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Pro-ecological bioconversion of buckwheat waste into biologically active compounds and useful products for food and feed purposes

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ABSTRACT

The article examines the possibility of environmentally safe bioconversion of buckwheat straw as a secondary raw material of the agro-industrial complex. The aim of the study was to evaluate the efficiency of extraction, thermal, and enzymatic processing methods for converting straw into biologically active substances, dietary fibers, and biotechnological products. It was established that about 6.4 t of straw is formed per 1 ha of crops, from which up to 14% of biologically active compounds can be extracted, while up to 86% of the mass is preserved and remains suitable for further processing. Thermal treatment at 100–122 °C promotes the breakdown of the lignocellulosic complex and increases the fiber content to 68.5%. Enzymatic processing ensures a polysaccharide hydrolysis degree of up to 50–55% and utilization of protein components at a level of 43–68%. It is shown that modified enzyme systems increase cellulolytic activity by 38–60%, whereas nitrosamines and pesticides reduce the proteolytic activity of enzymes by 36–50%. The obtained results confirm the prospects of using buckwheat straw for the production of functional ingredients and biotechnological products. Comparative analysis with published data on wheat, barley, and rice straw shows that buckwheat straw, with a cellulose content (45.0%) comparable to wheat straw (35–45%) and exceeding that of barley (37.5%) and rice straw (30–38%), contains a significantly higher level of bioactive compounds (≈14%, mainly flavonoids such as rutin, which is absent in cereal straw) and a moderate lignin content (21.6%). Therefore, it is a promising raw material not only for dietary fiber and bioethanol production but also for obtaining pharmacologically valuable flavonoid compounds.

Keywords: waste processing, waste bioconversion, buckwheat, buckwheat straw, biologically active substances, biological waste processing, nitrosamines and pesticides.

INTRODCTION

Bioconversion of agricultural waste is one of the modern approaches to biological utilization, allowing for the efficient use of organic components contained therein. Biotechnological utilization methods are environmentally friendly technologies that provide economic benefits and ensure the rational use of renewable natural resources for industrial purposes [Akhundova and Babashli, 2025a; Sadigov and Macnunlu, 2023].

In various sectors of the food industry, significant volumes of secondary resources are generated during the processing of primary raw materials, which can be further utilized to obtain food compositions, additives, and biologically active substances [Gurbanov et al., 2022; Brench, 2016].

At present, the issue of increasing the nutritional and biological value of food products through the rational use of domestic raw materials remains relevant [Gadimova et al., 2022a]. Biologically high-quality combined products that meet the requirements of nutritional science are particularly popular [Gurbanov et al., 2020].

Buckwheat is considered a functional crop with pronounced health-promoting potential and the ability to reduce the risk of developing chronic non-communicable diseases [Zhou et al., 2015; Zhou et al., 2015; Gadimova et al., 2022b]. Buckwheat seeds contain a significant amount of proteins with high biological value and a balanced amino acid composition, represented by the main protein fractions [Jin et al., 2022]. The protein complex of buckwheat is characterized by a high content of essential and conditionally essential amino acids [Bhinder et al., 2020; Amela and Sanja, 2022].

Protein digestibility may be reduced due to the presence of antinutritional compounds, such as tannins and protease inhibitors associated with protein fractions [Mattila et al., 2018].

Polyphenolic compounds, primarily flavonoids – including rutin, quercetin, and others – make a significant contribution to the functional properties of buckwheat [Akhundova et al., 2024; Lee et al., 2016; Zhu, 2016; Raguindin et al., 2021; Zhang et al., 2012; Kazimova et al., 2025].

In addition, buckwheat contains starch, tannins, phytosterols, and fagopyrins, which complement its functional and biological characteristics [Ahmed et al., 2014].

Buckwheat plays an important role in addressing nutrient deficiencies and enhancing food security [Jha et al., 2024]. Interest in this crop is driven not only by its seeds but also by its less-studied components, including sprouts and hulls, as well as extracts obtained from seeds and by-product fractions. Buckwheat extracts have also been investigated for their antioxidant and functional properties [Hęś et al., 2017; Akhundova and Babashli, 2025b; Atambayeva et al., 2024].

Buckwheat sprouts are rich in biologically active compounds [Atambayeva et al., 2023], whereas the hulls, often discarded as waste, have potential applications in the food industry and other sectors [Kan et al., 2023; Zhang et al., 2023].

Buckwheat straw is a by-product of the agro-industrial complex and, if not properly managed, can serve as a source of organic environmental pollution, including contamination of surface and groundwater. In this regard, the development of environmentally safe technologies for processing plant waste, aimed at reducing the anthropogenic impact on ecosystems, is a relevant area of research.

The use of microbial and enzymatic methods for biomass processing aligns with modern approaches to environmentally friendly technologies, analogous to bioremediation processes in polluted aquatic ecosystems [Babashli et al., 2025; Hasanova et al., 2025; Veliev et al., 2013]. It has previously been shown that microorganisms isolated from the rivers and seas of Azerbaijan are capable of effectively degrading petroleum products, phenols, and other organic pollutants, confirming the high potential of biotechnological methods in environmental protection [Babashli et al., 2022; Hasanova et al., 2023; Hajiyeva et al., 2020; Hajiyeva et al., 2025].

