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Technologies for Environmental Safety Application of Digestate as Biofertilizer

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ABSTRACT

The purpose of the paper is to determine the environmentally safe and economically feasible technology of biofertilizer production from the digestate including dewatering process. Methodological basis is based on the systematic approach to the determination of factors effected on the distribution of nutrients and pollutants between liquid and solid fractions after digestate separation. We studied modern technologies aimed at dewatering the digestate and reduction of its volume, showed their effectiveness. These technologies allow expanding the opportunities for commercialization of the digestate, increasing the cost of its transportation and application to the soil instead of complex fertilizers, using some valuable products. The results of the study showed that the ecological quality of the digestate is the highest as well as co-digested thermally pre-treated feedstock is used for solid-liquid separation in centrifuge with polymer addition as post-treatment approach to the flocculation. In order to increase efficiency of biofertilizer application the technological scheme of production process of granular fertilizers from digestate was proposed. Special feature of this scheme is in the use of phosphogypsum binder for the production of organo-mineral fertilizer that contributes phosphogypsum recycling in the waste management system.

Keywords: anaerobic residues, digestate, fertilizing, low-carbon society, pollution, renewable energy.

INTRODUCTION

Producing energy from renewable sources with the goal of achieving energy independence has been the focus of many nations. The potential of energy production from anaerobic digestion of agricultural substrates has been pointed out as one of the major sustainable energy sources [Mamica et al., 2022; Voytovych et al., 2020; Yentekakis and Goula, 2017]. Agricultural residues, refuses from the food industry, green waste, as well as wastewater sludge are proved feedstocks for anaerobic digestion [Biernat et al., 2012; Malovanyy et al., 2021] a process that also produces a solid-liquid by-product, also known as digestate, that can be applied as a biofertilizer.

Fertilizing fields with digestate provides several advantages like: reducing the demand for plant protection products as weed seeds are degraded during anaerobic degradation, reducing unpleasant odors and eliminating pathogens [Abubaker, 2012]. The high need of nutrients for plant growth can be provided by biofertilizer that has at least 20 kg N, 60 kg P and 80 kg K per 1 ton of dry granular fertilizer [Koszel and Lorencowicz, 2015]. This is possible due to the use of solid or dried fraction of the digestate as an organic component of organo-mineral fertilizers [Prask et al., 2018; Yu et al., 2021].

The digestate can be applied in many ways on the top of the soil surface, and the use of granular fertilizers has been increasing in popularity. A significant advantage by using granular fertilizers is their high solids content, as it allows their storage in bags or containers as well as their transportation. Granulation of the digestate requires specific conditions, one of which is the moisture levels of the sludge, that should be in the range of 20–25%, a much lower water percentage that digestates have after leaving the biogas reactor (>90%) [Jewiarz et al., 2017].

Several European countries have decided that up to 40 % of all food waste should be an energy source [Chiew et al., 2015]. This problem is topical for Ukraine too, since according to the data of the Bioenergy Association of Ukraine, the number of biogas plants is increasing every year and reached 68 units running on different type of feedstocks, primarily manure and agricultural residues [Geletukha and Matveev, 2021]. This trend supports the sustainable development of Ukraine, as acknowledged by theEuropean Biogas Association, which further underlined the current biogas potential in Ukraine [Geletukha and Zheliezna, 2021]. An appropriate digestate management needs special infrastructure, including the availability of special tanks for temporary storage of digestate. An effective and low cost digestate distribution is also dependent on the transportation costs. Given the relatively higher water content in the digestate, a proper separation of the water and solid digestate content can decrease the transportation costs for the biofertilizer, as the digestate is rich in macro- and microelements [Al Seadi, et al., 2013; Mudryk et al., 2016].

Several technologies with a focus on the digestate water and solid separation have been developed, being the main decanter centrifuges, screw press and belt presses. Flocculating or precipitating agents are also commonly applied to improve water solid separation. Mechanical processes of digestate dewatering have increasingly been the subject of several studies. Jewiarz et al. [2017] reported two major ways to produce granular fertilizers from digestate. The first method is the addition of ash, sulfur, urea, silage with phosphorite to the digestate and the second is the inoculation of the fungus *Trichoderma*, which increases the absorption of nitrogen by plants. In this case, the production of granules is carried out using a flat press for granules. Mangwandi et al [2013] proposed that the production of granular fertilizers of a certain rigidness and shape could be achieved by the addition of granulating limestone powder using a liquid phase of the digestate as a granulating liquid. However, these authors recognized that this granulation process has some limitations since there is a poor nutrient distribution and as the dry digestate should be used as biofertilizer it is important to ensure that the granules of fertilizers have a uniform nutrient content [Mangwandi, et al., 2013].

A very significant problem in the use of digestate as a granular fertilizer is the variability of its chemical composition, but granulation performed with a high-speed impeller seems to solve this problem, as its promotes a good mixing of the components, leading to an improvement of the granules homogeneity. The increase in granulation time also seems to have a positive effect by improving digestate mixing and homogeneity. Furthermore, the production of granular fertilizers with a high-speed impeller is considered to be environmentally friendly, safe for humans and animals, and due to the addition of other materials sources, like plant silage, natural minerals, limestone, ash, it is also an excellent fertilizer for use in organic farming. As the granulate is highly hydrophobic, 95 % of the granular substance is absorbed by plants throughout the growing season, and therefore harmless to the environment [Mangwandi, et al., 2013].

