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A SYSTEMATIC APPROACH TO THE FORMATION OF QUALITY AND ENVIRONMENTAL SAFETY OF BIOFERTILIZER FROM DIGESTATE

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Abstract. The use of anaerobic digestate as a biofertilizer is quite promising in terms of soil protection technologies in view of the reduction of environmental risks from the use of mineral fertilizers and the positive impact on soil productivity, improvement of their quality and restoration of the humus layer. However, anaerobic digestion does not ensure the complete absence of environmental hazards due to a certain probability of heavy metals, pharmaceutical substances, and pathogenic microorganisms entering the soil with biofertilizer. The article is aimed at determining effective methods of processing raw materials and digestate, as well as technological approaches for obtaining biofertilizer from digestate for use in geosphere protection technologies.

The methodological basis of the study was a meta-analysis based on scientific publications within the framework of a systematic approach to the formation of the quality and ecological safety of fertilizer from digestate. It was established that the type of substrate initially affects the content of nutrients and pollutants, but the use of methods of pretreatment of raw materials, thermal and chemical, has the potential to balance the ratio of NPK and remove heavy metals. The most relevant is the choice of digestate separation technology.

Thus, it is essential to apply post-treatment methods to raw digestate and its individual fractions. The creation of granulated organo-mineral fertilizers and the production of biochar from the solid fraction of digestate are suggested as environmentally safe products for soil protection technologies.

Keywords: anaerobic digestion, granular biofertilizer, heavy metals, micronutrients, soil protection technologies, digestate post-treatment.

1. Introduction

The biogas industry makes it possible to obtain not only biogas itself, but also digestate as an organically fermented residue containing a high content of nitrogen N, phosphorus P, potassium K and other substances, which determine its utilization as fertilizer (Kalnina et al., 2018). The level of macro- and microelements depends on the type of substrate for anaerobic digestion and their composition, among which several categories are distinguished: food waste (O'Connor et al., 2024) and agro-food industry waste (Rittl et al., 2023); energy crops (Suchowska-Kisielewicz, Jędrczak, 2019); slaughter waste and manure (Matjuda et al., 2023); waste from municipal sewage treatment plants (Havukainen et al., 2022). At the same time, the highest NPK indicators are typical for digestate from chicken manure. Such a biofertilizer contains a higher proportion of nitrogen in a plant-available form, the optimal ratio between carbon and nitrogen for the soil, and from 1 to 3 % of organic carbon. Biofertilizer contains active bacteria that have a direct impact on the process of organic decomposition in the geosphere (Ndubuisi-Nnaji et al., 2020).

Quite often, not only individual types of waste are subjected to anaerobic digestion, but also their

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mixtures, which improves the properties of the obtained digestate. For example, mixing household waste with sewage sludge improves the environmental and economic aspects of the processes. In the same way, agricultural and manure (Sica, Magid, 2024), sewage sludge and plant biomass (Malovanyy et al., 2022), or animal manure, municipal sewage and brewery sewage sludge (Nascimento et al., 2023). The content of nutrients and pollutants, which determine the quality and ecological safety of the fertilizer, varies greatly both from these factors and from other parameters. An urgent scientific task is to improve the quality of digestate, in compliance with the requirements of national and European legislation regarding the form of use of the final product, in particular organic fertilizer or amendment in agriculture, as well as regarding possible ways to improve its properties by composting, drying or granulation (Pinasseau et al. 2018).

Since biogas plants work continuously throughout the year, the use of digestate as a biofertilizer, its treatment and processing solve another problem – the need for long-term storage. This usually occurs in leaky tanks (lagoons) and is accompanied by the settling of solid particles and their accumulation. Long-term storage leads to an increase in the mass of organic matter and an increase in greenhouse gas emissions into the atmosphere (Yan et al., 2023). From the standpoint of a systemic approach to the use of digestate in soil protection technologies, it is worth considering the impact on the environment during the processing of digestate and its transportation, as well as in the case of replacing mineral fertilizers.

Valorization of digestate for soil protection consists in a positive effect on the physicochemical properties of the soil (Doyeni et al., 2021), enzymatic and microbiological activity of the soil (Garsia-Lopez et al., 2023), prevention of soil pollution due to the replacement of synthetic fertilizers (Ablieieva et al., 2022b). The biofertilizing properties of digestate depend on a number of factors, the core of which is the composition of the substrate from which the digestate is obtained, the thermal regime of digestate production, and technological solutions for digestate processing and fertilizer production (Ablieieva et al., 2022a). The question of optimizing the production of biofertilizer from digestate in accordance with the requirements of environmental safety remains unsolved, therefore it is relevant to study the impact of digestate processing technologies and fertilizer production on its environmental safety and quality in accordance with the current standards of quality of organic and mineral fertilizers.

The purpose of the article is to determine effective methods of processing raw materials and digestate, as well as technological approaches for obtaining biofertilizer from digestate for use in geosphere protection technologies. To achieve the goal, the following research tasks were set:

1) on the basis of the conducted meta-analysis, to investigate the influence of methods of pre-treatment of the substance on the quality and environmental safety of fertilizer from digestate;

2) analyze the influence of digestate separation technologies on the distribution of nutrients and pollutants in solid and liquid fractions;

3) to evaluate the positive ecological effect of the use of granular biofertilizer from digestate.

2. Theoretical part

The research methodology is based on a systematic approach to the use of anaerobic digestate in soil protection technologies, which involves establishing patterns and factors of quality and environmental safety of biofertilizer obtained from digestate. Synthetic mineral fertilizers create a significant technogenic load on the environment in the process of their production using non-renewable natural resources that cannot be renewed yet (fossil fuels), and at the stage of use, the soil and soil ecosystems are primarily negatively affected. Biofertilizer from digestate has not only a direct positive effect on the properties and structure of the soil, but also an indirect compensatory effect due to the replacement of mineral fertilizers. Technological solutions at various stages of the digestate life cycle, ending with the production of fertilizer from digestate, determine the quality and environmental safety of the fertilizer. In order to achieve the goal of the research, the key factors that affect the quality and environmental safety of the final product from digestate are highlighted. The systematization and formalization of technological options and related influencing factors is shown in the structural diagram describing the research methodology (Fig. 1). Thus, technologies of pre-treatment of the substance for anaerobic digestion, technologies of separation of raw digestate into two fractions, technologies of post-processing of digestate, including production of fertilizer, are highlighted as significant. At the same time, special emphasis is placed on the technological solutions of the process of obtaining organo-mineral fertilizers by the granulation method.

A literature search among scientific publications for the period 2015–2024 in the international scientometric databases Web of Science Core Collection and Scopus was chosen as the methodological base of the systematic review. The study was based on the use of a special code from the keywords "(digestate OR "anaerobic digestate" OR "biogas digestate") AND (pre-treatment OR post-treatment OR "solid liquid separation" OR granulation) AND (fertilizer OR biofertilizer OR "organic fertilizer")". 188 documents were found, after specifying the year of research (2015–2024), subject area, type of publication (original article) and language (English), 119 documents were obtained that were subject to further meta-analysis. A bibliometric map was built on the basis (tool) of the VOSviewer software and the frequency of use of keywords was visualized (Fig. 2) in the found scientific works.