Buckwheat straw possesses a number of beneficial properties and contains biologically active compounds that stimulate plant growth and serve as components of plant protection agents against diseases and pest infestations [Vazhov et al., 2019]. After extraction of these compounds, the straw provides an excellent substrate for biofermentation by Aspergillus, Trichoderma, and Fusarium, which produce glucoamylases and xylanases capable of hydrolyzing lignin, cellulose, and hemicellulose. As a result, products are formed that can be utilized in various sectors of the processing industry and agriculture [Chipeta et al., 2008].

Modern approaches to biomass bioconversion include extrusion processing of biological waste into feed, microbial proteinization of carbohydrate-containing raw materials, methane fermentation for energy production and fertilizers, and other methods [Kadyrov et al., 2015].

Thus, due to the quantity of biologically active compounds contained in buckwheat, there are significant prospects for research that could lead to innovative applications across various fields.

MATERIALS AND METHODS

The use of buckwheat straw as a source of biologically active compounds (BACs) is promising. Buckwheat straw contains approximately 1.5% of various biologically active substances, predominantly of flavonoid nature. The extraction of BACs is carried out using both hot and cold extraction methods. Plant material was cleaned of mechanical impurities and dried at a temperature not exceeding 40 °C until air-dry. The dried samples were ground into a powder using a laboratory mill. The resulting powders were stored in airtight containers at room temperature until extraction.

Cold extraction was carried out using the maceration method. A weighed portion of the ground plant material was extracted with a 40–70% hydroalcoholic solution (or distilled water) in a ratio of plant material to solvent of 1:10 (w/v). The extraction was performed at 20–25 °C for 24–72 hours with occasional stirring. At the end of the process, the extracts were separated from the solid residue by filtration through a paper filter. The resulting extracts were used for further analysis.

Hot extraction was carried out using a water bath. A weighed portion of the ground plant material was extracted with water or a 40–70% hydroethanolic solution in a 1:10 (w/v) ratio at 60–80 °C for 30–90 minutes. After extraction, the samples were cooled to room temperature and filtered to remove insoluble residues. The applied extraction methods allowed obtaining extracts containing flavonoids, phenolic compounds, and other biologically active substances characteristic of buckwheat.

At the same time, thermal treatment of the substrate induces a series of chemical reactions that reduce its selectivity. As a result of thermal processing, the fibers swell, their dimensions increase, and the orientation and alignment of cellulose fibrils are disrupted. The ratios and distribution of components in submicroscopic fibrous structures are altered, and previously separate layers and sheaths are destroyed, while the orientation of the main cell axes is preserved.

The effect of environmental pollutants on the enzymolysis process was evaluated using N-nitrosodimethylamine (0.51 μg/cm^3) and α-hexachlorocyclohexane (0.02 μg/cm^3), added at a rate of 10 mL per 100 g of straw [Shepel, 2021].

Enzymolysis of mixed waste after the extraction of BACs was carried out according to a standard method using Creon and an enzyme preparation derived from chicken stomach mucosa at various concentrations. The process was performed at 37 °C for 24 hours with a raw material-to-water ratio of 1:6.

The concentration of the enzyme preparation was set at 1, 2, 3, 4, and 5%, while Creon was used at 25% (250 mg/g – 25 U) and 50% (500 mg/g – 50 U) (Table 1).

Enzymatic hydrolysis of buckwheat straw was carried out with the aim of environmentally oriented processing of lignocellulosic plant material and converting structural polysaccharides into soluble sugars suitable for subsequent bioconversion. The hydrolysis process was based on the coordinated action of a cellulolytic enzyme complex, including endoglucanases, exoglucanases, and β-glucosidase. Endoglucanases catalyzed the cleavage of internal β-1,4-glycosidic bonds in the amorphous regions of cellulose, generating new chain ends; exoglucanases cleaved di- and oligosaccharides from the chain ends; and β-glucosidase hydrolyzed cellobiose and cellotriose into glucose.

The enzyme preparations used included Celloviridin G20x (produced by *Trichoderma viride*), containing a cellulase complex, β-glucanase, xylanase, and other hydrolytic enzymes, as well as OmniGen® AF (produced by *Aspergillus foetidus*), characterized by pectinesterase,

Table 1. Content of the enzyme preparation depending on the variant

Enzyme preparation	№Variant number	Concentration of the enzyme preparation
Creon	1	25% (250 mg/g-25 U)
	2	50% (500 mg /g-50 U)
Enzyme preparation	3	1%
	4	2%
	5	3%
	6	4%
	7	5%
Celloviridin G20x	8	0.25%
	9	0.5%
OmniGen® AF	10	0.25%
	11	0.5%

endo- and exopolygalacturonase, hemicellulase, and protease activities.

Enzymatic treatment was carried out both using individual enzyme preparations and using their mixture in a 1:1 mass ratio. Hydrolysis was performed in a citrate-phosphate buffer at pH 5.6. The substrate-to-buffer ratio was 1:10 (w/v). The reaction mixture was incubated under thermostated conditions with constant stirring at 150 rpm. The concentrations of enzyme preparations were 0.10, 0.25, and 0.50 g per 100 g of air-dry straw. The duration of enzymatic treatment varied depending on the enzyme dosage.