The main aim of this study was evaluate the existing technologies and solutions to increase the digestate dewaterability with the subsequent use of the solid phase as a biofertilizer. We expect that the results presented here will increase the attractiveness of the development of the Biogas sectors and reduce the costs for transporting digestate. More specifically we also focus on the specific aims: a) to make an analysis of existing technologies for digestate dewatering ; b) to provide recommendations for improving digestate dewatering technologies and c) to investigate the best pathways for the production of granular fertilizers from digestate. Based on the analysis, most studies involve the valorization of digestate and of its components as biofertilizer and soil amendment. The digestate can either be stored and used as fertilizer or can be separated into liquid and solid fractions.

MATERIALS AND METHODOLOGY

This study was based on a literature search and we focus on publications from the last 10 years (time-span) in publications indexed by the international database Scopus based on the following codes: TITLE-ABS-KEY ((digestate OR "biogas digestate" OR "anaerobic digestate") AND (dewatering OR separation)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))). This search resulted in 259 documents. A bibliometric network on kinship and matching keywords was performed on the result from the latest code and these results were built and visualized with the software tool VOSviewer (version 1.6.15), certifies the relevance of the selected topic for this research. Based on this literature search, we evaluated the separation technologies that are applied to produce organic fertilizers to reduce its water content with a special focus on mechanical technologies. We classified the use of screw press with a slotted screen in three dimensions: 0.1; 0.2, and 0.3 mm. Cascading methods for dewatering was also evaluated. The four-time passage of raw material through the dewatering system allows obtaining raw material moisture at the level of 78-79 % [Mudryk, et al., 2018].

Vacuum evaporation of digestate at the 1.3 MW Bersenbrück biogas plant is used for dewatering of digestate in Germany. To prevent evaporation of ammonia, the pH of the digestate before heating is lowered by adding sulfuric acid. Due to this evaporation, the costs of transportation and use of the digestate are reduced by approximately 70%. The evaporated liquid condenses and is discharged into the reservoir [Vondra et al., 2018].

Decanter centrifuges are used to separate for slurries with a relative low-content of solids and often in combination with chemical conditioners. Under the influence of high centrifugal forces, the larger and heavier fractions of solids are separated from the suspension thank to their higher weight and densities. ecanter centrifuges are for example used to separate digestate from the digestion of manure, as well as for processing of industrial waste streams [Al Seadi, 2013]. Despite their higher costs and technical complexities, centrifuges, unlike belt filter presses, can run continuously.

Screw press separators are often used in biogas plants with a high fiber content in the digestate, as in the case of energy crops., The screw presses literally compress and squeezes the input flows against an outer cylindrical sieve, filterting the liquid fraction through it [Al Seadi, 2013]. Unlike decanter centrifuges, screw press separators cannot separate the fine solids from the digestate. However, screw presses separator is characterized not only by lower investment and operational costs, than e.g. centrifuges [Bauer et al., 2009] but also lower energy consumption (0.4–0.5 kWh/m^3_input).

The main object for this research was digestate and its nutrient content as well as distribution of the nutrients between liquid and solid fractions after separation depends on different factors. Digestate contains many nutrients and trace elements, does not contain pathogens and viable weed seeds [Mudryk, et al., 2016]. Digestate has a variable composition depending on different factors, in particular the type of feedstock (table 1).

This is most likely due primarily to the type of substrate and the separation technology. To assess the quality and environmental safety of the

Table 1. Biochemical properties of typical anaerobic digestates reported in the literature

Parameters	Value range	References
pH	6.35–10	Du et al., 2018; Singla et al., 2014; García-Sanchez et al., 2015
DM, %	6.2–948	Cao et al., 2016; Lanza et al., 2015
OM, % DM	7–917	Elbashier et al., 2018; Martin et al., 2015
NO_3^--N, mg·kg^{-1}	0.3–396	Koster et al., 2015; Maucieri et al., 2017
NH_4^+-N, mg·kg^{-1}	9.7–124000	Mazzini et al., 2020; Tambone et al., 2017
Total N, g·kg^{-1}	0.7–157	Vu et al., 2015; Tambone et al., 2017
Total C, g·kg^{-1}	5–442	Iocoli et al., 2019; Mazzini et al., 2020
C/N	1.38–40.2	Iocoli et al., 2019; Fernandez-Bayo et al., 2017
Total P, g·kg^{-1}	0.025–10,2	Iocoli et al., 2019; Maucieri et al., 2017
Total K, g·kg^{-1}	0.18–14	Zheng et al., 2017; Maucieri et al., 2017
Total S, g·kg^{-1}	0.12–0.16	Abubaker et al., 2012; Maucieri et al., 2017

digestate some comparisons of digestate and substrate were done in terms of predominant nutrients, chemical pollutants and pathogenics. Such parameters are decisive when using it as a biofertilizer according to the quality standards of organic fertilizers as presented in the table 2 for some European countries.

