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BIOCHEMICAL INDICATORS AND AGRONOMIC VALUE OF DIGESTATE DERIVED FROM COFFEE, BARLEY, AND CHICORY WASTE MIXTURES

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The need for sustainable agriculture and a circular economy encourages the search for effective ways to utilize organic waste and transform it into valuable resources. Digestate, a by-product of anaerobic digestion of organic materials (biogas residue), is a promising organic fertilizer. This article presents a comprehensive analysis of the quality of digestate obtained from a mixture of coffee, barley and chicory waste, based on detailed biochemical studies.

Purpose. The aim of the study was to assess the physicochemical properties of the digestate, the content of macro- and microelements, the amino acid profile, the potential presence of biostimulants, microbiological safety, and the concentration of heavy metals in comparison with regulatory requirements.

Materials and Methods. The physicochemical and microbiological parameters of the digestate derived from a mixture of coffee, barley, and chicory wastes were analyzed using standard methods.

Results. The obtained data indicate the agronomic feasibility and environmental safety of using this digestate as an organic fertilizer. The analysis of digestate derived from coffee, barley, and chicory wastes demonstrates its potential as a high-quality, safe, and multifunctional organic fertilizer that provides essential macro- and microelements, improves the physicochemical and biological properties of the soil, and exhibits biostimulant activity.

Conclusions. The digestate produced from a mixture of coffee, barley, and chicory wastes is an environmentally friendly and safe organic fertilizer with high agronomic potential and may be recommended for use to improve soil fertility and crop yields.

Key words: digestate, waste mixture, anaerobic digestion, biogas, organic fertilizer, macro- and micronutrient content, amino acids, agronomic value.

Modern agriculture faces a dual challenge: the increasing demand to enhance productivity and the urgent need to mitigate adverse environmental impacts [1]. Conventional linear "production–consumption–disposal" models contribute to the accumulation of large volumes of organic waste, which frequently become sources of environmental pollution. At the same time, these residues represent a substantial and underexploited resource of nutrients and organic matter for soil improvement. The circular economy framework provides an effective alternative by promoting the conversion of waste streams into valuable resources [2].

In this context, anaerobic digestion (biogas technology) has emerged as a key approach for the simultaneous production of renewable

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energy (biogas) and high-quality organic fertilizer in the form of digestate [3–5]. This study focuses on the characterization and analysis of digestate derived from a specific mixture of coffee industry residues, namely coffee, barley, and chicory. Rather than treating digestate as a secondary by-product, this work considers it as a central component in optimizing resource efficiency and advancing sustainable agricultural practices

Food and agro-processing wastes, such as coffee grounds, barley residues, and chicory by-products, have traditionally posed significant disposal challenges. Although they are rich in organic matter, their direct application to soil without proper treatment may lead to undesirable effects, such as soil acidification, pest attraction, or uneven decomposition.

Anaerobic digestion is an effective process that enables:

– the production of biogas, a valuable renewable energy source that can be used for electricity and heat generation, thereby reducing dependence on fossil fuels [6];

– the stabilization of organic matter, during which complex organic compounds are broken down into simpler substances, while pathogenic microorganisms are destroyed or their abundance is significantly reduced [7];

– the preservation and concentration of nutrients, as, unlike composting, anaerobic digestion minimizes nitrogen losses (mainly in the form of ammonium) and reduces the volatilization of other nutrients [8].

Thus, digestate represents a transformed, stabilized, and nutrient-enriched organic resource with significantly higher agronomic value compared to untreated waste [9, 10].

The aim of the study was to evaluate the physicochemical properties of digestate, including the content of macro- and microelements, amino acid profile, potential presence of biostimulatory compounds, microbiological safety, and heavy metal concentrations, in comparison with regulatory standards.

Materials and Methods

Liquid digestate samples (2 L), obtained from a mixture of coffee production wastes (coffee, barley, and chicory residues), were collected directly from the outlet pipeline of a biogas plant operated by LLC “BIT”.

Physicochemical, agrochemical, and microbiological analyses were conducted in accredited laboratories. The physicochemical properties of the digestate were determined at the Laboratory of Agrochemistry and Analytical Research of the Institute of Agriculture of the Carpathian Region of the NAAS, including moisture content (gravimetric method), organic matter and ash content (dry combustion in a muffle furnace), pH (potentiometric method), total nitrogen (Kjeldahl method), phosphorus (spectrophotometry), and potassium (flame photometry).

