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Towards a bio-based circular economy in organic waste management and wastewater treatment – The Polish perspective

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ABSTRACT

Bio-based solutions are expected to ensure technological circularity in priority areas such as agriculture, biotechnology, ecology, green industry or energy. Although Poland, unlike the other EU member states, has not yet adopted a precise political strategy to promote bioeconomy, it has taken several actions to enable smart, sustainable and inclusive growth. This goal can be achieved by developing selected bioeconomy-related areas such as the biogas industry together with novel technologies implemented to optimize treatment of municipal sewage and management of organic solid waste. Here, the relatively strong status of the Polish biogas sector is presented. The widely used practice of sewage sludge biomethanation has led to construction of numerous complex installations combining biological wastewater treatment plants with anaerobic digesters. Based on physico-chemical processing of biostabilized sludges, a novel method for efficient granulated soil fertilizer production is elaborated, in line with the concept of circular economy and the notion of "waste-to-product". It is also shown that anaerobic fermentation of sewage sludges can be optimized by co-digestion with properly selected co-substrates to increase bioprocess yield and improve the resultant digestate fertilizer quality. The problem of post-fermentation eutrophic sludge liquors, environmentally hazardous waste effluents requiring proper treatment prior to discharge or field application, is addressed. Attempts to optimize biological treatment of digestate liquors with complex microbial consortia are presented. The Polish innovations described show that the "zero waste" path in circular bioeconomy may bring advantageous results in terms of transformation of waste materials into commercial, added-value products together with recovery of water resources.

Introduction

Poland, unlike many other countries, has not formally issued a precisely defined strategy or agenda towards bioeconomy, nor has it directly identified particular priority areas [1,2]. However, as an EU member state, Poland is obliged to harmonize its economic, social and environmental policies with basic European principles and values and, consequently, conform to EU legislation. Several European horizontal actions and strategies have been launched aiming at climate protection, energy security and environmental conservation. The bio-based economy has been assigned an important role in achieving these goals [3–7]. One of the key programs is RIS3 (Research and Innovation Smart Specialization Strategy) [8], within which particular countries have defined their National Smart Specializations (NSS) [2,9]. In Poland, 18 NSS were specified [9,10] and bioeconomy-related tasks can be identified in at least 7 NSS focused mostly on agriculture, food, ecology, green industry or energy. Statistical data for 2017 [11] reveal 121 economic entities related to bioeconomy and biotechnology, of which 72 are involved in the agricultural, environmental and material processing industries. The respective numbers of economic entities in 2012 were 77 and 42, implying a growing trend in the Polish bioeconomic sector.

The EU Bioeconomy Strategy [12] emphasizes the need for sustainable production of primary biomass and conversion of both primary and waste organic resources into food, feed, and bioenergy as well as other bio-based products. In this context, various sectors of economic activity should be connected with progressive achievements in basic knowledge

Abbreviations: NSS, National Smart Specializations; RIS3, Research and Innovation Smart Specialization Strategy; RE, renewable energy; RES, renewable energy sources; CHP, combined heat and power (cogeneration); WWTP, wastewater treatment plant; OFMSW, organic fraction of municipal solid wastes; RDI, research development and innovation; d.m, dry mass *Units*; J, joule; W, watt; Wh, watt-hour (1 Wh =3.6kJ); toe, tonnes of oil equivalent (1 toe=11.63MWh).

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and applied sciences, especially biotechnology. The general principle of the *cascading use* of biomass and waste streams [1,12,13] defines priority actions and a sequential approach in bioeconomy. Following this idea, generation of the higher-value products such as food and animal feed should be assured first, then sustainable reuse/recycling of byproducts, wastes and raw materials together with bioproduct manufacturing and, finally, implementation of energy-yielding technologies. The cascading principle is in agreement with the waste minimization concept defined as "a zero waste programme" [14] and considered as a strategy crucial for circular economy [15–18], protecting valuable materials against "leaking from economies". In this program, (bio)economic circularity is understood as a systemic approach towards maintaining the value of any product contingent on simultaneous waste elimination. In other words, an ideal goal for any bioeconomy-oriented technology is to fulfill the *zero waste* criteria, thus enabling reuse of all byproducts in the value chain.

Bio-based technologies are particularly applicable to optimization of wastewater treatment and management of organic waste and sewage sludges. The achievements to date [6,19–25], comprise both large-scale implementations and pilot- or laboratory-scale tests. Wastewaters, apart from conventional biological treatment with the activated sludge, might undergo direct biomethanation [19] or become sources for a variety of bioproducts [25]. Similarly, organic residues (including dedicated biomass crops) and municipal sewage sludges can serve as substrates suitable for biorefineries [19,21,24–30]. However, organic waste is most often processed by anaerobic digestion [19,30–34], which is a still expanding technology holding the dual role of waste treatment combined with biogas production [19,35–39]. Since the waste-utilizing biogas plants are based on organic matter circulation, they should be regarded as important elements capable of closing the product/material loops in a modern bioeconomy.