The general tendency to change these indicators of digestate in comparison with the substrate is as follows. Carbon (C) content is decreased on 25-53% due to the processes of methanogenesis resulted in biogas production. Potassium (K) and Total Nitrogen (TKN) content remain the same both in the digestate and feedstock, while ratio of total nitrogen to ammonium nitrogen (TAN) is increased based on the TAN loss during anaerobic digestion. Phosphorus (P) content is decreased as well as Calcium (Ca), Magnesium (Mg) and Manganese (Mn) contents on 10%, 44%, 32.5% and 32% respectively due to use by microorganisms for the processes of metabolism.

Dates from the table 3 indicate the dependence of the pollutant content in the digestate on the type of substrate that could include appropriate pollutant.

Nutrient content of the digestate depends on different parameters including type of substrate, using of additives, pre- and post-treatment technologies and so on. Application of the digestate as biofertilizer could be potentially danger for environment in some cases as shown in Figure 1.

Nevertheless, these risks could be avoided or at least decreased by the using of effective and ecological safety biogas production and digestate treatment technology. In the framework of this study a generalized scheme for the use of digestate as a biofertilizer is presented, which forms the methodological basis of the study (Fig. 2).

Methodological basis of the current research is based on the systematic approach to the determination of factors and their quantitative and qualitative characteristics effected on the distribution of nutrients and pollutants between liquid and solid fractions after digestate separation.

RESULTS AND DISCUSSION

Visualization Network of the technological solutions

A cluster visualization of technological solutions regarding digestate dewatering was generated (Figure 3) using VOSviewer software and can be described as follows:

- blue cluster – the process of anaerobic digestion and its substrates;

Table 2. Examples of national limits regulating nitrogen loading on farmland, required storage capacity for digestate, and its spreading season

Country	Maximum nutrient load	Required storage capacity	Compulsory season for spreading
Austria	170 kg N/ha/year	6 months	28 Feb – 5 Oct
Denmark	170 kg N/ha/year (cattle) 140 kg N/ha/year (pig)	9 months	1 Feb – harvest
Italy	170–500 kg N/ha/year	90–180 days	1 Feb – 1 Dec
Sweden	170 kg N/ha/year (calculated from livestock units per ha)	6–10 months	1 Feb – 1 Dec
Northern Ireland	170 kg N/ha/year	4 months	1 Feb – 14 Oct
Germany	170 kg N/ha/year	6 months	1 Feb – 31 Oct Arable land 1 Feb – 14 Nov Grassland

Table 3. Comparison of digestate and substrate quality

Pollutant in substrate	Digestate	Substrate
Cd, Zn, Co, Pb	–	Compost
Zn, Cu, Cd, Ni, Cr, Pb, Hg	–	Poultry litter, composted swine manure, organic food waste and municipal sewage sludge
Pesticides	–	Agricultural wastes
Antibiotics	–	Pig and cattle manure
Listeria, Salmonella, Escherichia coli, Mycobacterium, Clostridium, Campylobacter and Yersinia	–	Farm and slaughterhouse wastes and wastes from food processing industries
Clostridia and fungal spores	+	

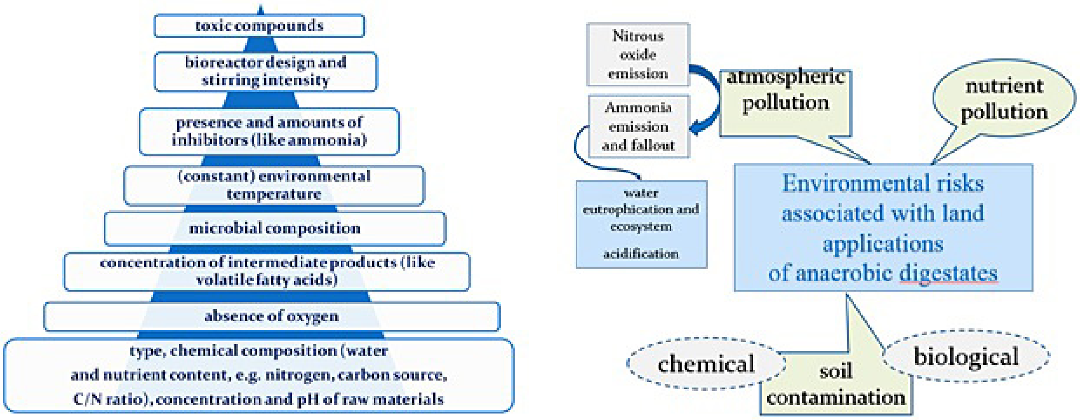

Figure 1. Anaerobic digestion factors (a) and potential risks for environment from the application of digestate (b)