The macro- and microelement composition was analyzed at the Laboratory of Ecological Physiology and Product Quality of the Institute of Animal Biology of the NAAS amino acids were determined at the Laboratory of High-Performance Liquid Chromatography of the DNDKI of Veterinary Drugs and Feed Additives by HPLC.

Heavy metals and microbiological indicators were analyzed at the Central Research Laboratory and the Laboratory of Industrial Toxicology of Danylo Halytsky Lviv National Medical University. Microbiological analyses included coliform bacteria (colony counting), *Escherichia coli* (IMViC tests), *Salmonella* spp. (horizontal method with enrichment and selective agar), *Pseudomonas aeruginosa* (plating on CN agar and fluorescence microscopy), *Proteus* spp. (inoculation on Ploskirev’s medium), and *Bacillus cereus* (MYP agar method).

All analyses were performed in accordance with Ukrainian State Standards (DSTU) and relevant methodological guidelines [11].

Results and Discussion

A detailed analysis of the quality of digestate derived from coffee, barley, and chicory wastes revealed its specific physicochemical characteristics, highlighting the potential of these substrates as raw materials for fertilizer production. The main parameters are presented in Table 1.

High moisture content (~92%) is typical for liquid digestates and necessitates appropriate application methods. A pH in the range of 7.5–8.0 indicates a slightly alkaline to near-neutral reaction. This condition is favorable for soils, as it helps prevent acidification, a common issue in many regions. The formation of such pH values is mainly associated with the neutralization of organic acids and the accumulation of ammonium nitrogen during anaerobic fermentation.

Organic matter accounts for approximately 55% of the dry weight, indicating a high

Table 1

Main physicochemical parameters of digestate derived from coffee, barley, and chicory wastes (mean values)

Physicochemical indicators	Value
Moisture, %	~ 92 %
pH (water extract)	7.5–8.0
Organic matter, % of d. m.	~ 55 %
Ash content (mineral substances), % of d. m.	~ 45 %
Total nitrogen (N), % of d. m.	~ 2.0 %
Phosphorus (as P_2O_5), % of d. m.	~ 1.0 %
Potassium (as K_2O), % of d. m.	~ 2.0 %

Note: d. m. — dry mass.

Table 2

Micronutrient composition of digestate from coffee, barley, and chicory wastes (dry matter basis)

Chemical Element (symbol)	Concentration, mg/kg d. m. (~)
Cobalt (Co)	< 1 mg/kg
Magnesium (Mg)	~ 3000 mg/kg
Manganese (Mn)	~ 10 mg/kg
Copper (Cu)	~ 15 mg/kg
Sodium (Na)	~ 200 mg/kg
Nickel (Ni)	~ 5 mg/kg
Zinc (Zn)	~ 50 mg/kg
Iron (Fe)	~ 1000 mg/kg
Chromium (Cr)	~ 2 mg/kg

potential for improving soil structure, increasing water-holding capacity, and enhancing humus formation [12, 13]. Residual undegraded components, such as lignin and cellulose, may undergo gradual decomposition in soil, contributing to long-term soil fertility. Ash content (~45% of dry matter) reflects the concentration of mineral residues remaining after organic matter degradation.

Regarding macronutrients, the digestate contains considerable amounts of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O). Total nitrogen (~2% of dry matter) is a key parameter, and its presence in readily available forms (ammonium nitrogen and soluble organic compounds) makes digestate an effective alternative to mineral nitrogen fertilizers [14–16]. Phosphorus (~1% P_2O_5 of dry matter), mainly in phosphate forms, provides gradual nutrient availability to plants. Potassium (~2% K_2O of dry matter) is particularly valuable, as it plays a crucial role in regulating plant water balance and enhancing stress tolerance. The overall NPK content indicates that this digestate can be compared with conventional organic fertilizers, highlighting its potential as a source of bioavailable nutrients [17].

In addition to macronutrients, digestate is also a source of essential micronutrients required for optimal plant growth and development [18, 19]. Table 2 presents the approximate concentrations of micronutrients in the digestate.