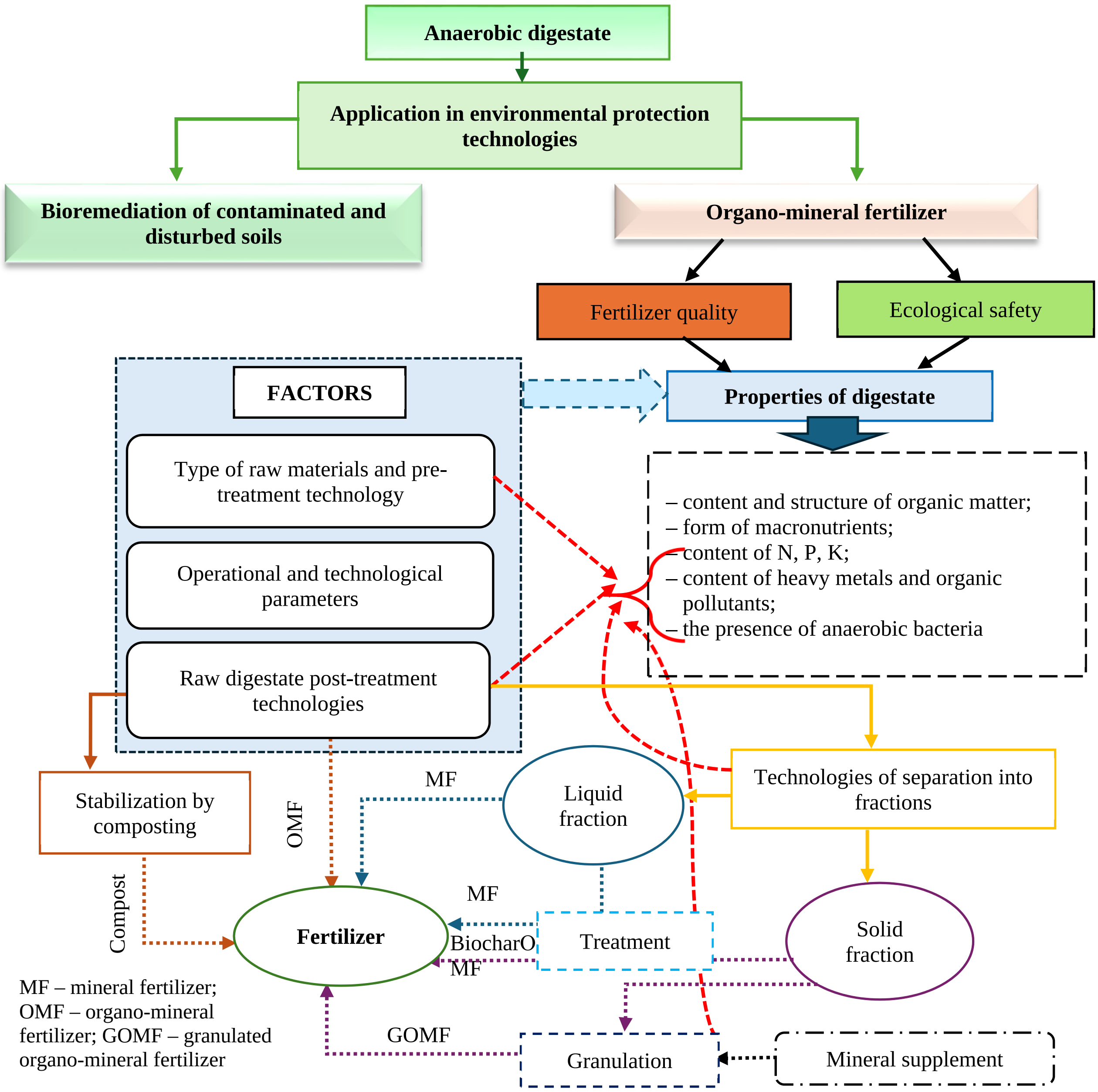

Fig. 1. Structural and logical scheme of the methodological basis of the study

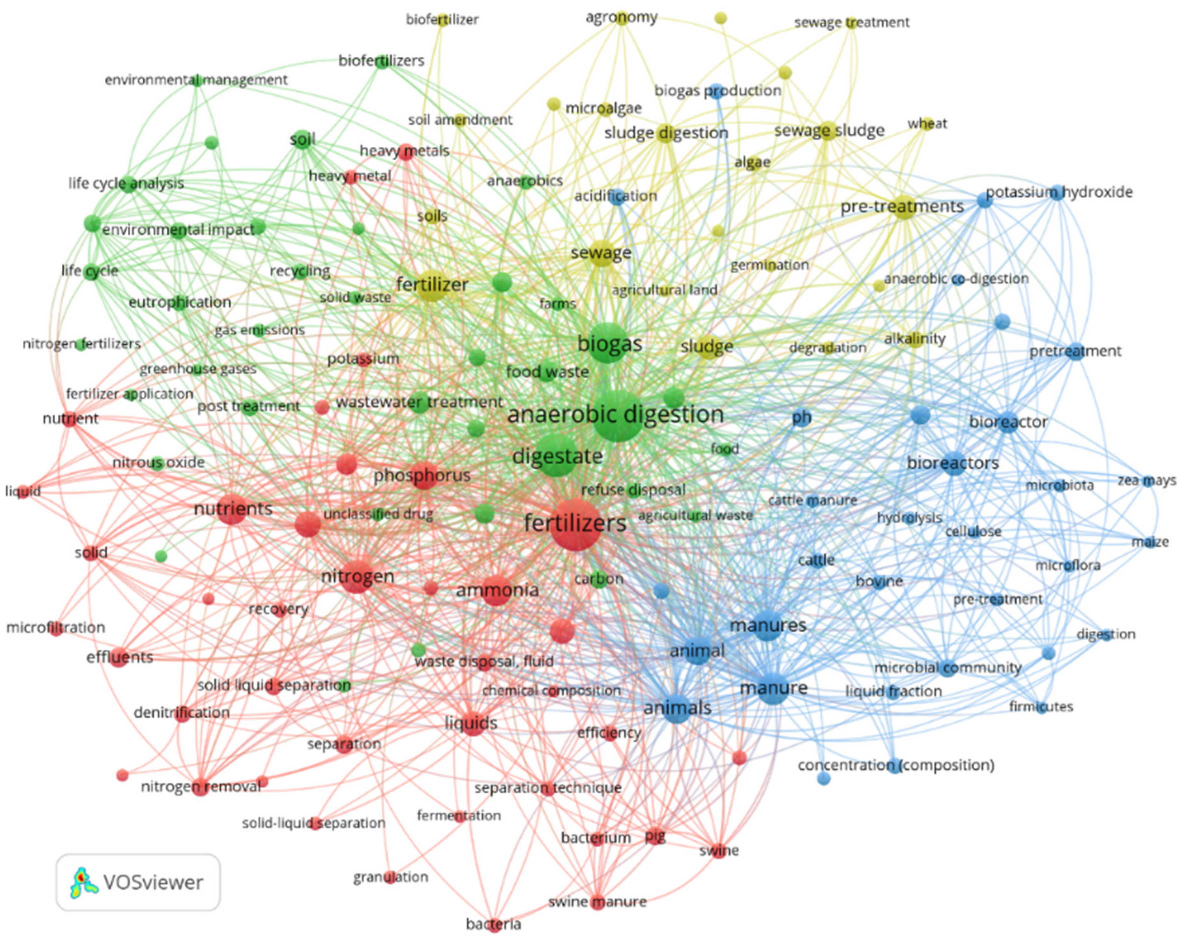

Fig. 2. Map of relationships between the most used keywords (occurrence frequency > 5) on the topic "Impact of technological solutions on the quality of fertilizer from digestate" for the research period 2015–2024

As a result of the analysis of the resulting network, clusters were selected based on key words describing four areas of research. Further analysis was carried out on the basis of selected clusters:

1. Blue cluster. Anaerobic fermentation processes and methods of preliminary treatment of livestock waste separately or as a co-substrate.