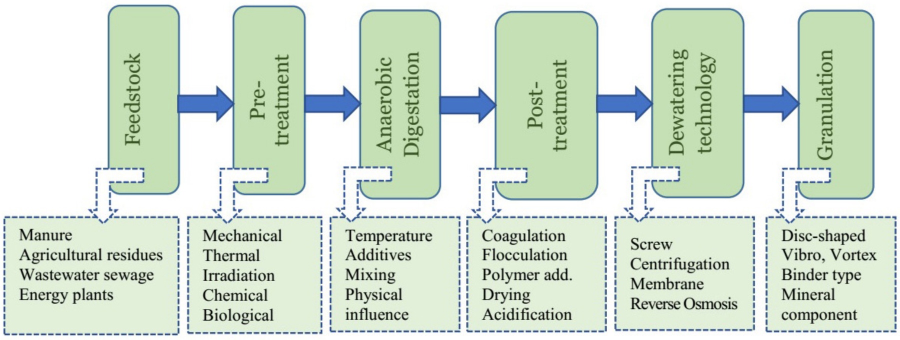

Figure 2. Methodological basis of the research

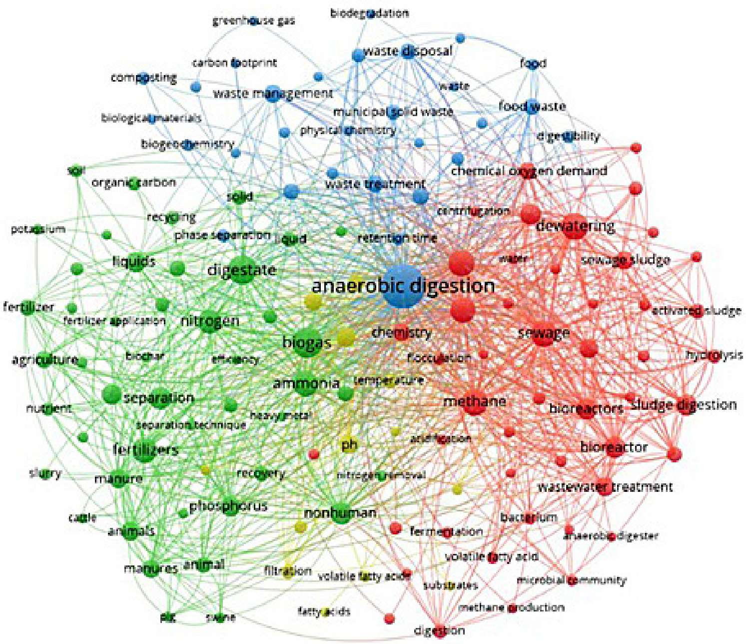

Figure 3. The most commonly used keyword network (frequency> 5). Cluster visualization of technological solutions regarding digestate dewatering. Blue cluster: the process of anaerobic digestion and its substrates; Red cluster –processes and terminology of the biogas sector as well as solid-liquid separators applied to digestate; Green cluster – the use of digestate as biofertilizer, of its nutrients, and the impact on soil quality and Yellow cluster – parameters and factors of the fermentation process that affect the yield of biogas and the quality of the digestate.

- red cluster –processes and terminology of the biogas sector as well as solid-liquid separators applied to digestate;
- green cluster – the use of digestate as biofertilizer, of its nutrients, and the impact on soil quality;
- yellow cluster – parameters and factors of the fermentation process that affect the yield of biogas and the quality of the digestate.

Dewatering processes are carried out with the use of the pressure phenomenon as well as under conditions of a raised temperature of the process amounting to 100–250 °C, due to which water will be removed by means of vaporization and impact of high pressure [Fernández-Bayo et al., 2017]. Mechanical dewatering processes of raw material have the greatest significance in the case of dewatering of production residues in the agri-food industry and in water purification sectors (dewatering of screenings and sludge).

According to Akhiar et al. [2021], the results of solid-liquid separation efficiency showed that centrifuge, screw press with coagulant, screw press with flocculant and centrifuge with polymer addition have the highest separation efficiency index (0.7, 0.83, 0.87 and 0.93 respectively).

Approaches to increase the digestate quality and N and P content quality and ecological safety of the digestate

The nutrient content of the digestate is dependent on it feedstock (Figure 4). Food residues have the lowest digestate total nitrogen content and therefore has a relatively lower economic value as biofertilizer. In contrast the highest level of the NH_4^+ percentage of total N were observed for plant biomass, co-digested substrate, poultry slurry and urine used as feedstock for anaerobic digestion.

Moreover, recent research [Pantelopoulos et al., 2017] showed the positive effect of acidification on TAN content of the digestate resulted in the TAN increase on 70 % in comparison with raw digesate, but decreasing of TKN and TOC after acidification. Nevertheless, acidification of the dried digestate improved all of these indicators and P, K and Ca content regardless of the drying temperature. Accordingly, acidification had a negative effect on the supply of nitrogen and phosphorus to the soil, their mineralization and availability to plants in a soluble form. While, drying of the digestate resulted in loss of ammonium-N (NH_4-N), but increased N mineralization and plant N uptake rates, and besides the higher drying temperature the higher these rates. Drying of the digestate decreased the soluble fraction of P in the solids and the plant P uptake, with higher drying temperatures resulting in lower P availability. Besides of this, the effect of acidification and drying on the solubility and availability of metals presented in the digestate solids is not investigated for today.