Among trace elements, iron (Fe) shows the highest concentration, which is essential for chlorophyll synthesis and plant respiration processes. Magnesium (Mg) and sodium (Na), although classified as macro- or meso-elements, are also present in relatively significant amounts. Elements such as zinc (Zn), manganese (Mn), and copper (Cu) occur at concentrations of tens of mg/kg dry matter. These micronutrients play a vital role in enzyme activity, hormonal regulation, and plant respiration. Regular application of digestate may help prevent deficiencies of these elements in soils, which is particularly important in intensive agricultural systems [20].

The concentrations of potentially toxic trace elements, such as cobalt (Co), nickel (Ni), and chromium (Cr), are very low and remain well below the maximum permissible limits for fertilizers [21]. This indicates that the trace element profile of the digestate is beneficial rather than hazardous and does not pose a risk of heavy metal contamination of soils.

The analyzed digestate contains a broad spectrum of free amino acids, indicating partial degradation of protein compounds during anaerobic fermentation and the formation of low-molecular-weight nitrogen compounds. The following amino acids were identified: alanine, arginine, valine, histidine, leucine, isoleucine, lysine, methionine, ornithine, proline, serine, taurine, tryptophan, phenylalanine, cystine, asparagine, glutamine, as well as the dicarboxylic amino acids aspartic and glutamic acids (Table 3).

The presence of free amino acids in the fertilizer provides several important agronomic benefits:

– **Nitrogen availability:** free amino acids serve as a readily available source of organic nitrogen for plants and soil microorganisms. They can be rapidly absorbed by plants or mineralized to ammonium nitrogen [22].

Table 3

Free amino acid content in digestate from coffee, barley and chicory waste

Amino acid	Concentration, mg/ml
Alanine	0.74
Arginine	0.18
Valine	0.20
Histidine	0.15
Leucine + Isoleucine	0.53
Lysine	0.25
Methionine	0.25
Ornithine	1.24
Proline	0.04
Serine	0.03
Taurine	0.16
Tryptophan	0.38
Phenylalanine	0.17
Cystine	0.14
Asparagine	1.08
Aspartic acid	0.03
Glutamine	0.33
Glutamic acid	0.04

– **Chelating properties:** certain amino acids (e.g., glycine and serine) are capable of forming chelate complexes with micronutrients (Fe, Zn, etc.), thereby enhancing their availability to the plant root system [23].

– **Biostimulatory effects:** amino acids such as tryptophan (a precursor of auxin) and arginine (a precursor of agmatine) act as biostimulants, promoting phytohormone biosynthesis, improving seed germination, and enhancing root development [24]. Proline, in turn, plays a key role in plant osmoregulation under stress conditions [25, 26].

Thus, the amino acid profile of digestate increases its agronomic value by providing not only a source of nitrogen but also biologically active compounds that stimulate plant growth.

The presence of natural biostimulants, such as phytohormones and humic substances, represents an additional advantage of organic fertilizers [27, 28]. Although direct measurements of phytohormones and fulvic acids were not performed in this study, their presence in digestates derived from organic raw materials is highly probable.

Regarding phytohormones, compounds such as gibberellic acid, indole-3-acetic acid (auxin), and abscisic acid have been detected in the liquid fractions of digestates of different origins [29]. Their occurrence is attributed both to the composition of the initial feedstock and to microbial activity during anaerobic fermentation [30]. Even at low concentrations, these substances can positively influence plant growth and development by stimulating germination, root formation, and increasing tolerance to abiotic stress factors [31].

Digestate is typically rich in humic substances, particularly fulvic acids, a low molecular weight fraction of humic acids. Fulvic acids are formed during the anaerobic decomposition of organic matter. They act as powerful biostimulants, improving soil structure, moisture retention, and nutrient uptake by plants [32]. Studies have shown that fulvic acids promote root development and increase crop yields [33]. Although these compounds have not been directly identified, their potential presence confers biostimulant properties to digestate, enhancing its overall beneficial effects on plants and soil [34, 35].

Microbiological purity is a critically important parameter for any organic fertilizer. The digestate analyses for the presence of indicator and pathogenic bacteria showed a high level of microbiological safety (Table 4), namely:

– absence of pathogens: no Salmonella spp. was detected in the digestate sample (in 25 g of the sample), which meets the strict sanitary requirements for organic fertilizers;

– low level of Escherichia coli: the number of E. coli was below the detection limit or at the level of units of CFU / g, which is significantly below the maximum permissible level of 1000 CFU / g, according to European standards;

– absence of other bacteria: Pseudomonas aeruginosa and Bacillus cereus were also not detected or were present in insignificant, safe quantities.