The degree of hydrolysis was calculated using the formula:

$$h = \frac{m}{18} \times 100 \quad (1)$$

where: h is the degree of hydrolysis (%); m is the amount of monosaccharides in the hydrolysate (g); 18 is the monosaccharide potential in the straw.

In separate series of experiments, buckwheat straw was subjected to enzymatic hydrolysis after preliminary alcohol extraction of biologically active compounds to assess the effect of extraction treatment on cellulose accessibility and the efficiency of cell structure disruption. During enzymatic treatment, cell walls were degraded and the fibers of the plant material were thinned, which enhanced the accessibility of polysaccharides for hydrolysis.

The resulting hydrolysates were used to determine the content of soluble sugars and to evaluate the efficiency of enzymatic processing of buckwheat straw in the context of environmentally safe utilization of plant waste.

RESULTS AND DISCUSSION

Buckwheat straw has a high potential in tannins, coloring substances, a complex of biologically active compounds, and mineral compounds, and it largely contains cellulose and lignin. The amounts of three industrially significant groups of substances that can be obtained from 1 ha of crops of different buckwheat genotypes with the most valuable agronomic traits, widely cultivated in the Ganja Gazakh region of Azerbaijan one of the important economic regions of the country in recent years are presented in Table 2.

Based on the analyzed data, it is estimated that, on average, 6.44 t of straw can be harvested from 1 ha, from which 2.92 t of cellulose, 1.89 t of lignin, and 322 kg of biologically active compounds can be obtained.

As a result of extracting BACs from plant material, a large amount of valuable waste remains, namely, the yield of extractive substances in buckwheat straw is 14.0%, while the amount of resulting waste is 86.0%.

For the targeted use of the remaining straw in feed products, in the microbiological industry, and for cellulose production, it is necessary to understand not only the structural changes but also the chemical composition of the straw after preliminary preparation for fermentation, as the lignin layer hinders enzyme accessibility.

Table 3 shows the variability in the component composition resulting from the processing of buckwheat straw during the production of biologically active compounds (BACs), plant protection products (PPPs), and hydrolysate.

Data analysis showed that a significant amount of crude fiber remained in the spent buckwheat straw after BAC extraction. Therefore, OmniGen® AF, containing polygalacturonase, hemicellulase, protease, and other enzymes, and Celloviridin G20x, containing cellulase, xylanase, β-glucanase, and other enzymes, were used to obtain the hydrolysate.

As a result of enzymatic hydrolysis in a citrate-phosphate buffer (pH = 5.6) at a 1:10 ratio, the optimal concentrations of the added enzyme were determined based on the degree of straw hydrolysis (Table 4).

Thus, enzymatic hydrolysis of buckwheat straw, both with and without thermal treatment, is a

Table 2. Potential amounts of chemical composition components in buckwheat straw per 1 ha

Morphotype name	Potential of components			
	Biomass, t/ha*	Cellulose, t/ha	Lignin, t/ha	Active compounds (AC), kg/ha
Bogatyr	6.12±0.12	2.755±0.21	1.271±0.25	305±14
Krupinka	6.47±0.47	2.912±0.11	1.411±0.73	323±12
Dikul	6.42±0.32	2.954±0.45	1.407±0.46	321±24

Table 3. Organic components of buckwheat straw processing waste, averaged across buckwheat genotypes

Indicator	Buckwheat straw	Residues after flavonoid extraction	Enzymatic hydrolysate of straw
Dry matter, g/100 g	86.00	86.00	10.01
Fats, g/100 g	1.15	0.71	0.02
Crude protein, g/100 g	1.83	2.53	0.22
Fiber, g/100 g	35.77	45.77	2.04
Ash, g/100 g	3.18	6.05	0.62
Bioactive compounds, g/100 g	44.02	30.91	7.15
Calcium, g/100 g	1.34	1.31	0.09
Potassium, g/100 g	3.12	2.51	0.21
Magnesium, g/100 g	0.13	0.11	0.06
Phosphorus, g/100 g	0.20	0.17	0.05
Vitamin B1, mg/100 g	0.03	0.008	0.0004
Vitamin B2, mg/100 g	0.01	0.004	0.0007
Vitamin B6, mg/100 g	0.01	0.003	0.0004

competitive approach for its utilization, producing a nutrient medium suitable for microbial cultivation.

Study of the effect of thermal treatment methods and enzymatic hydrolysis on the chemical composition components of buckwheat straw

As a result of the studies on the component composition, significant amounts of cellulose were identified, which can be used for the production of dietary fibers and purified cellulose.

Since thermal treatment leads to leaching and degradation of the water-soluble components of the straw, options for steam treatment and boiling at the water boiling temperature for 1.5 hours under atmospheric and elevated pressure were studied.

Figure 1 shows the dependence of cellulose content in buckwheat straw samples on the boiling time.

It was found that the cellulose content increases proportionally with boiling time. Over 1.5–2 h, the cellulose content increased by 17–18%. When the temperature is increased to 120–122 °C, the boiling time is reduced, and the maximum cellulose content reaches 68.5% (Figure 2) within 0.25 h.