European countries have special Directives for soils EU Nitrates Directive (91/676/EEC) according which such nutrients as nitrogen, could not to be applied in an unlimited quantity due to the features of their content in the soil [Kalinichenko and Minkova, 2014]. Much of the nitrogen leached from agricultural land or drained from agricultural land enters groundwater and surface water as a result of excessive manure use. In fact, environmental regulation of this issue imposes a significant financial burden on farmers in terms of long-term storage and accumulation

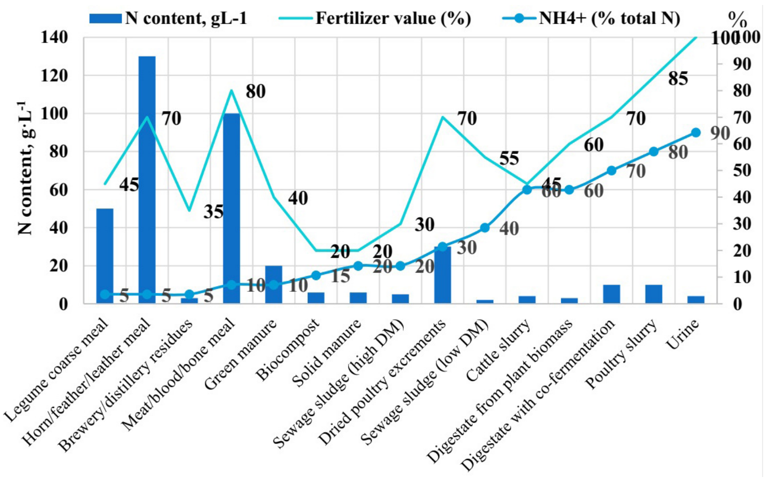

Figure 4. Fertilizer properties of different types of substrates

of manure. Farmers in the Member States of the Directive, especially Denmark, the Netherlands and Belgium, which have high stock numbers per hectare, often oppose new obligations to use manure and fertilizers needed to control nitrates in groundwater and surface water [Brussaard and Grossman, 1990].

In contrast, in Ukraine, such directives do not apply, since Ukrainian soils are depleted inof nutrients. However, for the first case, the use of membranes for the purpose of obtaining a concentrate is highly relevant and economically justified in connection with a decrease in the cost of transporting large volumes of liquid fertilizer. The application of concentrates in agriculture could have a value of €6.3±1.1 t^{-1} FW, if both nitrogen and potassium are appreciated by the agriculturist [Vaneeckhaute et al., 2012].

It should be noted that the phosphorus in manure exists in many forms, such as inorganic residual P, acid-soluble organic P, and lipid P, which are neither very soluble nor easily hydrolised [Vaneeckhaute et al., 2017]. Due to this ecologically efficiently use of phosphorous could be managed using various combinations of mechanical (microwave, ultrasonic, heating, mixing) and chemical (addition of HCl, citric acid, formic acid) pre-treatments at pH 4, 5, and 6. According to the research [Vaneeckhaute et al., 2017] microwave heating at pH 5 using citric acid has the best result of the P release.

Quality of the digestate depends also on the pre-treatment technique. Physical method can be applied in different type of influences as follows: mechanical (milling, grinding machines), thermal (liquid hot water), irradiation (microwave, ultrasound, gamma-ray, electron beam), extrusion-friction heating, mixing and vigorous shearing upon pressure release. Chemical method involves alkaline and acid addition, oxidative with peroxidesa, use of ozone. These technologies affect the structure of the substrate and the degree of its decomposition, which ultimately determines the efficiency of the digestion process and the mineralization of the nutrients.

Different effect of such types of pre-treatments like as: temperature, pressure, ultrasound, microwave, UV and gamma radiation, addition of several alkali and acid solutions up to application of different electric voltages was observed for digestate quality. Obtained results showed the positive effect on methane production that can increase in up to two orders of magnitude. These results strongly indicate that these pre-treatments may also have a strong effect on the relatively amount of N and P from the digestate from different biogas reactors.

It was observed that drying followed by rewetting promoted an increase in total methane production in 25 to 35% depending on the origin of the substrate and that this increase was attributed to the physical stress caused by the loss of water and not by the oxidation caused by the presence of air. These results indicated that pre-treatments influence overall anaerobic digestion and are very likely to influence the nutrient concentration in the digestate. The thermal pre-treatment resulted highly efficient in transferring the colloidal fraction of COD into the extract. Moreover, after the pre-treatment, the residue was depleted by a significant fraction of solids, transferred into the liquid extract [Gallipoli et al., 2021]. The thermal pretreatment carried out with autoclave with an optimized duration of 20 min did not affect solids and organic content, but the inherent distribution between particle and soluble forms [Gianico et al., 2013].