The effective hygienization occurring during anaerobic methane fermentation (particularly under mesophilic or thermophilic conditions) ensures the inactivation or significant reduction of pathogenic microorganisms. Compliance with European regulations (e.g., Regulation (EU) No. 142/2011) [36], which define hygienization requirements and limit values for indicator microorganisms, confirms that the digestate is microbiologically safe for agricultural application. Consequently, the risk of microbiological contamination of soils or agricultural products following fertilizer application is minimal.

Table 4

Microbiological indicators of digestate from coffee, barley and chicory waste

Indicator, units of measurement	A definite result
Coliform bacteria in 1 cm^3	detected
Escherichia coli in 1 cm^3	not detected
Salmonella spp. in 25 cm^3	not detected
Pseudomonas aeruginosa in 1 cm^3	not detected
Proteus in 1 cm^3	detected
Bacillus cereus in 1 cm^3	detected

Heavy metal content is one of the key environmental and safety indicators of organic fertilizers. Analysis of digestate derived from coffee, barley, and chicory wastes revealed very low concentrations of potentially toxic elements. Lead (Pb) was detected at approximately 1 mg/kg dry matter, while cadmium (Cd) was below 0.5 mg/kg dry matter. Other regulated elements, such as nickel (Ni) and chromium (Cr), were also present at minimal levels (a few mg/kg).

These values are substantially lower than the maximum permissible limits established for organic fertilizers (e.g., EU recommendations: Pb ~300 mg/kg dry matter, Cd ~2 mg/kg, Ni ~100 mg/kg, Cr ~600 mg/kg, Zn ~1500 mg/kg, Cu ~600 mg/kg). Accordingly, the lead content represents only ~0.3% of the permissible limit, while cadmium is below 25% of the threshold value.

The low heavy metal content is consistent with the plant-based origin of the feedstock and the absence of industrial contamination. Anaerobic digestion does not introduce additional heavy metals into the final product [37]. Therefore, the application of such digestate does not pose a risk of hazardous accumulation of heavy metals in soil or their transfer into the food chain.

Moreover, certain so-called heavy metals, such as copper (Cu), zinc (Zn), cobalt (Co), and manganese (Mn), are essential micronutrients required by plants in trace amounts; thus, their presence at safe concentrations may be beneficial for plant nutrition [38].

Digestate derived from coffee, barley, and chicory wastes is suitable for application in agricultural practice. It represents an effective component of organic farming systems and circular economy approaches, enabling the return of nutrients to soils and contributing to the sustainable development of agroecosystems.

It is recommended to apply digestate prior to sowing or during main fertilization. Due to its high moisture content, the use of specialized equipment for liquid organic fertilizers is advisable, or alternatively, its incorporation with dry structural materials (e.g., straw). Application rates should be calculated based on nitrogen content and crop requirements, at approximately 20–30 t/ha of raw digestate to supply 100–150 kg N/ha (dry matter basis), taking into account regional guidelines and soil fertility status.

Although digestate is a ready-to-use fertilizer, it may be further composted or aged to reduce moisture content, stabilize ammonium nitrogen into more stable forms, and eliminate residual weed seeds. Proper storage in impermeable tanks is essential to prevent nutrient losses.

Digestate is particularly effective for nitrogen-demanding crops (e.g., cereals and maize) and for soils with low organic matter content. Its near-neutral pH allows application across a wide range of soil types. The potassium content makes it suitable for potassium-demanding crops (e.g., potatoes, sugar beet, and vegetables), while trace elements support the nutrition of perennial crops such as orchards and vineyards.

When handling digestate, standard hygienic precautions should be observed, including the use of protective clothing and avoidance of direct skin contact. Application is recommended prior to soil incorporation or before the growing season, avoiding direct contact with edible plant parts. To minimize ammonia volatilization, application under cool weather conditions or in the evening is preferable.

For sustainable management, periodic soil monitoring is recommended, including the analysis of organic matter, macro- and microelements, and soil pH at intervals of several years. This allows optimization of application rates and maintenance of balanced soil fertility. Monitoring of potentially toxic elements (e.g., every five years) may also be conducted to ensure long-term environmental safety, although the risk of accumulation is considered minimal.

