation of previous studies and the results obtained during experimental investigations, a comprehensive technology for the integrated processing of all major wastes generated during malt and beer production has been developed. To obtain feed products, the components of brewer's grains, malt sprouts, barley screenings, protein sediment, residual yeast, and lager sediments were utilised. The technology also provides for the treatment, neutralisation, and reuse of wastewater. The basic technological scheme for the integrated processing of solid and liquid brewing waste is shown in Figure 7.

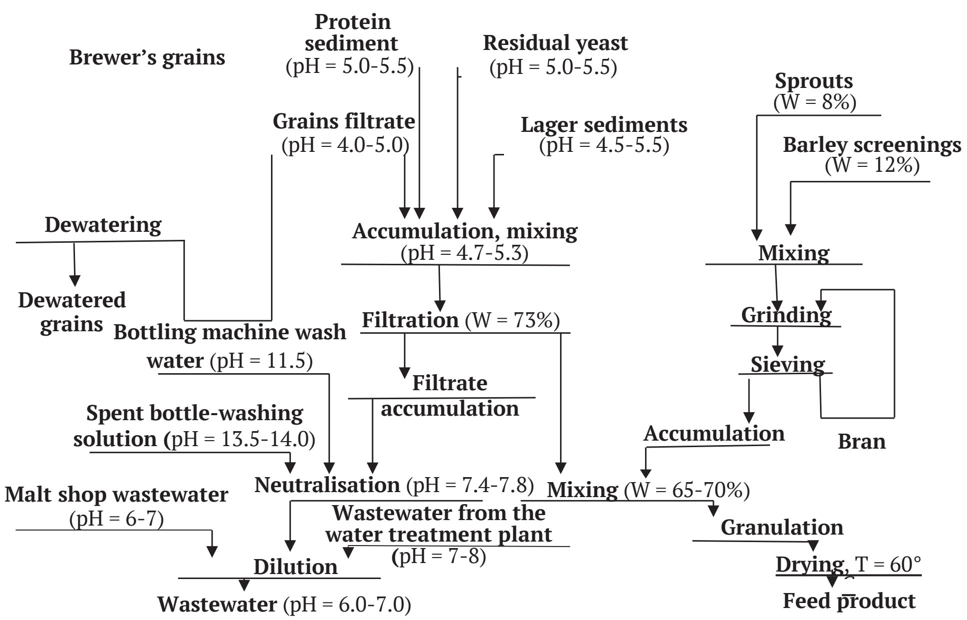

Figure 7. Basic technological scheme for the integrated processing of waste at Mykulynetskyi Brewery
Source: developed by the authors

According to the proposed technology, all highly concentrated liquid waste from the fermentation and brewing plant, consisting of suspensions of grain transport water (grain filtrate), protein sediment, residual yeast and lager sediment, are mixed for further phase separation by filtration. The resulting filtrate is sent to neutralise alkaline wastewater from the finished product bottling plant, and the concentrated protein fraction of the suspensions with a humidity of 73% is used as a basis for the production of a feed product. Solid waste from the malting plant (sprouts and screenings) can be added to the feed composition after grinding and sieving through a 0.5 mm sieve (Tymchuk & Stasyuk, 2010). The ground fraction that has passed through the sieve is added to the filtered product until the mixture reaches a moisture content of 65-70%, and the coarse fraction is returned for re-grinding. The resulting feed mixture is then mixed, granulated and dried. The spent alkaline solution from the bottle washing machine, after being cleaned of suspended matter by filtration, can be reused, and the washing solution containing insoluble label fibres and other impurities can be neutralised with the acidic filtrate of the fermentation and brewing plant suspensions. The resulting neutral mixture should then be diluted with conditionally clean washing waters from the malting and water treatment plants. After these technological operations, the wastewater after analysis met all the standards for the discharge of pollutants established for Mykulynetskyi Brewery. According to the developed technology, the beer grains were dehydrated to a moisture content of 75-80%. The dehydrated product is suitable for use as feed for cattle. The developed technology allows for the comprehensive processing of all major liquid and solid wastes of Mykulynetskyi Brewery, resulting in two types of feed products – granulated feed and dehydrated beer grains, as well as providing for the neutralisation, reuse and treatment of wastewater in accordance with established environmental standards.

The development of this technology was informed by extensive research into brewery waste valorisation strategies. S. Aliyu & M. Bala (2011) emphasised that brewer's spent grain, representing approximately 85% of total brewing by-products, possesses strong potential for recycling due to its rich content of cellulose and non-cellulosic polysaccharides. They highlighted the global pressure towards green environmental technology as a driving force for academic and industrial researchers to explore alternative uses beyond conventional animal feed applications. This perspective aligns with the objectives of the present study, which seeks to maximise the utilisation of brewery waste through integrated processing approaches. The methodological framework for waste valorisation in the food and processing industries has been well established. G. Krusir *et al*. (2014) provided comprehensive methodologies for determining quantitative and qualitative indicators of secondary raw material formation, utilisation, and consumption in production processes. Their work on the ecological and economic efficiency of processing secondary resources in the food industry informed the environmental and economic considerations underlying the technology developed in the current study, particularly regarding waste reduction and resource efficiency optimisation. Recent advances in extraction and concentration technologies have expanded the possibilities for brewery waste utilisation. K. Silva *et al*. (2023) reviewed emerging technologies and alternative solvents that enable higher extraction yields of phytochemical compounds, particularly bitter acids and polyphenols from hot trub and spent hops. Whilst the present study focused primarily on feed production rather than phytochemical extraction, the purification and concentration principles discussed by K. Silva *et al*. informed the phase separation and filtration methodologies employed for processing highly concentrated liquid wastes. Their emphasis on the importance of scale-up and economic feasibility studies resonates with the practical, industrially applicable approach adopted in this research.