Investigation of the dewatering technologies of the digestate

The fermented residue after the biogas plant is first divided into liquid and solid fractions by means of a rotating drum after the addition of phosphogypsum. The resulting solid fraction is then sent to an auger press for further dewatering, and then sent to the dryer to obtain the final product. The liquid fraction is filtered twice with Reverse Osmosis (RO) membranes. Each filtration step leads to a flow of concentrate and permeate. The formed permeate by the second filtration is sent to municipal treatment facilities. In particular, the entire stage of purification of the liquid fraction of the digestate can be omitted and return the liquid to the fermentation compartment of the biogas plant or used as a liquid fertilizer, having previously determined the nutrient content and the presence of contaminants [Vaneeckhaute et al., 2012].

However, using of RO membranes for the purification of the liquid phase of the digestate is not always economically justified in the connection with environmental safety. After all, the presence of pollutants in the digestate directly depends on the quality of the used substrate, and the set of nutrients in the liquid phase allows it to be used directly as a liquid fertilizer. On the other hand,

However, there are cases when additional costs for cleaning the liquid phase are justified, in particular, this concerns the material after hydrothermal carbonisation of the digestate. For an example, using cascade membrane systems: microfiltration (MF) → ultrafiltration (UF) → nanofiltration (NF) with polymeric membranes, can increase the purification of the liquid fraction after hydrothermal carbonisation of the digestate from the agricultural biogas plant. In the case of sequential treatment of the solution by MF 0.2 μm → UF PES 10 → NF NPO30P COD removal efficiency was reached of almost 60 % [Urbanowska et al., 2021].

In this relation ultrafiltration performance could be improved using ozone treatment that had a capacity to reduce the biopolymer concentration and apparent viscosity of different digestate centrates. In this way the process of purification of the liquid fraction of the digestate could be economically feasible resulted in the obtaining of several different products: an organic N-P-fertilizer (solid digestate), a recirculate (UF retentate), a liquid N-K-fertilizer (RO retentate) and water. Ozone treatment doesn't have any negative effect on the nutrient content of the digestate which also confirmed a study by [Gienau et al., 2020].

Centrifugation is one of the most effective separation technology for the digestate to obtain solid fraction with high level of dry matter and improve balance of nutrient content between two fractions resulted in the production of clean liquid fraction for farm technical water use. Moreover, centrifuge with addition of coagulant, flocculent or polymer is considered high efficiency separation process equipment while screw press, vibrating screen and rotary drum should be a low efficiency separation processes which is in line with the recent stydies [Akhiar et al., 2021; Hanserud et al., 2017].

Generalized information on the distribution of dry and organic matter (DM and OM consequently) and several nutrients (total N, ammonium N, P and K) in solid and liquid fractions when using a screw press (SP) and decanter centrifuge (DC) is shown in Figure 5. These results confirm previous mentioned above.

To intensify this process flocculation can be used based on the addition of different chemicals capable to increase the sizes of particles, which form flocs and increase floc resistance to further mechanical separation. The addition of chitosan as a new type of flocculent followed by centrifugation produced 27% solid fraction (8.8% dry matter) that improved centrifugation efficiency for K, Cu, and Zn and had no effect on total N or P [Popovic et al., 2017].

From the ecological standpoint, dewatering technologies are of the great interest according to the nutrient and pollutant distribution between solid and liquid fractions. As can be seen from the graph in the Figure 6, nitrogen, potassium pass mainly into the liquid phase, and the metals copper and zinc, and phosphorus accumulate in the solid phase, which is associated with the formation of complex compounds. In this regard, the use of chitosan as polymer enlarger of complexing agents has a positive environmental effect in the case of reliable incorporation of heavy metals into the ligands of the complex.

When using chitosan, after centrifugation, more nitrogen, potassium and copper pass into the solid fraction, compared with experiments without the use of chitosan. As for the liquid

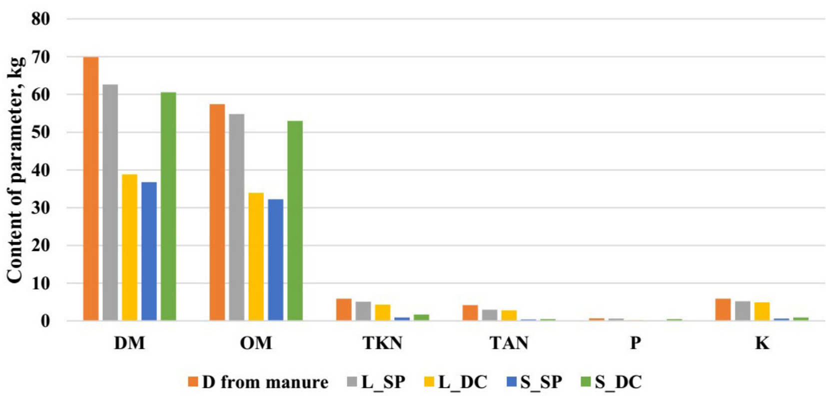

Figure 5. Comparison of the efficiency of a screw press and decanter centrifuge on the nutrient distribution between solid and liquid fractions of the digestate (D)