Conclusions

As a result of a comprehensive analysis of the quality of digestate obtained from coffee, barley and chicory waste, the high

quality of such organic fertilizer with valuable agronomic and environmental characteristics was confirmed:

– Nutritional value: digestate is a rich source of macronutrients (N, P, K) in bioavailable forms, which allows it to partially or completely replace mineral fertilizers, especially in organic farming. It also provides plants with essential micronutrients (Fe, Mn, Zn, Cu), preventing micronutrient starvation.

– Organic matter and biostimulants: the high content of organic matter contributes to the improvement of the physical properties of the soil and an increase in the content of humus. The presence of free amino acids, as well as the probable presence of phytohormones and fulvic acids, give digestate confers biostimulatory properties, promoting plant growth and development beyond a purely nutritional effect.

– **Microbiological safety:** the product complies with sanitary requirements, as evidenced by the absence of major pathogenic microorganisms (e.g., *Salmonella* spp., *Escherichia coli* at elevated levels, *Pseudomonas aeruginosa*, *Bacillus cereus*). This ensures its safety for soil, crops, and human health.

– **Environmental safety:** concentrations of heavy metals in the digestate are extremely low and significantly below permissible regulatory limits, eliminating the risk of toxic accumulation in soils and transfer into food chains.

Thus, digestate derived from coffee, barley, and chicory wastes is a safe, environmentally friendly, and highly effective multifunctional organic fertilizer. It combines the roles of nutrient source, soil conditioner, and biostimulant, thereby contributing to improved soil fertility and enhanced crop productivity.

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Author Contributions

O. Sv.: conceptualization, data curation, literature review, bibliography compilation, analysis and interpretation of results, and drafting of the manuscript. Z. B.: research organization, preparation of the original draft, and approval of the manuscript. O. Shv.: critical revision of the manuscript, editing, language polishing, translation editing, and final approval of the manuscript. O. Sht.: data analysis, interpretation of results, formulation of conclusions, and approval of the manuscript.

All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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БІОХІМІЧНІ ПОКАЗНИКИ ТА АГРОНОМІЧНА ЦІННІСТЬ ДИГЕСТАТУ, ОТРИМАНОГО З ВІДХОДІВ КАВИ, ЯЧМЕНЮ ТА ЦИКОРІЮ

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Необхідність розвитку сталого сільського господарства та циклічної економіки спонукає до пошуку ефективних шляхів утилізації органічних відходів та їх трансформації у цінні ресурси. Дигестат, що є побічним продуктом анаеробного зброджування органічних матеріалів (біогазовий залишок), є перспективним органічним добривом. Ця стаття є комплексним аналізом якості дигестату, отриманого із суміші відходів кави, ячменю та цикорію, на основі детальних біохімічних досліджень.

Мета. Оцінити фізико-хімічні властивості дигестату, вміст макро- та мікроелементів, амінокислотний профіль, потенційну наявність біостимуляторів, мікробіологічну безпеку та концентрацію важких металів у порівнянні з нормативними вимогами.

Матеріали й методи. Проведено аналіз фізико-хімічних і мікробіологічних показників дигестату з суміші відходів кави, ячменю та цикорію з використанням відповідних загальноприйнятих методик.

Результати. Отримані дані дозволяють зробити обґрунтовані висновки щодо агрономічної доцільності та екологічної безпеки використання дигестату як органічного добрива. Аналіз дигестату з відходів кави, ячменю та цикорію яскраво демонструє його потенціал високоякісного, безпечного та багатофункціонального органічного добрива, яке не тільки забезпечує рослини необхідними макро- та мікроелементами, але й покращує фізико-хімічні та біологічні властивості ґрунту, діючи як ефективний біостимулятор.

Висновки. Дигестат, отриманий з суміші відходів кави, ячменю та цикорію є екологічно чистим, безпечним і високоефективним органічним добривом, яке можна рекомендувати до широкого застосування з метою покращення родючості ґрунтів та урожайності сільськогосподарських культур.

Ключові слова: дигестат, суміш відходів, анаеробне зброджування, біогаз, органічні добрива, вміст макро- та мікроелементів, амінокислоти, агрономічна цінність.

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