In this paper the current state of the biogas sector in Poland is presented in the context of other EU countries. Apart from the statistical data, the novel attempts to optimize anaerobic digestion technologies are described and the progress in organic waste management is discussed. A special emphasis is placed on biomethanation and stabilization of sewage sludges, which appears as a sustainable solution combining a bioeconomic approach with the waste-to-product concept. A newly developed sewage sludge-processing method is described, which yields new-generation soil fertilizers. A technique of sludge co-digestion with organic household waste is proposed to improve bioprocess parameters. Finally, the necessity of proper management of eutrophic and potentially toxic digester liquors is substantiated and the recent achievements in elaboration of biological treatment methods are reviewed.

The biogas sector in Poland

The biogas industry has become an important part of the Polish bioeconomy [2,40]. Production of electrical energy and/or heat upon biogas combustion represents an important renewable energy sources (RES) category. Among other efficient RES carriers (wind, photovoltaics), biogas installations provide the advantage of being operational for most of the year and having a high annual power capacity factor. It is widely accepted that this sector is in line with the idea of sustainable development by contributing to economic circularity and green industry. Anaerobic fermentation is particularly useful in organic waste and sludge management [19,31,36,38,39]. In addition to RE generation, the end products have substantially reduced volume while becoming deodorized, hygienized and less environmentally hazardous. Furthermore, the digestate pulp may serve as valuable material to obtain soil-fertilizing or improving bioproducts.

The main problem of the Polish energy system is an extensive use of fossil fuels, dominated by coal burning [41,42]. To meet the rigorous criteria for the coming decades 2030/2040/2050, it is necessary to search for optimal solutions, including RES development, as referred to in new legislation imposed in 2018 (Suppl. ref. [1]) and discussed thoroughly in a recently released document on priorities of the 2030 Polish national environmental policy [43]. The proposed energy strategy [44] outlines several objectives and priorities. Selected RES types will be promoted with a successive increase in the share of biogas-borne energy, especially that obtained from agricultural facilities. The complex policy and formal procedures regarding this market have been elaborated [45], which include support for the most competitive technologies as well as price control and regulation. For more detailed information and analyses on Poland's RE strategy with a special focus on the agricultural biogas sector, see the thorough reviews of Igliński et al. and Koryś et al. [46,47].

In Poland, the RES carriers amounted to 8.2% of the total energy consumption (4490.7 PJ; per capita: 115.9 GJ) in 2018 [41], decreasing from 11.8% in 2015 [48]. This is far below the planned value of 15% for 2020 [48] and below the EU average (18.0% in 2018 [42]). Poland ranks 21st on the list of 28 EU countries with a total installed power of 8.23 GW, contributing a 1.77% share to the total EU generated RE (0.35% of the world's RE production [49]). Note, however, that this share has increased considerably since 2009 (0.6% for EU and 0.15% for the global market) due to a 3.5-fold increase in installed power [49]. Polish RES contributed 14.46% to the primary energy production (12.7% contribution to electricity), and the share of biogas sector equaled 0.47%. Biogas production shared 3.25% in all RES carriers and was the third most important source after wind energy and biomass, and ahead of photovoltaics. Recent reports reveal that the installed power of all Polish biogas plants (245.4 MW [45]) contributed 3.0% to the total installed power [49]. The annual production of biogas (3.17 TWh in 2017) made up only 1.5% of overall gas use (211.6 TWh) [45], whereas in the EU this share was 4.2% [50]. In 2017, Poland was the 8th largest biogas producer (272.8 ktoe of annual primary energy production) in the EU (16.1 Mtoe) [50]. Polish biogas energy is produced exclusively upon cogeneration (combined heat and power, CHP), which yields both heat (8th largest EU producer) and electricity (6th on the EU list with 1049 GWh of electric power in 2016 compared to the EU total of 62.5 TWh) [50].

The structure of the Polish biogas industry reveals some distinct features compared to other European countries. In 2018 there were 18,202 biogas plants operating in Europe [51]. Preferential systems of biogas production and utilization as well as types of feedstock differed within Europe [36,37,50]. There are two dominant market models: the first promotes agriculture-originated feedstocks, whereas the second focuses on landfill gas recovery. Poland, together with Norway, Switzerland and Sweden belongs to the minority adopting the third model, i.e. a relatively high (approx. 35%) contribution of biogas produced from sewage sludges. In 2018 there were 308 operational biogas plants, of which 95 used agricultural materials to produce 291.4 Mm^3 of biogas (103 MW, 608 GWh of electricity produced); 109 biogas plants (power of 60 MW) utilized wastewater treatment plant (WWTP) sewage sludges, 102 stations were operating at landfill sites for gas recovery and combustion (65 MW), and 2 plants running on mixed feedstocks (3 MW) [11,45]. The whole sector tended to grow dynamically from 2011 to 2016 (by 126%, peaking at 234 MW); then, despite the claimed governmental support, stagnation was observed [11,44], clearly as a result of the market legislation-based uncertainty.