At the same time, cooking contributes to the degradation of the lignin layer (Figure 3). Thus, for the purpose of obtaining dietary fibers, the following processing options for the fibrous material were proposed:

1. Thermal treatment at t = 100–110 °C, p = 1.0 atm;

Table 4. Comparison of enzymatic hydrolysis of buckwheat straw with thermal treatment and without it

Indicator	Buckwheat straw	Residues after flavonoid extraction	Enzymatic hydrolysate of straw
Dry matter, g/100 g	86.00	86.00	10.01
Fats, g/100 g	1.15	0.71	0.02
Crude protein, g/100 g	1.83	2.53	0.22
Fiber, g/100 g	35.77	45.77	2.04
Ash, g/100 g	3.18	6.05	0.62
Bioactive compounds, g/100 g	44.02	30.91	7.15
Calcium, g/100 g	1.34	1.31	0.09
Potassium, g/100 g	3.12	2.51	0.21
Magnesium, g/100 g	0.13	0.11	0.06
Phosphorus, g/100 g	0.20	0.17	0.05
Vitamin B1, mg/100 g	0.03	0.008	0.0004
Vitamin B2, mg/100 g	0.01	0.004	0.0007
Vitamin B6, mg/100 g	0.01	0.003	0.0004

2. Thermal treatment at t = 120–122 °C, p = 1.97 atm, τ = 0.25 h;

The lignin and cellulose contents for the best variants are summarized in Table 5. The cellulose content in buckwheat straw samples increases 1.4-fold at 100 °C and 1.5-fold at 120 °C.

Comparative assessment of buckwheat straw with other types of agricultural straw

To evaluate the bioconversion potential of buckwheat straw, the results obtained in this study were compared with the available literature data on wheat, barley, and rice straw.

In our study, the initial cellulose content of buckwheat straw was 45.0%, which is comparable to the upper range reported for wheat straw (35–45%) [Jia et al., 2021; del Río et al., 2013], higher than barley straw (37.5%) [Sun et al., 2011], and considerably exceeds that of rice straw (30–38%) [Tufail et al., 2021]. The relatively high cellulose content of buckwheat straw confirms its suitability as a substrate for dietary fiber production and enzymatic hydrolysis. After thermal treatment at 120–122 °C, the cellulose content in our buckwheat straw samples reached 68.5%, which exceeds the values achieved for wheat straw cellulose isolation via organosolv processes at 150 °C (cellulose purity ~86.8%, but recovery ~55%) [Jia et al., 2021], and is comparable to pretreated rice straw (76% cellulose in solid residue after glycerol-$AlCl_3$ treatment at 147 °C) [Tang et al., 2019]. This suggests that the lignocellulosic structure of buckwheat straw is relatively amenable to thermal disruption compared to cereal straws.

The lignin content in buckwheat straw in our study was 21.6%, which is somewhat higher than that typically reported for wheat straw (15–20%) [del Río et al., 2013; Tufail et al., 2021] and barley straw (15.8%) [Sun et al., 2011], but within the range reported for rice straw (15–28%) [Marques et al., 2010]. The higher lignin content in buckwheat straw may be attributed to its botanical classification as a pseudocereal belonging to the Polygonaceae family, which differs structurally from true cereal grasses (Poaceae). After thermal treatment at 120–122 °C, the lignin content decreased from 21.6% to 14.4%, representing a 33% reduction. For comparison, Lee et al. [2021] achieved only a 14% reduction in lignin content in barley straw through

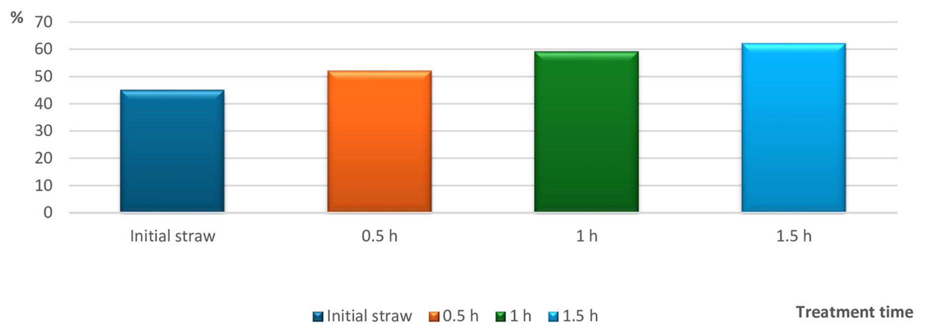


Figure 1. Cellulose content in buckwheat straw samples depending on boiling time at t = 100–110 °C