2. Yellow cluster. Methods of preliminary treatment of sewage sludge as a substrate for anaerobic digestion to improve the quality of fertilizer from digestate.

3. Red cluster. The influence of digestate separation technologies, as well as granulation, on the content of nitrogen, phosphorus and heavy metals (HM) in fertilizer.

4. Green cluster. Anaerobic fermentation of food waste, with the formation of digestate. Life cycle evaluation and methods of post-treatment of digestate to obtain biofertilizer.

The main emphasis is on the analysis of the content of nutrients and heavy metals depending on various factors, as described in the scheme of Fig. 1. At the same time, the studied values were compared with the normative ones respectively with Regulation (EU) 2019/1009 (Regulation (EU), 2019) (Table 1).

The results of the studies were subject to a detailed meta-analysis to identify significant dependencies and patterns that affect the quality and environmental safety of the digestate. Statistical analysis of data from different sources under different initial conditions was performed to determine the statistical significance of the studied factors. MS Excel and Statistical Program for the Social Sciences – SPSS (IBM SPSS Statistics, 29.0.0.0) software were used for the research. Treatment of data on nutrient content (NPK) and pollutant content (PM) depending on various factors, including different technological solutions, was carried out using ANOVA analysis of variance and Tukey HSD (honestly significant difference) test as a post hoc analysis to establish statistically significant differences between the data ($p < 0.05$).

Table 1

Content of nutrients and heavy metals in various fertilizers according to EU standard 2019/1009

Indicators	Organic fertilizer		Organo-mineral fertilizer	
	Solid	Liquid	Solid	Liquid
Nutrients, not less (% by weight):				
Nitrogen – N	1	1	2	2
Phosphorus – P	1	1	2	2
Potassium – K	1	1	2	2
NPK amount	4	3	8	6
Heavy metals, not more than (mg/kg DM*):				
Cadmium – Cd	1.5	1.5	3	3
Chrome – Cr	2	2	2	2
Nickel – Ni	50	50	50	50
Lead – Pb	120	120	120	120
Copper – Cu	300	300	600	600
Zinc – Zn	800	800	1500	1500

* DM – dry matter

3. Results and Discussion

3.1. Influence of the type of substrate and methods of pre-treatment of substrates on the quality of digestate

The analysis of scientific works made it possible to divide waste, which is used as raw matter for anaerobic fermentation, into several groups: waste of animal origin (animal manure, chicken droppings, waste from animal slaughter), agricultural raw materials (silage of various crops), food waste, sewage sludge, in its pure form and their mixture in different percentage ratios. The results regarding the content of NPK in the digestate obtained from different types of substrates are shown in Fig. 3.

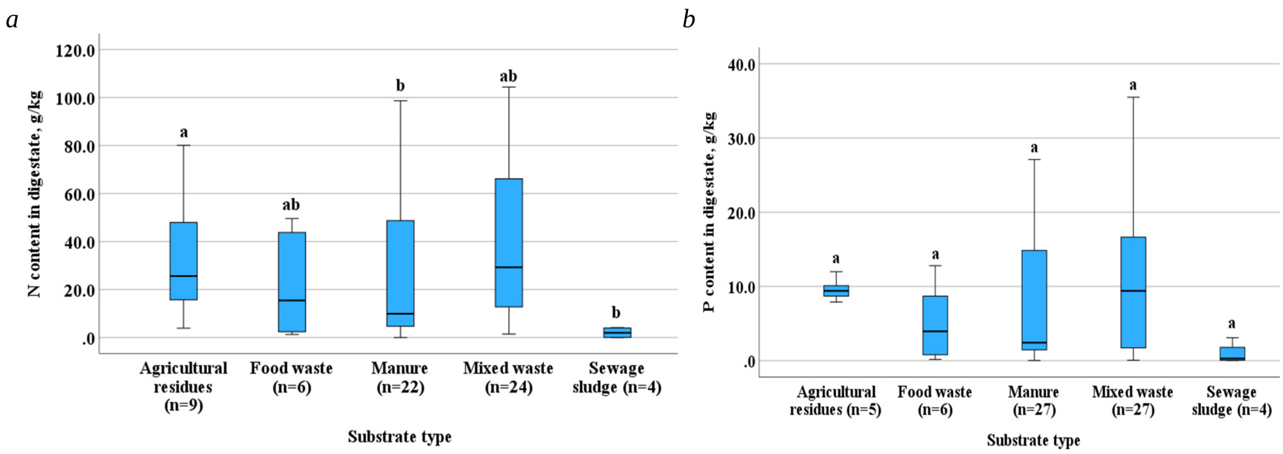

Fig. 3. Boxplot for content values (means ± SD, 95 % confidence interval; significantly different values ($p < 0.05$) are indicated by lowercase letters) for total nitrogen (*a*), total phosphorus (*b*) and total potassium (*c*) in samples of digestate obtained from different types of raw materials (agricultural residues, food waste, animal manure, sewage sludge and mixed waste)

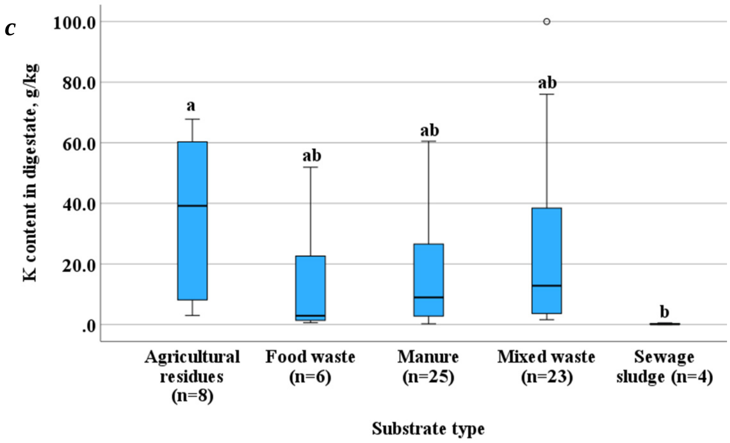

Fig. 3. (Contunuation) Boxplot for content values (means ± SD, 95 % confidence interval; significantly different values ($p < 0.05$) are indicated by lowercase letters) for total nitrogen (*a*), total phosphorus (*b*) and total potassium (*c*) in samples of digestate obtained from different types of raw materials (agricultural residues, food waste, animal manure, sewage sludge and mixed waste)

According to the results of the analysis (Fig. 3), it was established that digestate obtained from agricultural residues, including plant waste and energy crops, has statistically significantly higher nitrogen content than digestate from animal manure and sewage sludge. Differences for total phosphorus in digestate samples based on different substrate types were not identified as statistically significant, although digestate from agricultural residues also showed higher results. Digestate obtained from agricultural residues has statistically significantly higher nitrogen content than digestate from sewage sludge. It should be noted that in the digestate from fermenters loaded with animal manure and food waste, the average indicators of N, P, K are lower than for those from agricultural residues, however, mixing these types of substrates allows obtaining higher indicators, which confirm the effectiveness of the use of co-digestion (co-digestion) to optimize the process and balance the content of nutrients.