The mainstream of biogas industry development in Poland is the construction of installations operating on agricultural materials and optimization of biomethanation processes [46,47]. Within the period 2012–2017, a dramatic (4-fold) increase in agricultural biogas production was observed [11,45]. From among 34 substrates used as feedstocks, the most common ones are agro-waste residues such as manure, slaughter effluents, animal fat and slurries, poultry waste, straw, silages, beet pulp, fruit and vegetable residues, decoction, molasses, distillery waste and other green wastes and slurries, which constitute 84% of the total 3.8 Mt of annual feedstock [46]. The remaining 16% belong to dedicated crops, mostly maize silages. Concerning the landfill gas-utilizing stations, apart from direct energy recovery by gas combustion, their climate-protecting role must be emphasized due to the limitation of methane release into the atmosphere. Landfill gas is spontaneously formed upon biodegradable organic waste anaerobic decomposition and contains approx. 50% methane, a powerful greenhouse gas. Nevertheless, the landfill-gas subsector is expected to gradually shrink due to restrictions demanding more waste sorting facilities and reduction of the amount of biodegradable residues [52].

Unlike other countries developing the biogas industry [36,37,50,51], Poland lacks any functional methane upgrading installations to enable its release to the grid, nor does it produce biomethane as a transportation fuel. Similarly, biorefinery concepts related to anaerobic fermentation and digestate utilization [21,22,25] still await more extensive research and implementation. As regards Polish biogas plants processing sewage sludges, they are typical elements of modern, integrated WWTP systems. The advantageous role of the anaerobic digestion bioprocess consists in combining the sludge stabilization with biogas generation and combustion to generate electricity and heat (CHP). The power produced can be directly consumed on site thus favoring increased WWTP profitability, as wastewater treatment is an energy demanding process. In 2018 there were 3257 municipal WWTPs (8 mechanical, 2439 biological, and 810 biological with enhanced removal of biogenic compounds) [11,41], which implies that only 3.3% of WWTPs were equipped with the sludge-digesting facilities. The annual volume of biogas obtained from sewage processing in Poland is estimated as 20 Mm^3 [53]; however, the technological potential for this biofuel production from sludges is estimated to be higher and to exceed 100 Mm^3 (approx. 2 PJ of electrical energy equivalent) [45].

Anaerobic digestion of organic waste

Anaerobic digestion is a process based on microbial methane fermentation where the biodegradable fraction of organic content undergoes partial mineralization accompanied by biogas generation [31,38,39]. It is believed to have substantial advantages over other treatment methods of organic waste and wastewaters due to its sustainability, ecological friendliness, and economic benefits. These benefits come from the energy produced and the ready recovery of important nutrients such as phosphorus or nitrogen [19], mobilized by fermentation from organically-bound forms. Fig. 1 shows a general scheme of the organic matter flow upon fermentation of different feedstocks. The diagram also illustrates generation of a digestate byproduct as well as reveals possible processing methods for this material. Digestate, also known as the post-fermentation mass or pulp, or post-ferment, is a nutrient-rich waste material categorized based on the input feedstock type and receives an appropriate 6-digit code as defined in the waste classification document, "List of Waste" [54]. Accordingly, the digestate from anaerobic treatment of municipal waste has the waste code 19 06 04, whereas that obtained from animal and vegetable waste is given the code 19 06 06. Note that for the biogas-producer this waste product is regarded as an additional process cost since it requires further management and utilization. In contrast, for farmers this material may reveal substantial value as a potential fertilizing product [23,55–57].

Post-fermentation pulp is most often separated into solid (approx. 25% d.m. content, again codes 19 06 04 or 19 06 06) and liquid (3.3% of d.m.) fractions of the "liquor from anaerobic treatment", with new codes of 19 06 03 and 19 06 05, for municipal waste, and animal and vegetable waste, respectively [54]. Digester liquors are usually recirculated as technological liquid into the WWTP systems, or, less frequently, used for diluting nutrients or substrates, or applied directly to the field for fertigation, provided that they bear no ecological or sanitary risks (see below).

Interestingly, for the case of agricultural feedstock fermentation, there are legislative changes aimed at simplifying management procedures and facilitating direct digestate soil applications and market commercialization. Recent EC regulations [58] amending Annex V to the REACH Regulation [59], state that the digestate produced upon biodegradable feedstocks (food waste, manure and energy crops but not sewage sludges) shall not be registered among other chemicals. Moreover, the draft amendment of the currently applicable Polish act on fertilizers (Suppl. ref. [2]) has been recently submitted for consideration. It concerns the introduction of a novel category of "biogas products", that is soil-fertilizing post-fermentation products, not regarded as waste provided their characteristics fulfill the relevant criteria for organic or organic-mineral fertilizers. Note, however, that despite the new regulations, the other digestate types (such as 19 06 04) will continue to require treatment to remove their waste code and enable field application.