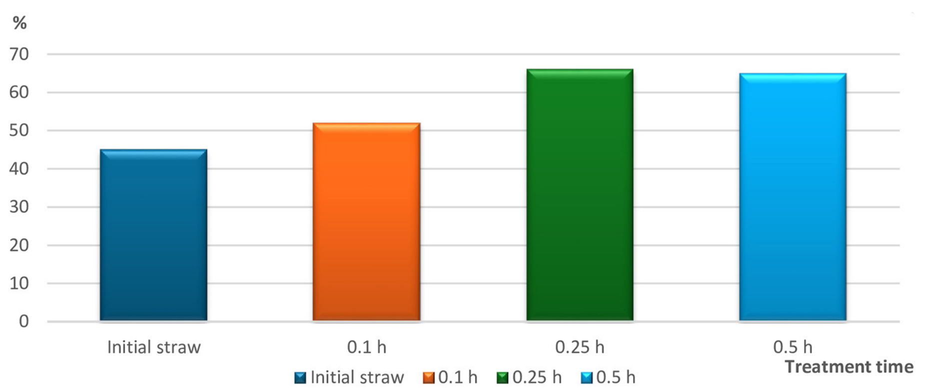
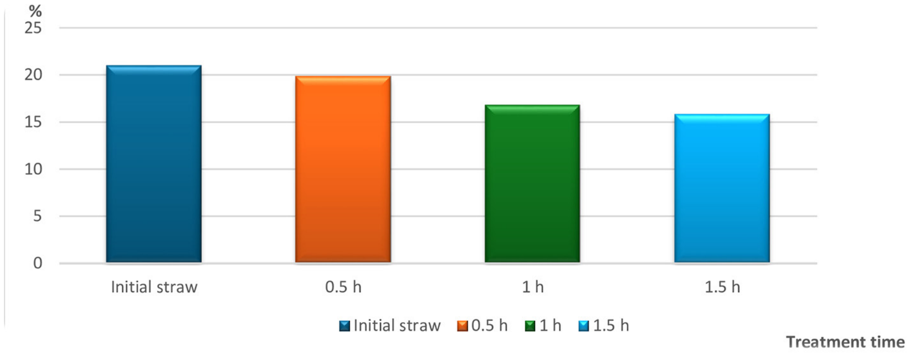
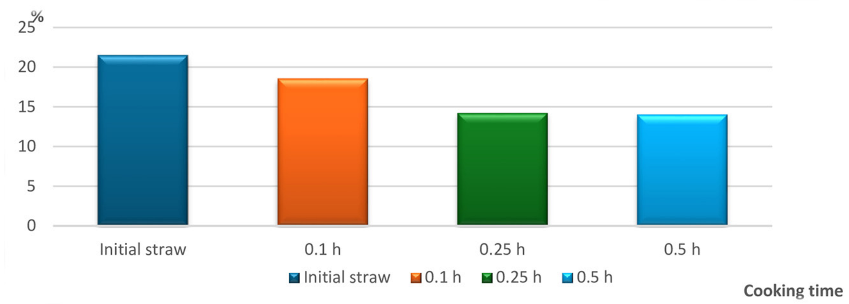


Figure 2. Cellulose content in buckwheat straw samples depending on cooking time at t = 120–122 °C



a)



b)

Figure 3. Lignin content in buckwheat straw samples depending on cooking time: a) at t = 100–110 °C; b) at t = 120–122 °C

Table 5. Content of main components in buckwheat straw

Sample ID and characteristics	Lignin mass fraction, %	Cellulose mass fraction, %
1. Initial straw	21.6%	45.0
2. Straw after thermal treatment at t = 100–110 °C, p = 1.0 atm, τ = 1.5 h	18.0	62.8
3. Straw after thermal treatment at t = 120–122 °C, p = 1.97 atm, τ = 0.25 h	14.4	68.5
4. Straw after fermentation, τ = 24 h	3.3	90.2

CRISPR/Cas9-mediated modification of the HvCOMT1 gene, while chemical delignification of rice straw using deep eutectic solvents achieved approximately 46% delignification [Thulluri et al., 2021]. Thus, the thermal delignification efficiency of buckwheat straw (33%) occupies an intermediate position among these approaches.

The crude protein content of buckwheat straw (1.83%) is lower than that of wheat straw (3–5%), barley straw (2.6%) [Sun et al., 2011], and rice straw (4–7%). However, the degree of protein utilization during enzymatic hydrolysis in our study reached 43–68%, with a residual utilization coefficient of 0.33–0.58, which represents a satisfactory result. Studies on white rot fungi (*Pleurotus* spp.) treatment of highland barley straw demonstrated significant increases in crude protein content and enhanced in vitro digestibility [Wang et al., 2023], suggesting that microbial bioconversion could also be applied to buckwheat straw residues to further enhance their nutritional value as a feed supplement.

The most significant distinction of buckwheat straw from cereal straws lies in its remarkably high content of biologically active compounds. In our study, the yield of extractive substances from buckwheat straw was 14.0%, predominantly consisting of flavonoid compounds including rutin, quercetin, and other polyphenols. This is substantially higher than the extractive content typically reported for wheat straw (2–5%), barley straw (2–3%), or rice straw (3–5%)

[Kraszkiewicz et al., 2015]. According to Amela and Sanja (2022), buckwheat contains 25–50 times more flavonoids than wheat and corn, while whole grain buckwheat was found to contain 2–5 times more phenolic components than barley and oats, with 2–7 times higher antioxidant activity [Zdunczyk et al., 2006]. Crucially, rutin – the key bioactive compound extracted from buckwheat straw – is entirely absent in cereal crops [Zhu et al, 2016], making buckwheat straw a unique raw material that enables a dual-purpose biorefinery approach: extraction of pharmacologically valuable flavonoids followed by enzymatic conversion of the remaining lignocellulosic residue.