It has been established that the use of the same type of substrate has different results, therefore, in some cases, digestate meets the requirements of the standard for different types of fertilizers in terms of nutrient content (see Table 1), in particular in the case of using a substrate based on animal waste and food waste – 26.5 g/kg N, 34 g/kg P, 12.6 g/kg K (Sica, Magid, 2024); animal manure and silage – 25 g/kg N, 8.4 g/kg P, 76 g/kg K (Sogn et al., 2018); 29.7 g/kg N, 4.8 g/kg P, 17 g/kg K (Garcia-Lopez et al., 2023). At the same time, the content of N, P, K at the level of 16.02 g/kg N, 1.24 g/kg P, 2.25 g/kg K (Monti et al., 2021) does not meet the requirements of the standard and requires additional technologies for enrichment mineral composition of fertilizer.

Moreover, the type of substrate for anaerobic digestion affects the content of HM in the obtained digestate, therefore, the regularities of the content of HM in different types of mono-raw material and mixture of organic waste were investigated (Fig. 4).

According to the conducted research (Fig. 4), it is interesting that a statistically significant amount of cadmium, zinc and lead is determined in the digestate from sewage sludge ($p < 0.05$) higher values than in digestate obtained from other types of raw materials. Moreover, Cd was recognized as the most concerning HM in agricultural soils due to its high amount in mineral fertilizers (Ballabio et al., 2024). That's why digestate from other substrates excluding sewage sludge has a high potential to prevent Cd migration into soil. For chromium, nickel and copper, no difference was established between the results obtained for digestate from different types of substrates. It was determined that regardless of the type of input raw material for digestate, fermented biomass contains a fairly large amount of zinc compared to other biomaterials, but within the limits of permissible values respectively with Regulation (EU) for both organic and organo-mineral fertilizers (see Table 1). Similarly, no excesses were found for Ni, Pb and Cu, regardless of the type of substrate, however, the content of Cd in the digestate from sewage sludge had an excess for both organic and [illegible]rs. excess of Cr content in the digestate based on all investigated types of substrates, which necessitates the use of substrate pre-treatment and digestate post-treatment technologies.

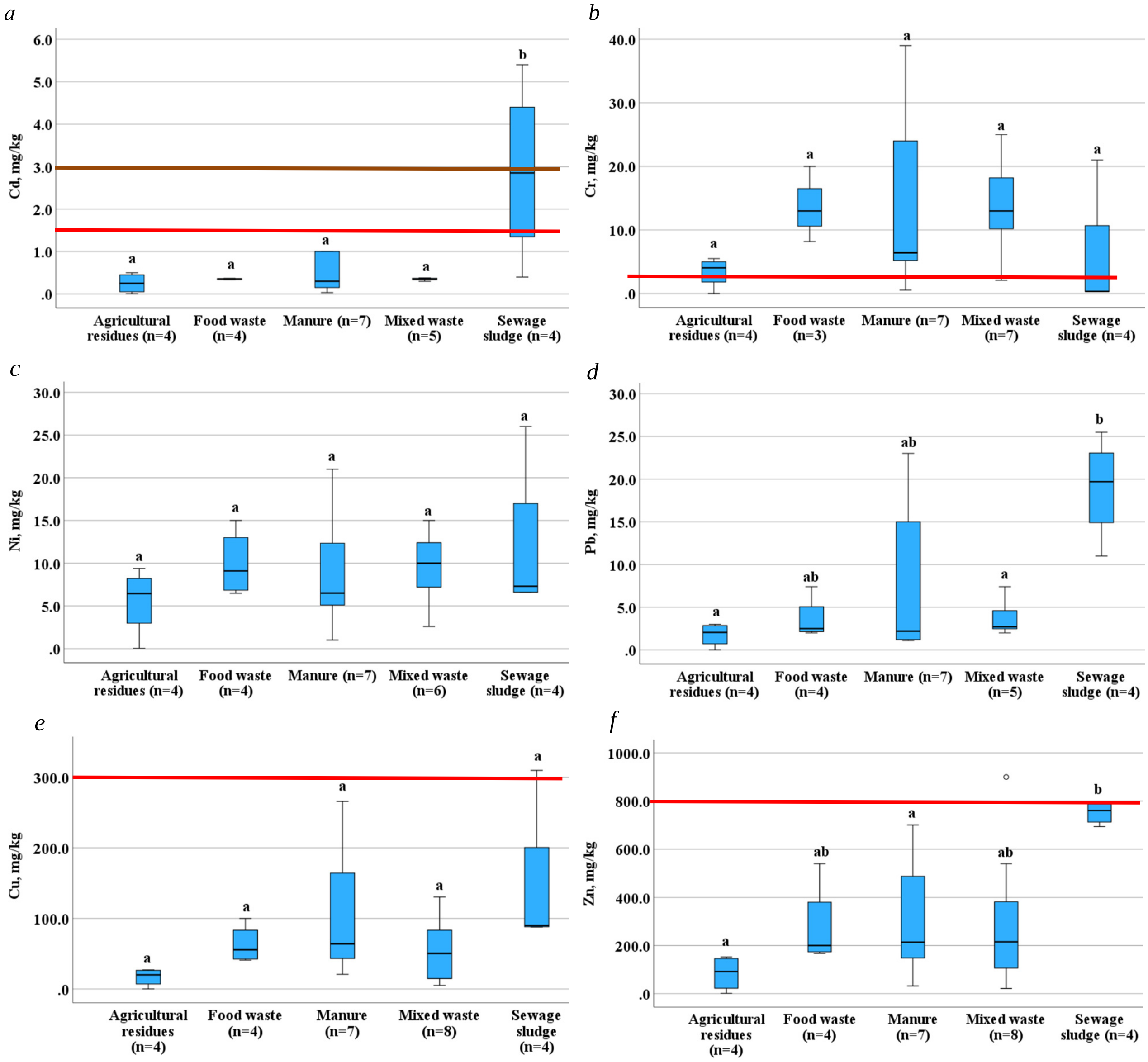

Fig. 4. Boxplot for content values (means ± SD, 95 % confidence interval; significantly different values ($p < 0.05$) are indicated by lowercase letters) for copper Cu (*a*), zinc Zn (*b*), cadmium Cd (*c*), chromium Cr (*d*), nickel Ni (*e*) and lead Pb (*f*) in samples of digestate obtained from different types of raw materials

Notes: ——— requirements of Regulation (EU) for organic fertilizer; ——— requirements of Regulation (EU) for organo-mineral fertilizer.

As a result of the selected clusters according to research directions, it was established that raw material pre-treatment technologies are used most frequently for the following types of substrates: sewage sludge and livestock waste as a mono- or co-substrate (Table 2).