Anaerobic digestion of sewage sludges

Biological treatment of municipal wastewaters yields large amounts

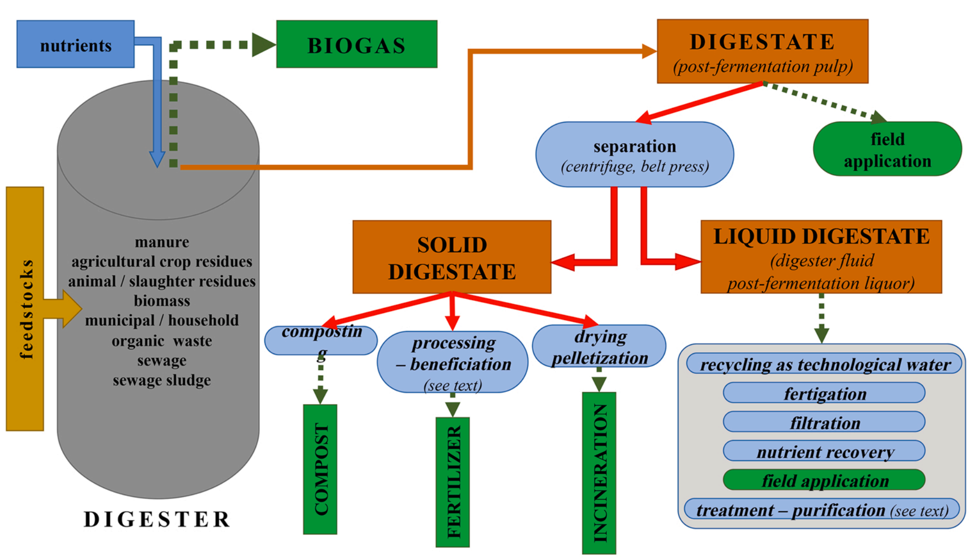

Fig. 1. General view of digestate formation, its subsequent treatment techniques, and final application of the resultant products.

(up to 2% of the influent stream volume) of sewage sludges of several types (primary, secondary, mixed and excess sludges), which are in fact byproducts defined as separable organic-mineral phases. They must undergo further multistage processing to eliminate ecological risks and microbiological hazards [60,61]. These complex operations lead to volume reduction, odor depletion, hygienization, stabilization of chemical content and decreased susceptibility for further decomposition and putrefaction. For these purposes several physico-chemical and biological processes can be applied, namely sludge thickening, dewatering, drying, pasteurization, irradiation, lime treatment, thermal stabilization by incineration, pyrolysis or gasification, conditioning, recovery of biogenic elements, aerobic composting, and finally anaerobic digestion [34,62–64].

Anaerobic digestion, relatively widely applied in Poland, is regarded as a particularly promising and innovative approach bringing environment-friendly and sustainable solutions. It enables energy generation from biogas and produces the so-called biostabilized sludge which can be further transformed into soil-fertilizing products. An estimated 10−20 m^3 of biogas (60% methane content, calorific value of 21.4 MJ/m^3) is obtainable from 1.0 m^3 of sewage sludge (typically 4% of d.m.) [65]. The resultant sludges become new waste products with codes 19 08 05 and 19 08 99 [54] and have to be further processed [60,61] as described earlier for digestates. The direct use of the stabilized sludge for agricultural purposes is very limited and strictly regulated by legislation which brings thorough qualitative criteria and requires effective sanitation [66], (Suppl. ref [3]). Among the advisable processing actions are the so-called recovery treatment operations [67,68] defined by appropriate “Recovery codes”, namely R3 (“Recycling/reclamation of organic substances … “) and more frequently used R10 (“Land treatment resulting in benefit to agriculture or ecological improvement”). The other sewage sludge handling procedures, such as incineration, pelletization, drying and landfilling are usually considered less environmentally and economically beneficial. According to the statistical data [41], the total mass of sewage sludges generated in Poland in 2018 was 583.1 kilotonnes (kt of d.m.), out of which 134.2 kt were applied in agriculture, 27.8 kt used for land reclamation, 26.0 kt for cultivation of plants to produce compost, 234.3 kt incinerated and 119.1 kt landfilled.

Fig. 2 presents a comprehensive scheme of typical methods employed in Poland for management of municipal sewage and waste sludges, as described in the Polish ministerial strategy (Suppl. ref. [4]). Raw sewage sludges from wastewater treatment are processed (Stage I) to generate waste products (main waste group codes 19 and 16). In particular, stabilization in anaerobic digesters followed by dewatering yields the waste sludge, code 19 08 05. Note that during Stage I it may also be possible to obtain a commercial end product, provided that the treatment has been sufficient to meet the qualitative requirements. For example, the dewatered primary sludges have been proposed as fillers in production of aggregated concrete in the energy-saving building construction industry [69]. In all other cases however, the sludge should be further processed by variant actions taken during Stage II.

As can be seen in Fig. 2, not all technological paths allow the “zero waste” result to be achieved, that is to obtain a desired soil fertilizer or other plant growth-promoting product. Many sludge treatment actions can still be optimized. Current efforts to elaborate best handling methods focus on refinement of the sludge digestion bioprocess to optimize biogas production and development of novel sludge processing techniques including enrichment with microbiological components. The main goal of these actions is to obtain beneficiated, added-value products and facilitate closing circulation loops of materials and wastes. Selected examples of such successful attempts are given in the following sections.