The ash content in buckwheat straw (3.18%) is comparable to wheat straw (2–4%) and barley straw (4.2%) [Sun et al., 2011; Kraszkiewicz et al., 2015], but significantly lower than that of rice straw (10–18%), which contains high levels of silica. The low ash content of buckwheat straw represents a practical advantage for bioconversion processes, as high silica content in rice straw creates considerable difficulties in chemical recovery during pulping and substantially increases processing costs [Passoth et al., 2019].

The polysaccharide hydrolysis degree achieved in our study using Celloviridin G20x and OmniGen® AF (45–56%) is comparable to results reported for enzymatic hydrolysis of pretreated cereal straws. Satlewal et al. (2021) reported approximately 58% hydrolysis of DES-THF-pretreated rice straw at an enzyme loading of 5 FPU/g, while untreated rice straw showed only 27–40% hydrolysis even at 20 FPU/g. For wheat straw, steam explosion pretreatment followed by enzymatic hydrolysis typically yields 60–80% glucose conversion [Brandenburg et al., 2018]. The use of modified enzyme systems (AAEC-DMA and α-GHCG) in our study increased cellulolytic activity by 38–60%, which represents a promising novel approach that has not been widely reported for other types of agricultural straw. Furthermore, it was established that the presence of nitrosamines and pesticides reduces the proteolytic activity of enzymes by 37–50%, an effect that has not been systematically investigated in the context of wheat, barley, or rice straw bioconversion, and which has important implications for the processing of straw from contaminated agricultural sites.

Effect of nitrosamines and pesticides on the enzymatic hydrolysis of buckwheat processing waste

To study the effect of enzymatic hydrolysis on the chemical properties of the hydrolysates, the protein and cellulose contents were determined. In the waste samples after BAC extraction, the protein content was 8.86% and the cellulose content was 51.25%. After enzymatic hydrolysis, the protein and cellulose contents changed. Figure 4 shows the dependence of protein mass fraction on the concentration of the enzyme preparation.

Analysis of the graph showed a proportional decrease in protein concentration with increasing enzyme preparation concentration. The highest proteolytic activity was observed with chicken stomach mucosa: a 5% concentration of this preparation is comparable to 26% and 51% Creon. The correlation is negative, with a correlation coefficient of –0.97333. During enzymatic hydrolysis, the amount of processed protein ranged from 43% to 68%, with a residual utilization coefficient of 0.33–0.58.

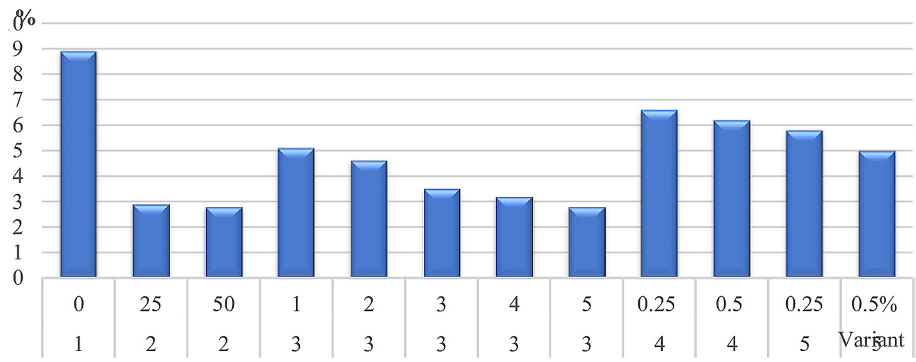


Figure 4. Effect of Creon concentration on protein hydrolysis, 1 – initial sample; 2 – Creon; 3 – enzyme preparation; 4 – Celloviridin G20x; 5 – OmniGen® AF

Figure 5 shows the dependence of cellulose content on the concentration of the enzyme preparation during enzymatic hydrolysis.

Analysis of the graph showed a proportional increase in cellulose concentration with increasing concentrations of Creon and the enzyme preparation. The correlation is positive, with a correlation coefficient of +0.95065. In the case of Celloviridin G20x and OmniGen® AF, the cellulose content decreased by 24–29%. No correlation with enzyme concentration was observed, with a negative correlation coefficient of –0.13926. The utilization coefficient ranged from 0.48 to 0.56.

Figures 6–7 show the results of the effect of the acid-active enzyme complex modified with dimethylamine (AAEC-DMA) and α-GHCG (alpha-subunit of human chorionic gonadotropin) on the hydrolysis of plant waste.

The addition of AAEC-DMA to the reaction mixture revealed that the cellulose content in the hydrolyzed residues decreased by 20% across all variants, indicating that AAEC-DMA stimulates the enzymatic hydrolysis of the waste. Similar values were observed in the experiment with α-GHCG. The addition of α-GHCG resulted in a 32% reduction of cellulose in the hydrolyzed residues.

The experimental results revealed that the cellulolytic activity of the enzyme preparations increased by 38% and 60% with the addition of AAEC-DMA and α-GHCG, respectively.

Figures 8–9 present data on the effect of AAEC-DMA and α-GHCG on the protein content during enzymatic hydrolysis.

Unlike previous findings, nitrosamines and pesticides do not improve protein utilization; on the contrary, a decrease in enzymatic protein hydrolysis is observed due to inhibition of the proteolytic activity of enzymes. The experimental results showed that the proteolytic activity of the enzyme preparations decreased by 37% and 50% with the addition of AAEC-DMA and α-GHCG, respectively.