The most widespread methods of pre-treatment of substrates differ in the mechanism of influence on the substrate and biochemical processes that then take place in the bioreactor. But the differ between them is that as a result of the chemical pretreatment of the raw materials, an increase in the NPK content of the raw materials was observed (2.7–54.3 %), which is consistent with the results of (Dahunsi et al., 2019). At the same time, as a result of thermal pretreatment, a decrease in the content of these elements (14–38.5 %) was noted according to research (Matjuda et al., 2023). It is worth noting that a similar situation was observed in the study of the effect of processing on the content of heavy metals (Dahunsi et al., 2019; Matjuda et al., 2023). Accordingly, the nature of the impact on quality and environmental safety indicators of the digestate formed will be different.

Table 2

Analysis of methods of pretreatment of raw materials for anaerobic digestion with the production of digestate

Group methods	Method (specification)	Substrate type	References
Mechanical	Mechanical (milling)	Lignocellulosic biomass	Bharadwaj et al., 2024
Thermal	Thermal (850 °C, 2 sec)	Sewage sludge	Havukainen et al., 2022
	Pasteurization (60 °C, 96 h)	Cattle and sheep slaughter waste	Matjuda et al., 2023
	Sterilization (133 °C, 15 min)		
	Pyrolysis (400 °C without access to oxygen)	Cow manure with the addition of corn silage	Radawiec et al., 2023
Physico-chemical	Electrokinetic (4.37 kWh)	Livestock waste with grass silage	Rittl et al., 2023
	Ultrasound (20 kHz)		
Chemical	Alkali treatment (NaOH, KOH, $Ca(OH)_2$)	Livestock manure and food waste; straw with activated sludge	Lee et al., 2023; Alrowais et al., 2024
	Acid treatment (HCl, H_2SO_4)	Corn straw; food waste and straw	Xie at al., 2022; Dahunsi et al., 2019
	Addition of iron nanoparticles	Spent sludge; pig manure	Puyol et al., 2018; Sun et al., 2024

3.2. The influence of technologies of separation and post-treatment on the composition of digestate fractions and their environmental safety

Application of raw digestate can cause secondary soil contamination due to high ammonia content due to strong reducing conditions in methane tanks. Usually, at biogas plants, as the first stage of processing “raw” digestate, its separation into two fractions is used. At the same time, various technologies and equipment are used: screw press, vibrating screen, centrifuge, rotating drum, filter press, etc., which have excellent efficiency and energy consumption (Ablieieva et al., 2022b). Additionally, coagulants and flocculants, polymers, material drying, etc. can be used (Akhiar et al., 2017), in particular, the use of chitosan for separation using a decanter centrifuge showed the highest efficiency indicators (Ablieieva et al., 2022a).

However, from the point of view of environmental safety, it is important to establish the patterns of distribution of micronutrients (NPK) and pollutants (HM and organic pollutants). The solid fraction is enriched with carbon and phosphorus – up to 60 % of the initial content in raw digestate, liquid – with nitrogen and potassium (up to 75 % of the initial content in raw digestate), which is consistent with the results obtained for individual fractions of digestate based on fruit and vegetable waste (Tavera et al., 2023) and pig and cow manure (Doyeni et al., 2021). In addition, it is worth paying attention that the liquid fraction of the digestate by the sum of the content of NPK nutrients (at least 6 %) can meet the requirements for liquid organo-mineral fertilizer (see Table 1), and the solid fraction – for solid organic fertilizer (not less than 4 %). However, an important aspect from the point of view of environmental safety is the study of the content of heavy metals in fertilizer.

As for pollutants, the transition of HM (Cd, Cr, Hg, Pb, Ni, Cu, Zn, As, Fe) to the solid fraction of the digestate is observed, and the use of a decanter centrifuge from an ecological point of view is a more effective technology in relation to the purification of liquid digestate due to the binding of HM by organic matter contained in the solid fraction. However, in the case of separation of the digestate by both mechanical separation and centrifugation, a rather high (from 100 % to 752 % relative to the raw digestate) concentration level of some HM (Cd, Cr, Ni, Zn, Fe) in the solid fraction is observed, which is consistent with with the results of research conducted (Sfetsas et al., 2023), although their content does not exceed the regulatory values for fertilizers. Moreover, other studies (Tambone et al., 2017) show a statistically significant higher distribution of HM (Ni, Zn, Pb, Cu, Cd, Cr) for the liquid fraction (69–95 % relative to raw digestate) than for the solid fraction (58–85 % relative to raw digestate), provided that mixed substrates based on livestock waste and energy crops are used. In addition, chromium was observed to have a higher content for the two compared fractions to the raw digestate at 113 % and 135 %, respectively. To increase the environmental safety of fertilizer obtained from the liquid fraction of digestate, an effective method is the use of flocculants and coagulants during chemically enhanced separation of digestate. In particular, the use of polyaluminum chloride, epichlorohydrin-dimethylamine with ethylenediamine, and polyacrylamide showed a positive effect on cleaning the liquid fraction from HM (Pb, Cu, Ni, Zn, and Cr) by an average of 50 % after centrifugation (Beggio et al., 2022). These data are consistent with the results obtained with the application of coagulants $Ca(OH)_2$ and $Al_2(SO_4)_3$ in relation to the removal of zinc from liquid digestate based on livestock waste (Cattaneo et al., 2019). It can be assumed that HMs are strongly bound and immobilized in the crystal lattice, indicating the overall lower solubility of these elements in water and a potentially reduced risk to the environment. Accordingly, organic pollutants, including pharmaceuticals and personal care products, pesticides, industrial chemicals, and stimulants, are transferred mainly to the solid fraction of the digestate formed as a result of anaerobic digestion of municipal sewage sludge (Yang et al., 2017), indicating an ecological the safety of the liquid fraction of digestate and the need to use additional technologies for cleaning the solid fraction of digestate from organic and inorganic pollutants.

Due to the change in the composition of the digestate fractions after separation, the properties of the two phases of the digestate will be different compared to raw digestate, which directly affects the quality and environmental safety of the fertilizer. Thus, Pelayo Lind et al. (2021) investigated the liquid phase of digestate as a liquid fertilizer, which is used more often, because in addition to the classical use as foliar fertilizers, they are also increasingly used in new fertilization technologies, such as fertigation (fertilization simultaneously with watering). However, depending on the kind of matter for digestion and other process parameters, the liquid fraction of the digestate can vary significantly (Akhiar et al., 2017).

The liquid fraction will primarily differ in the ratio of C, N and P, and may contain extremely high levels of them in a water-soluble ionic form. For example, the phosphate content usually ranges from 100–200 g/m^3 but can reach 900 g/m^3. At the same time, the level of organic carbon is often very low, so the ratio C:N < 1, which is much lower than the optimal 25–30. The liquid fraction of the obtained digestate can also differ in pH level, content of potentially toxic volatile fatty acids with a short or branched chain, low biodegradability due to the presence of humic substances, as well as other parameters that have a general impact on the environment. For this reason, the direct use of the liquid digestate fraction may carry an environmental risk of certain toxicity or lead to eutrophication. Therefore, they resort to the application of post-treatment technologies of both raw digestate and separate two fractions (Table 3).