Optimization strategies for sewage sludge biomethanation: co-fermentation with organic waste

Anaerobic digestion parameters, overall system performance and the resultant digestate physico-chemical properties depend strongly on the feedstock type and mode of fermentation (meso-, thermophilic) [23,31,35,70]. Many researchers have stressed the fact that both the biogas yield and the organic-mineral content of the digestate can be ameliorated by defining the well-matched proportions of substrates applied for co-fermentation (co-digestion) [31,34,70–73]. For sewage sludge biomethanation, most studies have dealt with the organic fraction of municipal solid wastes (OFMSW) used as a co-substrate [74–76]; however, other input materials have also been suggested for bioprocess improvement [34,77–79].

In a series of systematic studies [76,80–82] and references therein], various feedstocks were considered as potential supplements to municipal sewage sludges for optimized co-digestion. Among the tested co-substrates were swine and poultry manure, slaughterhouse waste, sugar beet pulp stillage, OFMSW fraction and food waste. The authors concluded that the working capacity of most Polish sludge-utilizing biogas installations allowed for co-digestion of additional feedstock amounts and that mesophilic co-fermentation was the most efficient process.

At present there are no publicly available data on Polish WWTPs equipped with biogas installations carrying out co-digestion processes. A recent RDI project launched by the Central Mining Institute (GIG), Katowice, entitled “Development of technology for selectively collected kitchen organics from the city of Żory” may serve as an example. The project has been in pilot-scale production since 2017 and its main idea is to optimize wastewater treatment and waste management based on the well-balanced use of biodegradable kitchen (municipal organic) waste as a co-substrate for sewage sludge digestion. The fraction of

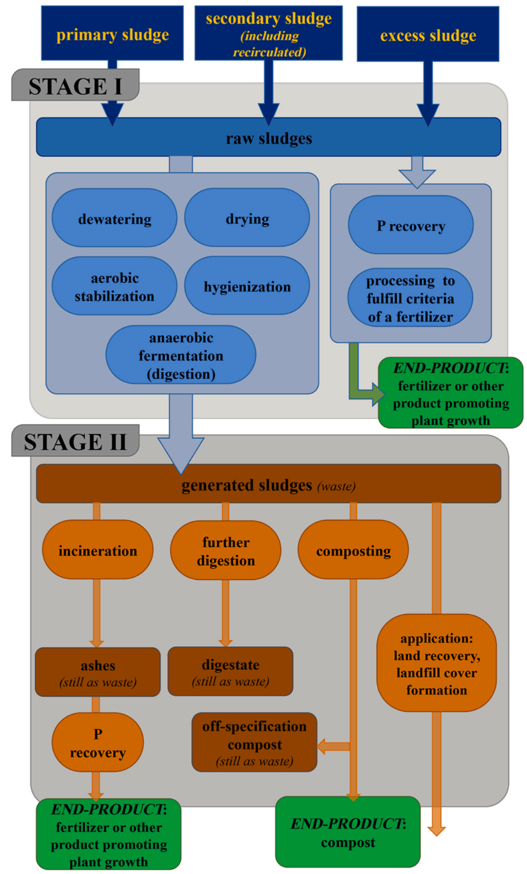

Fig. 2. Schematic representation of the main technological paths of management and processing of municipal sludges in Poland (based on Suppl. ref. [4]).

"biodegradable kitchen and canteen waste" (code 20 01 08) is rich in carbon sources, readily available for microbial consortia proliferating within the digester. The waste is collected from local school canteens and then processed employing the newly elaborated, innovative technology. The waste streams are macerated and then directed to the separated fermentation chambers for mesophilic co-fermentation with the sewage sludge. The generated digestate is subjected to the R3 recovery procedure and then used as a fertilizer. In Poland, the contribution of biodegradable organic material in the total stream of segregated urban waste is expected to increase by 0.5% annually, which secures full future accessibility to the feedstock material. The goal is to implement technology that meets the environmental regulations of 2016 (Suppl. ref. [5]) setting down requirements of the 65% municipal waste portion to be recyclable by 2030.

Stabilized sewage sludge utilization: new generation fertilizers for agriculture

The anaerobic digestion of variant feedstocks produces large amounts of biogas digestate. A typical 500 kW plant is estimated to generate 10 kt of post-fermentation mass annually [83]. Direct field application of digestate as a low-grade fertilizing liquid is rare (see above) and according to the goals of circular economy, it should be processed and utilized to maximize final added product values while minimizing negative environmental impact (*zero-waste* concept, cf. Fig. 1). The incineration path (thermal conversion recovery procedure R1) is considered as competitive only when the post-fermentation material has sufficient calorific value (approx. 15 GJ/t) which in most cases is too low due to decay of organic matter upon biomethanation. Moreover, the R1 process is only applicable under economically reasonable conditions, such as the availability of heat for pulp drying and pelletization, access to combustion facilities, or transportation infrastructure. Composting (R3) in turn preserves most of the minerals otherwise lost in coarse ashes, yet requires high (30–35%) dry mass content, appropriate C:N ratio (20–26:1) and leads to nitrogen loss (up to 30% released as ammonia). The R10 recovery thus appears to be the most sustainable, environmentally favorable and economically profitable method, enabling promotion of plant growth, improvement of soil properties and reduction in the use of commercial mineral fertilizers produced using conventional fuels.