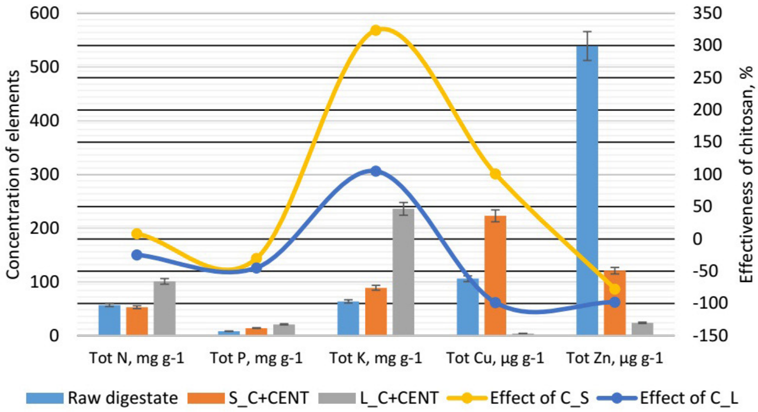

Figure 6. Nutrients and HM distribution between solid and liquid fractions after centrifugation with chitosan addition, and effectiveness of chitosan addition before centrifugation. Vertical bars stand for standard errors (n=3). Means that do not share a letter are significantly different ($p<0.05$)

fraction, the use of chitosan has a positive effect only for potassium, the concentration of other investigated substances in the liquid fraction decreases. This effect is positive from the point of view of the maximum purification of the liquid fraction and the transfer of the main nutrients into the solid fraction, which is planned to be used as biofertilizer.

Recent research of new types of chemically enhanced solid–liquid separation (CES) treatments indicated that polyaluminum chloride (PAC), epichlorohydrine-dimethylamine with ethylendiamine (DEED) and polyacrilamides (PAM) such as cationic and anionic polyacrylamide (CPAM, APAM respectively) in different ratio had a potential to improve the environmental quality of the solid fraction. The highest Total Suspended Solid (TSS) removal rate (up to 90 ± 1% with respect to the control) in the liquid fractions separated after centrifugation was achieved using PAC4 (3.6 $g \cdot L^{-1}$ of PAC and 0.2 $mg \cdot L^{-1}$ of CPAM), PACDE5 (3.2+4.2 $g \cdot L^{-1}$ of PAC + DE and 0.32 $mg \cdot L^{-1}$ of APAM) and PACDE6 (3.2+4.2 $g \cdot L^{-1}$ of PAC + DE and 0.32 $mg \cdot L^{-1}$ of CPAM) [Beggio et al., 2021]. Besides of this, such treatment provides the predominant transfer of phosphorus and heavy metals (cadmium, lead, copper, nickel, zinc and chromium) into the liquid fraction, regardless of the type of reagent, while organic nitrogen is concentrated in the solid phase.

Flocculation is a pretreatment step to facilitate separation by other means such as gravity sedimentation, filtration, centrifugation. Flocculation and gravity thickening prior to centrifugation or filtration greatly reduce the volume of the slurry that needs to be centrifuged or filtered. This reduces the capital and energy requirements of solids recovery, as both centrifugation and filtration tend to be expensive. Flocculants are the agents used to bring about flocculation. Chemical flocculants are highly effective and widely used. Inorganic flocculants or polymeric organic flocculants may be used.

Organic flocculants are mostly polymers. They may be polyelectrolytes, that is, polymers carrying anionic or cationic charge, or uncharged non-ionic polymers. They may be synthetic or natural. Examples of natural polyelectrolytes include the polysaccharides cationic starch and chitosan (a cationic polymer) and the polypeptide poly-γ-glutamic acid (a cationic polymer). Among synthetic polyelectrolytes, polyacrylamides (either cationic or anionic) are widely used. Polyelectrolytes are further reviewed by Haver and Nayar [2017]. Polyelectrolytes act through a combination of cell surface charge neutralization and particle bridging to form flocs.

Inorganic salts of multivalent metals are effective flocculants. The multivalent metal cations in these salts neutralize the cell surface charge and bridge cells together to facilitate flocculation. Salts of aluminum and iron are the most widely used because of their efficacy, availability, safety and relatively low cost. The aluminum-based flocculants include aluminum sulfate, aluminum chloride, sodium aluminate, aluminum chlorohydrate, and polyaluminum chloride. The iron-based flocculants include ferric chloride, ferric sulfate, ferrous sulfate, and ferric chloride sulfate. Aluminum sulfate or alum ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$) and ferric sulfate ($Fe(SO_4)_3$) are the most widely used flocculants [Chatsungnoen and Chisti, 2019].