Table 3

Analysis of digestate post-treatment methods (raw and individual fractions)

Group methods	Method (specification)	Substrate type and digestate fraction	References
Thermal	Vacuum evaporation	Municipal solid waste	Tavera et al., 2023
	Pyrolysis with obtaining biochar	Solid fraction of digestate from cow manure and food waste	Alberto et al., 2021
	Drying	Manure, sewage sludge of a brewery; cow manure and silage	Nascimento et al., 2023; Radawiec et al., 2023
Chemical	Acidification	Manure, sewage sludge of a brewery; animal manure and food waste	Nascimento et al., 2023, Sica, Magid, 2024
Biological	Composting	Animal dung	Vitti et al., 2021
	Post-fermentative incubation	Food waste	Holatko et al., 2022

Composting, acidification and vacuum evaporation are used most frequently as post-treatment of digestate (Table 3). In the case of applying vacuum evaporation, an increase in NPK content for the liquid fraction by 1.5–2 times was observed (Tavera et al., 2023). The solid fraction of the digestate can be sent for composting, but it is also possible to directly apply it to the fields, if sanitary indicators for the content of helminth eggs allow it. However, changes in the quality and environmental safety of bioproducts obtained after processing raw digestate using various technologies are of scientific interest. The regularities of NPK changes for compost and biochar compared to the original digestate were established.

As a result of comparing the quality of digestate with compost obtained from raw digestate, the following results were obtained for nitrogen: 10.4 g/kg DM N (raw digestate) and 90 g/kg DM N (compost from raw digestate) (Vitti et al., 2021); for phosphorus – 0.35 g/kg and 0.07 g/kg P, respectively (Vitti et al., 2021); for potassium – 1.29 g/kg and 4.91 g/kg K, respectively (Uzinger et al., 2021). Thus, there is a tendency to decrease the content of phosphorus and increase the content of potassium and nitrogen in compost compared to digestate, which allows to obtain fertilizer more enriched in potassium and nitrogen.

Based on the study (Rekasi et al., 2023), patterns were established regarding the NPK content of digestate, and biochar obtained from the solid fraction of digestate. The indicators are 39.4 g/kg N and 9.6 g/kg N, 32.5 g/kg P and 6.7 g/kg P, 3.4 g/kg K and 15.4 g/kg K, in accordance. The use of biochar is quite effective in reducing potassium losses. At the same time, smaller biochar can immobilize a larger volume of digestate and ensure faster infiltration of irrigation water than its larger particles.

Noticed difference between NPK values for fresh digestate, dried and pyrolyzed (Radawiec et al., 2023). Due to the post-treatment of digestate, a more ecologically safe product can be obtained than “raw” digestate, but the agronomic effect is reduced. But it is worth considering that its action is long-lasting and works for the perspective of the results. That is, it is possible to ensure more distant, safe impacts on the geosphere than to interconnect the increase in fertility and the systemic accumulation of HM, pathogenic organisms and other foreign inclusions.

In addition, the separation of digestate makes it possible to achieve a reduction of methane emissions into the atmosphere during long-term storage, to reduce the volume of tanks, to expand the variability of technical possibilities and methods of subsequent processing and introduction of biofertilizer into the soil. Both fractions can be used for fertilization and each of them has its own characteristics when used.

3.3. Positive ecological effect of using biofertilizer from digestate

In addition to the analyzed methods of pretreatment of the substrate and posttreatment of raw digestate, which directly affect the chemical composition of digestate, the quality of biofertilizer from digestate will be determined by the technology of obtaining the organo-mineral fertilizer. Recently, instead of using raw digestate, it is possible to obtain granules based on digestate, which is an enriched fertilizer with certain individual characteristics and properties and can be considered as an eco-fertilizer with additional value.

Obtaining such improved fertilizers is ecologically safe and economically feasible (Eco-innovation, 2022). Production of granular fertilizers from digestate changes its bioavailability and some properties. Valorization of digestate (for example, obtaining granulated amino acid fertilizers from digestate from organic waste with the addition of pig hemoglobin in the course of stepwise hydrolysis, neutralization, composition correction, granulation, drying and fractionation) leads to obtaining a solid organo-mineral multi-element fertilizer, and this form allows you to control its assimilation in soil and prevent the loss of useful products in biogeochemical cycles, which are necessary for growing plants (Barampouti et al., 2020). The content of toxic components in the obtained fertilizer, in particular Cd, Cr, Hg, Ni, Pb, As, is at a level below the permissible limits.

Nutrients from such fertilizer are absorbed gradually, without causing environmental problems, in addition, they contain easily digestible amino acids, which are directly absorbed by plants and are included in the composition of proteins, which not only increases yield, but also contributes to greater drought resistance of plants and allows them to survive on saline soils, which can be considered as a way to survive and increase productivity in the conditions of climate change (Skrzypczak et al., 2023).

Replacing 1 ton of synthetic fertilizer with digestate saves approximately 108 tons of water and greenhouse gas emissions of 4 tons of CO_2-eq. Biofertilizers are cost-effective and environmentally friendly, which not only prevent the destruction of natural resources, but also help rid plants of deposited synthetic fertilizers and increase soil fertility and productivity per unit area in a relatively short period of time.

In Ukraine, biogas processing of digestate in most cases is reduced to separation into two fractions. Further, actions with biofertilizer require additional technical and financial solutions. Such expenses must be justified. The following motivators for additional processing of fractions are distinguished:

– reducing the volume of biofertilizer allows to reduce transportation costs to the place of its use;

– high requirements for the quality of “raw digestate”, which are easier to achieve precisely due to processing;

– economic expediency of production and placement on the world market of products from digestate, i.e. the opportunity to become competitive for foreign enterprises;

– the need to comply with nitrogen application norms per 1 ha of land (Council Directive 91/676/EEC, 2008).

Thus, to obtain an environmentally safe product, it is necessary to apply additional processing of biogas digestate, instead of using it in its raw form.

Technological solutions to produce granulated organic-mineral fertilizers based on digestate will also affect the content of nutrients and pollutants. Therefore, the issue of optimization of the technological process of fertilizer production becomes important, which is the subject of further research.

4. Conclusions

In recent years, the frequency of pre- and post-treatment of digestate obtained from biogas plants has been increasing, as there is a high probability of secondary contamination of soils after application of biofertilizer with pharmaceuticals, heavy metals, and pathogenic microorganisms. The quality and environmental safety of biofertilizer from digestate is determined by various factors, particularly the type of substrate for anaerobic digestion, the method of processing (mechanical, thermal, physical, physical and chemical, biological), the technology of separating digestate into two fractions, and the method of production of mineral or organo-mineral fertilizers

Based on the conducted meta-analysis, it was established that the optimal ratio of NPK for fertilizer can be achieved in the case of using agricultural raw materials as raw materials for the bioreactor. The conducted studies show a decrease in the NPK content in the case of using methods of pre-treatment of substrates, but an increase in the environmental safety of the product at the exit, which is a higher priority. To achieve the optimal content of NPK in fertilizer, it is recommended to use a chemical method of preliminary processing of agricultural matter or mixed raw materials based on animal and vegetable waste as a substrate.

Technologies for separating digestate into two fractions have different patterns of distribution of nutrients and pollutants in the respective fractions depending on the method, equipment, addition of coagulants or flocculants. It was established that nitrogen and potassium as water-soluble elements are concentrated in the liquid fraction, and phosphorus and carbon are concentrated in the solid fraction, which determines the possibility of using liquid digestate in the form of an organo-mineral fertilizer. From an environmental point of view, the use of chemically enhanced separation on a decanter centrifuge ensures the purification of the liquid fraction from heavy metals and organic pollutants but causes their concentration in a bound form in the solid fraction of the digestate. The established regularities arouse scientific interest and the relevance of further research on environmentally safe valorization of fertilizer based on the solid fraction of digestate, due to pyrolysis with the production of biochar or granulation with the addition of mineral additives, which has a positive ecological effect for soil ecosystems.