The specific context of Ukrainian brewing operations provided additional insights. L. Telezhenko & A. Dubyna (2025) systematically reviewed modern technologies for secondary processing of grain residues in beer production, highlighting the potential for implementing circular economy principles in the brewing industry. Their analysis of drying, fermentation, and bioprocessing technologies, alongside comparative data demonstrating significant protein (up to 30%) and fibre (up to 50%) concentrations in dried brewer's spent grain, supported the selection of processing parameters in the present study. Furthermore, their emphasis on adapting foreign technological experience to Ukrainian realities – considering technical capabilities, climatic conditions, and market demand – proved particularly relevant for the development of a technology suitable for implementation at Mykulynetskyi Brewery. The integrated approach presented in this study synthesises these various perspectives, combining traditional mechanical processing methods (dewatering, drying, grinding) with modern separation technologies (filtration under vacuum) and granulation techniques. This comprehensive strategy addresses the multiple challenges of brewery waste management whilst creating economically viable feed products and ensuring environmental compliance through wastewater neutralisation and reuse.

Conclusions

Comprehensive research on the processing of brewing industry waste has led to several key findings. Three priority directions for the utilisation of brewery waste were identified: recovery of protein compounds from concentrated liquid wastewater for use as valuable components in feed formulations in the amount of 10-25% (up to 50% protein feed) for cattle, 10-11% for pigs and up to 800 g/t for poultry; neutralisation of alkaline wastewater to achieve compliance with discharge regulations pH 6.5-8.5; dewatering and drying of brewer's grains up to 10% to reduce waste volume and facilitate their further application in animal husbandry or as secondary raw materials. It was determined that dynamic dewatering using a rotating drum with a metal mesh surface is the most efficient method for drying brewer's grains. Studies of malt production waste demonstrated that the milled product obtained from this material possesses a uniform composition (the yield of the fine fraction (<0.5 mm)), with a moisture content of 9.15% for flour from barley screenings and 8.8% for flour from malt sprouts.

For effective protein recovery from highly concentrated liquid wastewater, separation into solid and liquid phases is recommended, which gives a concentrated protein product with a crude protein content of 35% and a filtrate containing a low concentration of suspended solids 0.1-0.45 mg/dm^3. Neutralisation of acidic and alkaline wastewater with subsequent dilution with conditionally clean washing waters from the malting and water treatment plants ensures that the concentrations of all pollutants in the final wastewater comply with the established standards for discharge into the environment. A comprehensive technology for the integrated processing of all major solid and liquid wastes generated during malt and beer production was developed. This technology enables the efficient conversion of brewery by-products into two types of feed products – granulated feed and dewatered brewer's grains – while simultaneously providing for the neutralisation, reuse, and purification of wastewater in accordance with environmental standards. In the future, with an increase in production capacity, it is promising to create a protein-vitamin granulated feed additive with the inclusion of waste from the brewing industry.

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Conflict of Interest

The authors declare no conflict of interest.

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Комплексна переробка відходів пивоваріння з отриманням кормової добавки

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Анотація. Одним із ключових напрямків розвитку сучасної пивоварної промисловості в Україні є раціональне використання органічних відходів, що утворюються під час виробництва пива та солоду. Метою статті було дослідити склад, фізико-хімічні властивості та методи утилізації основних відходів пивоваріння на прикладі ТОВ «Микулинецький пивоварний завод». Визначено кількісні та якісні характеристики сухих (пивна дробина, солодові паростки, ячмінний відсів, шлам) та рідких (транспортні води, суспензії дробини, білковий осад, залишкові дріжджі, лагерні осади, стічні води) відходів. Встановлено, що пивна дробина становить до 85 % усіх твердих залишків виробництва та є цінною сировиною для кормовиробництва завдяки високому вмісту білка, клітковини та мінеральних речовин. Були проведені експериментальні дослідження процесів зневоднення та сушіння дробини, подрібнення солодових паростків та ячмінного відсіву, а також фільтрації концентрованих суспензій з бродильно-пивоварного цеху. Визначено оптимальні умови для фазового розділення суспензій, що забезпечують отримання концентрованої білкової фракції з вмістом вологи 73 % та фільтрату з низькою концентрацією завислих речовин (0,1-0,45 г/дм^3). Запропоновано технологію комплексної переробки всіх основних відходів пивоваріння, в результаті якої отримано два типи кормових продуктів – зневоднену пивну дробину та гранульований білково-вітамінний корм, що містить 35 % сирого протеїну, 5–7 % клітковини та 8-10 % вологи. Розроблена технологія також передбачає нейтралізацію кислих та лужних стічних вод до стандартних параметрів та їх повторне використання у виробничому циклі. Практичне впровадження запропонованої технології значно зменшує вплив на навколишнє середовище, зменшує утворення відходів, підвищує ресурсоефективність виробництва та створює замкнуту систему утилізації вторинних ресурсів у пивоварній промисловості

Ключові слова: пивоварна промисловість; утилізація відходів; стічні води; кормові продукти; технологія; технічна екологія