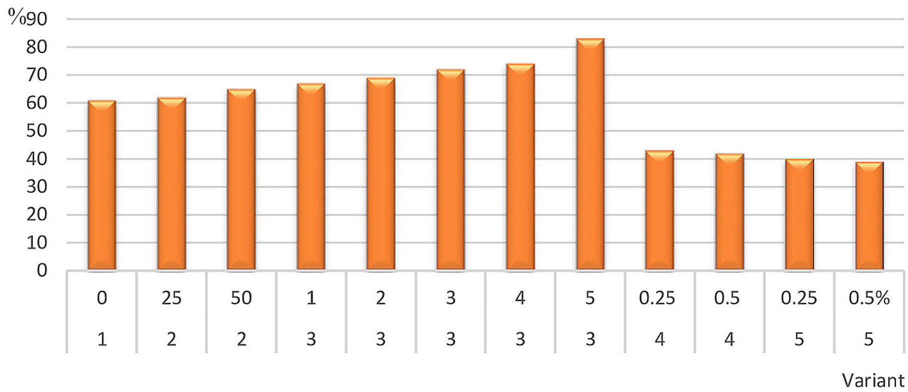


Figure 5. Effect of Creon concentration on cellulose content, 1 – initial sample; 2 – Creon; 3 – enzyme preparation; 4 – Celloviridin G20x; 5 – OmniGen® AF

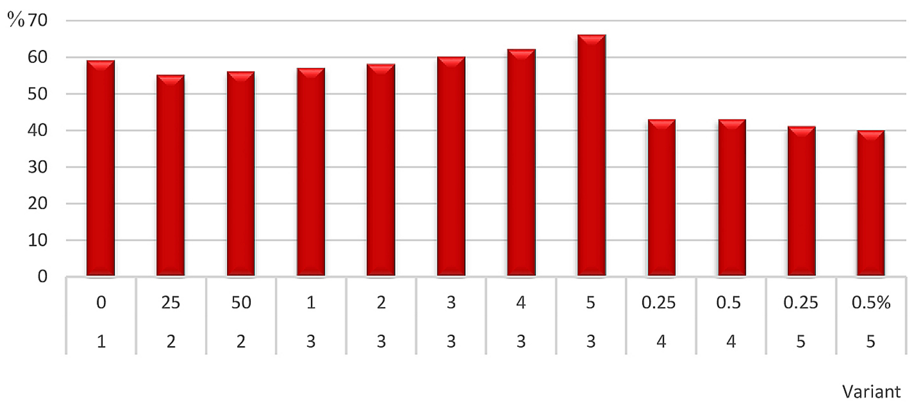


Figure 6. Cellulose content in the solid residues of hydrolysates with the addition of AAEC-DMA, 1 – initial sample; 2 – Creon; 3 – enzyme preparation; 4 – Celloviridin G20x; 5 – OmniGen® AF

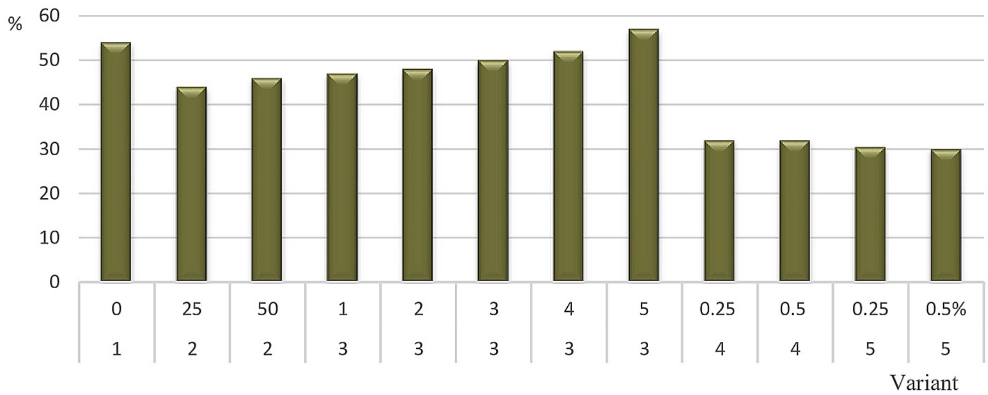


Figure 7. Cellulose content in the solid residues of hydrolysates with the addition of α-GHCG, 1 – initial sample; 2 – Creon; 3 – enzyme preparation; 4 – Celloviridin G20x; 5 – OmniGen® AF