The solid digestate fraction may become granulated and then beneficiated to form a valuable fertilizer. Several novel technologies have been developed and implemented, although they apply only to the agri-food organic waste substrates used as feedstocks. For example, the WAVALUE process [84] consists in mixing digestate with other organic wastes and/or other fertilizers to obtain well-balanced ratios of N:P:K. The blends then undergo granulation in a spouted bed dryer to yield commercial, high-quality products. This innovative and economically-efficient approach enables utilization of the digestate as a valuable material for further processing, rather than management as a waste product. Instead of direct spreading onto agricultural fields as a low-grade liquid fertilizer, the digestate-based granulate becomes enriched so as to produce tailored, added value eco-fertilizers. The process is environment-friendly as it requires mostly renewable materials; moreover, it shows relatively little dependence on fossil fuel use and thus minimizes CO_2 emissions substantially.

For the case of stabilized sewage sludges (Fig. 2), their applicability as potential soil improvers or fertilizers results from both the presence of organic fraction and the mineral content (nitrogen and phosphorus). Thus, proper sludge utilization gives rise to the rational use of organic carbon resources and brings a unique opportunity to ensure N and P environmental circulation by reusing these important biogenic elements. For the above reasons, the issue of elaboration and production of organic/mineral fertilizers from sewage sludges has attracted much attention and the worldwide achievements in this area including Polish inventory products and technologies have been reviewed in detail [85].

The recent method elaborated, patented (Suppl. ref. [6]) and described [86] by the Katowice GIG Institute allows for production of variant bio-based fertilizer products. The novel organo-mineral granulated fertilizer is a mixture of municipal dewatered stabilized sewage sludge (19–20% of d.m.) collected from municipal WWTPs, dolomite (50% $CaCO_3$ and 40% $MgCO_3$), lime (96% CaO), gypsum, ammonium carbonate and microcrystalline cellulose. The final product is generated as non-dusting, irregular-shape granulate, 1–6 mm in diameter. The granulation process is a key sequence of unit operations involving grain formation from either a powdery or solid substance of appropriate physico-chemical properties. Among the technological advantages are suppression of dusting, avoidance of caking, negligible segregation into multicomponent materials and easy transport. The block diagram revealing the production stages of the fertilizer is given in Fig. 3. The product meets the criteria of an eco-innovation [87] since it protects the environment by eliminating any adverse impacts and preventing misuse of natural resources. The fertilizer production follows the „waste-to-product" ideal because the sludge waste code is removed upon processing while the resultant fertilizer is further beneficiated to achieve significant added commercial value. The pilot-scale installation has already been implemented at the municipal WWTP of Żory (Fig. 4), and thus far several variants of the granulate (cf. Fig. 5) have been examined in pot-tests and field studies, demonstrating plant-growth promoting properties.

Post-fermentation eutrophic liquor utilization and treatment

The post-fermentation liquor obtained upon digestate separation is usually regarded as environmentally safe (especially when compared to raw, non-fermented organic fertilizers such as manure) and may be directly applied to agricultural fields on condition that it meets qualitative requirements [23,57] (see Fig. 1). However, depending on the feedstock type and other process parameters, the digester fluid may vary considerably in C-to- N and P ratios, monovalent cation concentration (Na^+, K^+), pH, rH (reduction potential), content of potentially toxic volatile short- or branched-chain fatty acids, as well as many other parameters affecting overall environmental impact. For this reason, in many cases, such as animal-borne waste utilization and sewage sludge digestion, this effluent bears ecological risks of toxicity or eutrophication and must be properly treated before reuse, discharge or field application.

The liquid post-fermentation fraction may contain high levels of water-soluble ionic forms of many elements, especially N, P, K, which are usually considered as nutrients readily available to plants. Note, however, that due to strong reductive conditions in digesters, nitrogen occurs predominately as the ammonium ion and its concentrations may reach 3000 g/m^3 [72,88,89]. Phosphate content typically ranges from 100 to 200 g/m^3 but may be as high as 900 g/m^3 [63,90,91]. At the same time the level of organic carbon is often very low, resulting in a C:N ratio <1, a value much lower than the optimum of 25–30 suitable for biological treatment with the activated sludge [31,33,92].

Although the toxicity of raw digester liquors has yet to be fully explained, it most likely results from certain physico-chemical characteristics such as adverse rH or pH values, high salinity, presence of low-molecular short-chain fatty acids together with other metabolic intermediates, and ammonium nitrogen. NH_4–N is known not to be preferentially taken up and assimilated by most plants including crops and for numerous species it may be toxic [93]. In addition, when introduced directly to the soil, NH_4–N can easily migrate towards the groundwater causing eutrophication. Free ammonia was found to be the main inhibitor of anaerobic digestion for a variety of substrates [76,80,92,94]. These problems imply the necessity to remove the excess ammonium nitrogen from the liquor, so that both the technological recycling as well as direct field applications are not strongly restricted or excluded.