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References

Ablieieva, I., Berezhna, I., Berezhnyi, D., Prast, A. E., Geletukha, G., Lutsenko, S., Yanchenko, I., & Carraro, G. (2022a). Technologies for Environmental Safety Application of Digestate as Biofertilizer. *Ecological Engineering & Environmental Technology, 23*(3), 106–119. doi: https://doi.org/10.12912/27197050/147154

Ablieieva, I. Y., Geletukha, G. G., Kucheruk, P. P., Enrich-Prast, A., Carraro G., Berezhna, I. O., & Berezhnyi, D. M. (2022b). Digestate potential to substitute mineral fertilizers: Engineering approaches. *Journal of Engineering Sciences (Ukraine), 9*(1), H1–H10. doi: https://doi.org/10.21272/jes.2022.9(1).h1

Akhiar, A., Battimelli, A., Torrijos, M., & Carrere, H. (2017). Comprehensive characterization of the liquid fraction of digestates from full-scale anaerobic co-digestion. *Waste Management, 59*, 118–128. doi: https://doi.org/10.1016/j.wasman.2016.11.005

Alberto, D. R., Tyler, A. C., & Trabold, T. A. (2021). Phosphate adsorption using biochar derived from solid digestate. *Bioresource Technology Reports, 16*, 100864. doi: https://doi.org/10.1016/j.biteb.2021.100864

Alrowais, R., Said, N., Mahmoud-Aly, M., Helmi, A. M., Nasef, B. M., & Abdel daiem, M. M. (2024). Influences of straw alkaline pretreatment on biogas production and digestate characteristics: artificial neural network and multivariate statistical techniques. *Environmental Science and Pollution Research, 31*, 13638–13655. doi: https://doi.org/10.1007/s11356-024-31945-7

Ballabio, C., Jones, A., & Panagos, P. (2024). Cadmium in topsoils of the European Union – An analysis based on LUCAS topsoil database. *Science of the Total Environment*, *912*, 168710. doi: https://doi.org/10.1016/j.scitotenv.2023.168710

Barampouti, E. M., Mai, S., Malamis, D., Moustakas, K., & Loizidou, M. (2020). Exploring technological alternatives of nutrient recovery from digestate as a secondary resource. *Renewable and Sustainable Energy Reviews, 134*, 110379. doi: https://doi.org/10.1016/j.rser.2020.110379

Beggio, G., Peng, W., Lü, F., Cerasaro, A., Bonato, T., & Pivato, A. (2022). Chemically enhanced solid–liquid separation of digestate: Suspended solids removal and effects on environmental quality of separated fractions. *Waste and Biomass Valorization*, *13*, 1029–1041. doi: https://doi.org/10.1007/s12649-021-01591-y

Bharadwaj, A., Holwerda, E. K., Regan, J. M., Lynd, L. R. & Richard, T. L. (2024). Enhancing anaerobic digestion of lignocellulosic biomass by mechanical cotreatment. *Biotechnology for Biofuels and Bioproducts, 17*, 76. doi: https://doi.org/10.1186/s13068-024-02521-5

Cattaneo, M., Finzi, A., Guido, V., Riva, E., & Provolo, G. (2019). Effect of ammonia stripping and use of additives on separation of solids, phosphorus, copper and zinc from liquid fractions of animal slurries. *Science of The Total Environment*, *672*, 30–39. doi: https://doi.org/10.1016/j.scitotenv.2019.03.316

Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. (2008). *EUR-Lex: Access to European Union law*. Retrieved from https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:31991L0676

Dahunsi, S. O., Adesulu-Dahunsi, A. T., Osueke, C. O., Lawal, A. I., Olayanju, T. M. A., Ojediran, J. O., & Izebere, J. O. (2019). Biogas generation from Sorguhum bicolor stalk: Effect of pretreatment methods and economic feasibility. *Energy Reports, 5*, 584–593. doi: https://doi.org/10.1016/j.egyr.2019.04.002

Doyeni, M.O., Stulpinaite, U., Baksinskaite, A., Suproniene, S. & Tilvikiene, V. (2021). The effectiveness of digestate use for fertitlization in an agricultural cropping system. *Plants*, *10*(8), 1734. doi: https://doi.org/10.3390/plants10081734

Eco-innovation at the heart of European policies. (2022). *European Commission.* Retrieved from https://ec.europa.eu/environment/ecoap/about-action-plan/objectives-methodology_en

Garsia-Lopez, A. M., Delgado, A., Anjos, O., & Horta, C. (2023). Digestate not only affects nutrient availability but also soil quality indicators. *Agronomy*, *13*, 1308. doi: https://doi.org/10.3390/agronomy13051308

Havukainen, J., Saud, A., Astrup, T. F., Peltola, P., & Horttanainen, M. (2022). Environmental performance of dewatered sewage sludge digestate utilization based on life cycle assessment. *Waste Management*, *137*, 210–221. doi: https://doi.org/10.1016/j.wasman.2021.11.005

Holatko, J., Hammerschmiedt, T., Latal, O., Kintl, A., Mustafa, A., Baltazar, T., Malicek, O., & Brtnicky, M. (2022). Deciphering the effectiveness of humic substances and biochar modified digestates on soil quality and plant biomass accumulation. *Agronomy*, *12*, 1587. doi: https://doi.org/10.3390/agronomy12071587

Kalnina, I., Rugele, K., & Rubulis, J. (2018). Digestate management practice in Latvia from nitrogen perspective. *Energy Procedia, 147*, 368–373. doi: https://doi.org/10.1016/j.egypro.2018.07.105

Lee, J. H., Min, K. J., An, H. J., & Park, K. Y. (2023). Comparison of solubilization treatment technologies for phosphorus release from anaerobic digestate of livestock manure. *Water*, *15*, 4033. doi: https://doi.org/10.3390/w15234033

Malovanyy, M., Voytovych, I., Mukha, O., Zhuk, V., Tymchuk, I., & Soloviy, C. (2022). Potential of the co-digestion of the sewage sludge and plant biomass on the example of Lviv WWTP. *Ecological Engineering & Environmental Technology, 23*(2), 107–112. doi: https://doi.org/10.12912/27197050/144958

Matjuda, D. S., Tekere, M., & Thaela-Chimuka, M.-J. (2023). Characterization of the physicochemical composition of anaerobically digested (digestate) high throughput red meat abattoir waste in South Africa and the determination of its quality as a potential biofertilizer. *Heliyon*, *9*(11). doi: https://doi.org/10.1016/j.heliyon.2023.e21647

Monti, M., Badagliacca, G., Romeo, M., & Gelsomino, A. (2021). No-till and solid digestate amendment selectively affect the potential denitrification activity in two Mediterranean orchard soils. *Soil System*, *5*, 31. doi: https://doi.org/10.3390/soilsystems5020031

Nascimento, G., Villegas, D., & Cantero-Martínez, C. (2023). Crop diversification and digestate application effect on the productivity and efficiency of irrigated winter crop systems. *European Journal of Agronomy*, *148*, 126873. doi: https://doi.org/10.1016/j.eja.2023.126873