Nevertheless, individual using of the chemical flocculation based on the addition of tannin (TA) and PAM showed negative effect on the SLS and could be unfeasible digestate pre-treatment due to the handling difficulties [Chini et al., 2021]. In this relation using of centrifugation under the condition of gravitational force at the level of 1400–3800 g and time 20 min provided the best TAN removal (26% of efficiency), TKN removal (36 % of efficiency) and total solids removal efficiencies were in the range of 60–83 %. Nitrogen as a soluble element distributes to the liquid fraction that explains relatively low rate of extraction into solid fraction. Unlike this, phosphorous has a high removal efficiency that could be explained by the P adsorption on the solid particles phosphorus precipitation into different inorganic substances such as calcium phosphate, hydroxyapatite or struvite due to the presence of Ca^{2+}, Mg^{2+} and NH_4^+ cations respectively in the liquid phase [Fernandes et al., 2012; Capdevielle et al., 2013]. Moreover, availability of P in the fractions of the digestate is no less important as its content. According to [Bachmann et al., 2015] the H_2O-P and the $NaHCO_3$-P fractions generally represent labile and highly soluble P forms, such as dicalcium phosphate dihydrate ($CaHPO_4 \cdot 2H_2O$), struvite ($MgNH_4PO_4 \cdot 6H_2O$), hydrated aluminum phosphate ($AlPO_4 \cdot 2H_2O$). It should be noted that the mineral form of phosphorus predominates in comparison with the organic form by 80–95%.

Prospects for the use of granular digestate fertilizers

Due to the great potential of using digestate as a biofertilizer and the need for its preliminary preparation, the processes of dehydration and granulation are relevant. On the basis of the above-mentioned processes, research will be carried out on the use of vibrating granulators for dispersing liquid digestate to obtain granular fertilizer. Compared to other granulators, vibrating ones allow to obtain sufficiently strong monodisperse granules with a size of 1.6–2.5 mm with a smooth surface. There is also an approbation of vortex granulator allows to get granular products without the use of granulation towers. Its work is based on the method of granulation from melts, solutions and suspensions, based on improving the dynamics of the flow of granules. The vortex granulator has a capacity of up to 10 t/h for the finished product, the final product has a degree of monodispersity up to 98%, humidity – up to 0.2%, the holding capacity in relation to diesel distillate is 7–8%, the strength of the granules is 300–350 g/granule.

Based on the best practices of the digestate treatment technological scheme for the production of granular fertilizer from digestate was developed (Fig. 7).

Post-treated anaerobic digestate with polymer is fed to a centrifuge to separate and obtain two fractions. After intensification of the process with ozone, the liquid fraction is sent to membrane purification and reverse osmosis to obtain concentrate and industrial water. The solid fraction is fed to a granulator for rounding fertilizer granules. In this case, the core of the granule is a mineral fertilizer, and the shell is made up of digestate and phosphogypsum binder. Then the granules are dried and transported for use in the fields as endproduct.

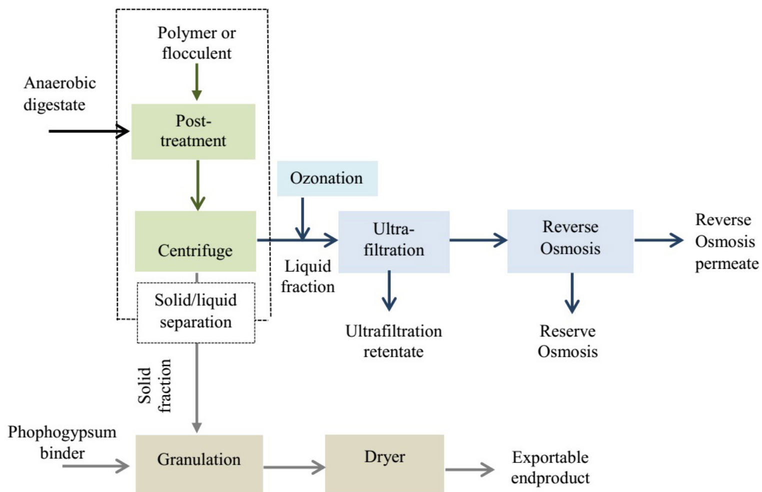

Figure 7. Complex technological scheme for the production of granular fertilizer from digestate

CONCLUSIONS

Increasing biogas production is directly connected to efforts in building societies with high efficiency in using resources through e.g. recycling and reusing of nutrients, decreasing utilization of chemical fertilisers and pesticides, stimulation of local and regional circular economy. Improvement of soil conditions by reducing the deficit of humus in the soil can be achieved due to the organic part of the solid fraction of the digestate. An analysis of existing technologies for dewatering of the digestate in indicated different distribution of nutrients and pollutants between liquid and solid fractions.

Environmentally safe use of the digestate as biofertilizer can be possible in cases of durable fixation of heavy metals in the solid matrix. In the terms of agronomic value of such fertilizer optimal transition of nutrients N, P, K to the solid fraction plays a decisive role. Based on mentioned above conditions using centrifuges for the solid-liquid separation with polymer addition is the most effective approach to dewatering technology development.

It is very important to maintain a constant repeated level of nutrients N, P, K, Mg, S. This can be achieved by adding to the dry fraction of split mineral supplements in the required amount during the production of granular fertilizers. As a result, the granulate does not contain pathogenic microflora, weed seeds and is hydrophobic, which reduces the problem of eutrophication of natural reservoirs. Processing digestate as a fertilizer is considered the most successful use of digestate, as it is able to benefit society in general and the environment in particular, and will help preserve fossil limited natural resources. The technological scheme of production process of granular fertilizers from digestate was proposed.

Further study will be connected with the experimental research of the investigated Complex technological scheme for the production of granular fertilizer from digestate.

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