High concentrations of biogenic elements in digestates led to elaboration of nutrient recovery methods and processing for further use as

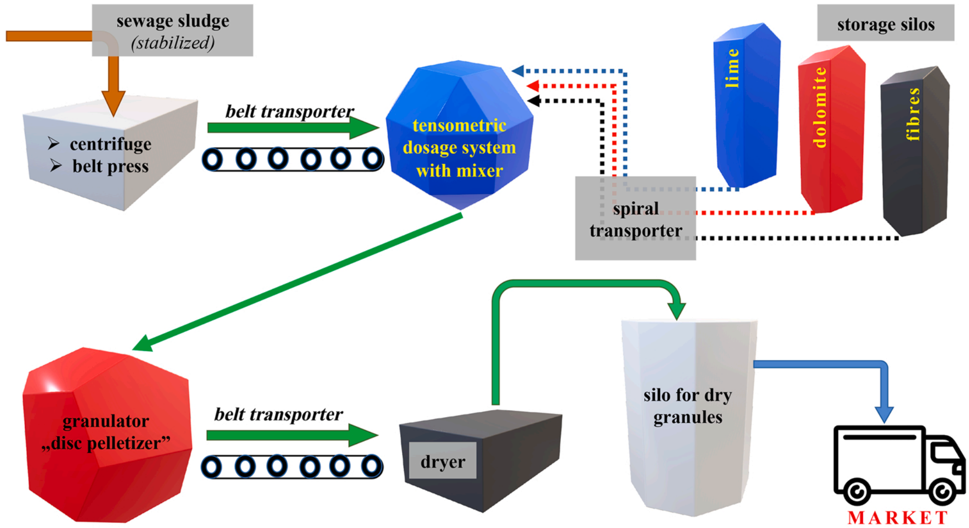

Fig. 3. Block scheme of the technology for production of granulated fertilizer from dewatered sewage sludge, as elaborated by the Central Mining Institute, Katowice.

Fig. 4. Pilot-scale technological line for production of granulated fertilizer from dewatered sewage sludge at WWTP in Żory.

mineral fertilizing products [57,95]. Among the most frequently applied treatments are physico-chemical technologies involving drying, struvite crystallization, stripping, evaporation, ion exchange and membrane techniques [96–102]. However, all these methods have several environmental and economic disadvantages (see e.g. [96,98,99] for struvite precipitation and [103] for ammonia stripping). Biological methods for digestate liquor treatment serve as eco-friendly and sustainable alternative approaches. Microbiological removal of excess ammonium nitrogen may reduce the digestate potential toxicity or inhibitory properties. The use of conventional activated sludges is difficult [104] since the eutrophic effluent often exhibits imbalanced C:N ratios. A low content of organic fraction hampers physiological activities of heterotrophic microbial consortia which require carbon sources for growth and energy metabolism. Moreover, high levels of NH_4–N were found toxic to the activated sludge [105], and taking into account other possible toxicants, we believe that direct post-fermentation liquid recirculation into WWTP chambers may have adverse effects on overall treatment system efficiency.

Noteworthy attempts to implement alternative methods towards eutrophic wastewater treatment [106] include the use of macrophytes

Fig. 5. Different types of granulated fertilizers made from dewatered sewage sludge according to technology developed in the Central Mining Institute, Katowice.

[107], constructed wetland plants [108,109], microalgal cultures [110–113] or hybrid algal–bacterial consortia [114]. In addition, a recent Polish R&D program focused on a search for optimized biological methods for treatment of ammonia-rich toxic digester effluents [115]. The project was carried out by three cooperating universities (Technological University of Łódź, Jagiellonian University in Kraków and University of Agriculture in Kraków) together with a company involved in the development of a large-scale biogas plant. The rationale of the work was based on the use of microalgae and other microorganisms for the management of recalcitrant, eutrophic liquors in an integrated, biorefinery-like system enabling efficient wastewater clean-up, re-use of the purified water and production of the added-value algal biofuel. The proposed post-fermentation waste bioconversion method was aimed at the elimination of the problems around treatment of ammonium-rich anaerobic sludge digester supernatants produced upon organic waste and biomass fermentation. This biotechnological innovation represents the waste-to-resource approach and follows the main ideas of the bio-based economy and circularity. The pro-ecological outcomes are expected to mitigate the risks of soil and water eutrophication, to recover mineral nutrients, and to provide additional sources of energy-rich fatty-acids. We believe the project results will have more than just a local impact, revealing the potential of subsequent implementation on the industrial scale in modern biogas facilities. Such advances are especially applicable for countries like Poland, regarded as a "sensitive area" [116] requiring strict control over water discharges of phosphorus, nitrogen and biodegradable waste. Although most of the relevant novel data are still being elaborated, some results have already been published or communicated [e.g. 117,118,119].