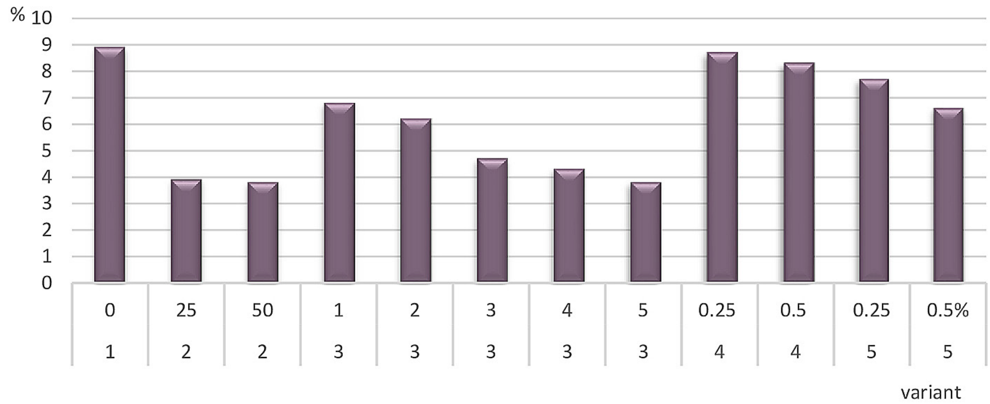


Figure 8. Protein content in the solid residues of hydrolysates with the addition of AAEC-DMA, 1 – initial sample; 2 – Creon; 3 – enzyme preparation; 4 – Celloviridin G20x; 5 – OmniGen® AF

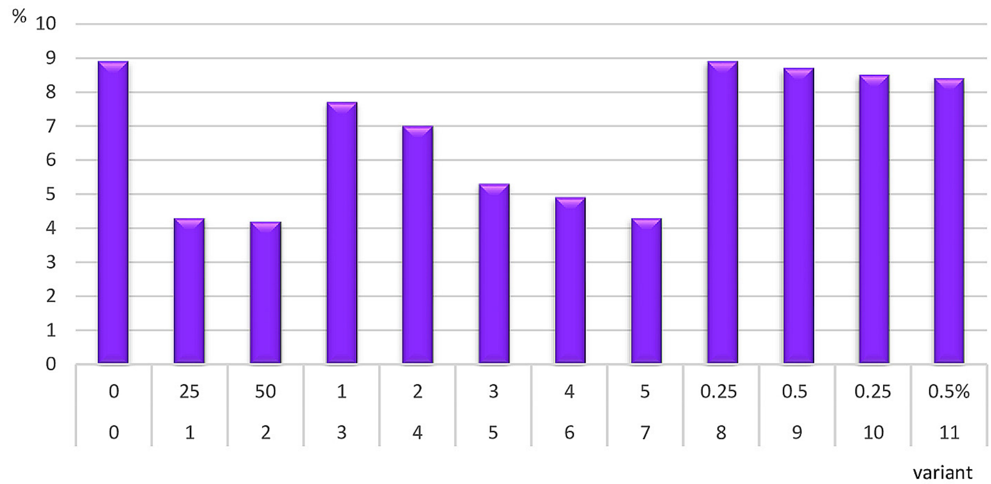


Figure 9. Protein content in the solid residues of hydrolysates with the addition of α-GHCG, 1 – initial sample; 2 – Creon; 3 – enzyme preparation; 4 – Celloviridin G20x; 5 – OmniGen® AF

CONCLUSIONS

It was established that, on average, about 6.4 t of straw is produced per 1 ha of buckwheat crops, from which up to 2.9 t of cellulose, 1.8–1.9 t of lignin, and approximately 320–325 kg of biologically active compounds can be obtained, confirming the high resource value of this agro-industrial by-product.The extraction of biologically active compounds provides a yield of extractive components of approximately 14%, while about 86% of the mass remains as secondary waste, retaining a significant amount of structural carbohydrates and mineral elements, suitable for further processing.

Thermal treatment of straw at 100–110 °C for 1.5–2.0 h leads to a 1.4-fold increase in cellulose content, whereas treatment at 120–122 °C and a pressure of 1.97 atm for 0.25 h results in an increase in cellulose content up to 68.5% with a simultaneous reduction of lignin to 14.4%.

Enzymatic hydrolysis using Celloviridin G20x and OmniGen® AF at a concentration of 0.10–0.50 g per 100 g of substrate provides a polysaccharide hydrolysis degree of 45–56%, while the use of combined enzyme systems achieves up to 50%.

During enzymatic hydrolysis, the degree of protein utilization ranges from 43–68%, while the residual utilization coefficient varies between 0.33 and 0.58, indicating effective degradation of the protein fractions in the straw.

The addition of modified enzyme complexes promotes the intensification of the process: cellulolytic activity increases by 38% with the use of AAEC-DMA and up to 60% with the addition of α-GHCG, while the cellulose content in the solid residues simultaneously decreases by 20–32%.

It was established that the presence of nitrosamines and pesticides leads to inhibition of the proteolytic activity of enzymes, reducing the efficiency of protein hydrolysis by 37–50%, which must be taken into account when developing environmentally safe processing technologies.

A comparison with wheat, barley, and rice straw showed that buckwheat straw has a competitive cellulose content (45.0%) and hydrolysis efficiency (45–56%), while its main distinction is the significantly higher content of biologically active compounds (14.0% extractives, including rutin absent in cereal straw), enabling a dual-purpose biorefinery approach. The low ash content (3.18%) compared to rice straw (10–18%) further simplifies downstream processing

Overall, the obtained data confirm the possibility of comprehensive bioconversion of buckwheat straw, resulting in the production of dietary fibers (up to 90% cellulose), soluble sugars, and functional components, which opens prospects for its practical application in the food, feed, and biotechnological industries.

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