Ndubuisi-Nnaji, U. U., Ofon, U. A., Ekponne N. I., Offiong, N.-A. O. (2020). Improved biofertilizer properties of digestate from codigestion of brewer's spent grain and palm oil mill effluent by manure supplementation. *Sustainable Environmental Research, 30*, 14. doi: https://doi.org/10.1186/s42834-020-00056-6

O'Connor, J., Mickan, B. S., Gurung, S. K., Buhlmann, C. H., Jenkins, S. N., Siddique, K. H. M, Leopold, M., & Bolan, N. S. (2024). Value of food waste-derived fertilisers on soil chemistry, microbial function and crop. *Applied Soil Ecology, 198*, 105380. doi: https://doi.org/10.1016/j.apsoil.2024.105380

Pelayo Lind, O., Hultberg, M., Bergstrand, K. J., Larsson-Jönsson, H., Caspersen, S., & Asp, H. (2021). Biogas digestate in vegetable hydroponic production: PH dynamics and pH management by controlled nitrification. *Waste Biomass Valorization*, *12*, 123–133. doi: https://doi.org/10.1007/s12649-020-00965-y

Pinasseau, A., Zerger, B., Roth, J., Canova, M., & Roudier, S. (2018). *Best Available Techniques (BAT) Reference Document for Waste treatment Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control).* Publications Office of the European Union, Luxembourg. doi: https://doi.org/10.2760/407967

Puyol, D., Flores-Alsina, X., Segura, Y., Molina, R., Padrino, B., Fierro, J. L. G., Gernaey, K. V., Melero, J. A., & Martinez, F. (2018). Exploring the effects of ZVI addition on resource recovery in the anaerobic digestion process. *Chemical Engineering Journal, 335*, 703–711. doi: https://doi.org/10.1016/j.cej.2017.11.029

Radawiec, W., Gołaszewski, J., Kalisz, B., & Przemieniecki, S. (2023). Chemical, biological and respirometry properties of soil under perennial crops fertilized with digestate. *International Agrophysics, 37*(2), 111–128. doi: https://doi.org/10.31545/intagr/158897

Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003 (Text with EEA relevance). (2019). *EUR-Lex: Access to European Union law.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1009

Rekasi, M., Ragalyi, P., Sandor, D. B., Szabo, A., Rivier, P.-A., Farkas, C., Szecsy, O., & Uzinger, N. (2023). Effect of composting and vermicomposting on potentially toxic element contents and bioavalability in sewage sludge digestate. *Bioresource Technology Reports, 21*, 101307. doi: https://doi.org/10.1016/j.biteb.2022.101307

Rittl, T. F., Gronmyr, F., Bakken, I., & Loes, A.-K. (2023). Effects of organic amendments and cover crops on soil characteristics and potato yields. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science, 73*(1), 13–26. doi: https://doi.org/10.1080/09064710.2023.2165963

Sica, P., & Magid, J. (2024). Placement of acidified digestate solid fraction as an efficient starter phosphorus fertilizer for horticulture crops. *Scientia Horticulturae, 328*, 112961. doi: https://doi.org/10.1016/j.scienta.2024.112961

Skrzypczak, D., Trzaska, K., Gil, F., Chawla, Y., Mikula, K., Izydorczyk, G., Samoraj, M., Tkacz, K., Turkiewicz, I., Moustakas, K., Chojnacka, K. (2023) Towards anaerobic digestate valorization to recover fertilizer nutrients: Elaboration of technology and profitability analysis. *Biomass and Bioenergy, 178*, 106967. doi: https://doi.org/10.1016/j.biombioe.2023.106967

Sogn, T. A., Dragicevic, I., linjordet, R., Eijsink, V. G. H., & Eich-Greatorex, S. (2018). Recycling of biogas digestates in plant production: NPK fertilizer value and risk of leaching. *International Journal of Recycling of Organic Waste in Agriculture, 18*, 49–58. doi: https://doi.org/10.1007/s40093-017-0188-0

Sfetsas, T., Sarikaki, G., Chioti, A. G., Tziakas, V., Falaras, P., & Romanos, G. E. (2023). Fractionation of anaerobic digestion liquid effluents through mechanical treatment and filtration. *Sustainability, 15*(14), 11178. doi: https://doi.org/10.3390/su151411178

Suchowska-Kisielewicz, M., & Jędrczak, A. (2019). The evaluation of indicators used to assess the suitability of agricultural waste for digestion. *International Journal of Environmental Research and Public Health, 16*(11), 1889. doi: https://doi.org/10.3390/ijerph16111889

Sun, H., Tang, R., Su, K., Yuan, S., Feng, J., Wang, W., & Hu, Z.-H. (2024). Effect of zero-valent iron addition on ammonia inhibition alleviation and fecal indicators reduction in anaerobic digestion of pig manure. *Biochemical Engineering Journal, 205*, 109276. doi: https://doi.org/10.1016/j.bej.2024.109276

Tambone, F., Orzi, V., D'Imporzano, G., & Adani, F. (2017). Solid and liquid fractionation of digestate: Mass balance, chemical characterization, and agronomic and environmental value. *Bioresource Technology, 243*, 1251–1256. doi: https://doi.org/10.1016/j.biortech.2017.07.130

Tavera, C. G., Raab, T., & Trujillo, L. H. (2023). Valorization of biogas digestate as organic fertilizer for closing the loop on the economic viability to develop biogas projects in Colombia. *Cleaner and Circular Bioeconomy, 4*, 100035. doi: https://doi.org/10.1016/j.clcb.2022.100035

Uzinger, N., Szecsy, O., Szucs-Vasarhelyi, N., Padra, I., Sandor, D. B., Loncaric, Z., Draskovits, E., & Rekasi, M. (2021). Short-term decomposition and nutrient-supplying ability of sewage sludge digestate compost, and vermicompost on acidic sandy and calcareous loamy soils. *Agronomy, 11*, 2249. doi: https://doi.org/10.3390/agronomy11112249

Vitti, A., Elshafie, H. S., Logozzo, G., Marzario, S., Scopa, A., Camele, I., & Nuzzaci, M. (2021). Physico-chemical characterization and biological activities of a digestate and a more stabilized digestate-derived compost from agro-waste. *Plants, 10*(2), 386. doi: https://doi.org/10.3390/plants10020386

Xie, Z., Zou, H., Zheng, Y., & Fu, S.-F. (2022). Improving anaerobic digestion of corn straw by using solid-state urea pretreatment. *Chemosphere, 293*, 133559. doi: https://doi.org/10.1016/j.chemosphere.2022.133559

Yan, J., Chen, X., Wang, Z., Zhang, Ch., Meng, X., Zhao, X., Ma, X., Zhu, W., Cui, Z., & Yuan, X. (2023). Effect of temperature and storage methods on liquid digestate: Focusing on the stability, phytotoxicity, and microbial community. *Waste Management, 159*, 1–11. doi: https://doi.org/10.1016/j.wasman.2023.01.023

Yang, S., McDonald, J., Hai, F. I., Price, W. E., Khan, S. J., & Nghiem, L. D. (2017). The fate of trace organic contaminants in sewage sludge during recuperative thickening anaerobic digestion. *Bioresource Technology, 240*, 197–206. doi: https://doi.org/10.1016/j.biortech.2017.02.020