Final comments and concluding remarks

In Poland, in line with the EU policy recommendations and OECD objectives, there is a strong political and social pressure to implement novel bio-based technologies favoring economically-efficient and environmentally-safe waste management methods. Currently, conventional approaches dealing with the problem of excessive waste production still suffer from outmoded linear processing. Newly developed biotechnologies enable reconciling the reduction of environmental impact with increased economic profit by optimizing value chains through closing product loops and minimizing waste disposal.

The Polish biogas sector is strongly linked to municipal waste management, especially sewage treatment. Organic waste utilization via anaerobic digestion will tend to expand, thus making the biogas industry an important part of the green energy market in the future. In this review examples have been presented of Polish eco-innovative approaches which demonstrate that circular bioeconomy is particularly relevant in optimizing urban wastewater treatment and management of sewage sludges. Biotechnological solutions as exemplified by a refined co-digestion bioprocess and production of novel granulated fertilizers enable achievement of full circularity of materials, further valorized to obtain added-value products. The problem of post-fermentation eutrophic sludge liquors is also addressed. These effluents need to be properly treated, which involves additional costs often ignored when considering the economic framework of complex waste-utilizing systems. Current trends in optimizing biological treatment of digester liquors accompanied by retention of mineral nutrients are presented suggesting the applicability of microalgal consortia.

Anaerobic digestion of organic materials followed by proper waste sludge processing and beneficiation demonstrate the advantages that correspond to the best values of bioeconomy. The optimized bioprocess brings pro-ecological solutions, fulfills the waste-to-product and zero-waste criteria, and is in accordance with the principle of the cascading use of waste streams. In addition, the standards of a green economy are met by minimizing environmental pollution, decreasing the CO_2 emission and increasing the efficiency of energy and resource use. Finally, economic and environmental circularity is achieved by facilitated product conversion via the path: soil/water environment → bioorganic compound→ bioorganic waste → wastewater → biological treatment (biotransformation, biodegradation, mineralization) → sewage sludges → biogas (energy) + digestate → fertilizer → soil/water.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.nbt.2020.11.005.

References

[1] Diakosavvas D, Frezal C. Bio-economy and the sustainability of the agriculture and food system: opportunities and policy challenges. OECD Food, Agriculture and Fisheries Papers, No. 136. Paris: OECD Publishing; 2020. https://doi.org/10.1787/d0ad045d-en.
[2] Woźniak E, Twardowski T. The current state of bioeconomy in Poland. Acta Biochim Pol 2016;63(4):731–5. https://doi.org/10.18388/abp.2016_1365.
[3] Berlina A. The bioeconomy in the Baltic Sea region. Some recommendations for policymakers. BSR Policy Briefing series. 2018. p. 3 [accessed 20 September 2020], http://www.centrumbalticum.org/files/3895/BSR_Policy_Briefing_3_2018_Berlina_.pdf.
[4] Hamelin L, Borzęcka M, Kozak M, Pudełko R. A spatial approach to bioeconomy: quantifying the residual biomass potential in the EU-27. Renew Sust Energ Rev 2019;100:127–42. https://doi.org/10.1016/j.rser.2018.10.017.
[5] OECD. Acronyms and abbreviations. In: Meeting Policy Challenges for a Sustainable Bioeconomy; 2018.
[6] Tsui TH, Wong JW. A critical review: emerging bioeconomy and waste-to-energy technologies for sustainable municipal solid waste management. Waste Disposal Sustainable Energy 2019:1–17. https://doi.org/10.1007/s42768-019-00013-z.
[7] Trømborg E, Jåstad EO. Report on market outlook and future viability of different bioenergy products and value chains in the Baltic Sea region energy system. BalticBiomass4Value Project No.#R095. Interreg Baltic Sea Region. European Regional Development Fund. Norwegian University of Life Sciences; 2019. Available at: https://balticbiomass4value.eu/wp-content/uploads/2019/06/BB4V_A_2.1_REPORT_17.10.2019_V2_FOR_WEB.pdf; [accessed 20 September 2020].
[8] Smart Specialisation Platform [Internet]. European Commission, Joint Research Centre, Seville (Spain). 2020 [accessed 24 August], https://s3platform.jrc.ec.europa.eu/contact.
[9] Dettenhofer M, Ondrejovič M, Vásáry V, Kaszycki P, Twardowski T, Stuchlík S, et al. Current state and prospects of biotechnology in Central and Eastern European Countries. Part I: Visegrad countries (CZ, H, PL, SK). Crit Rev Biotechnol 2019;39(1):114–36. https://doi.org/10.1080/07388551.2018.1523131.
[10] Miller M, Mroczkowski T, Healy A. Poland's innovation strategy: how smart is 'smart specialisation'? IJTIS. Int J Transit Innov Syst 2014;3:225–48. https://doi.org/10.1504/IJTIS.2014.065697.
[11] Statistics Poland. Warsaw (PL): Local Data Bank. 2020 [accessed 10 September 2020], https://bdl.stat.gov.pl/BDL/start.
[12] European Commission. Review of the 2012 European bioeconomy strategy. Brussels; 2017. https://doi.org/10.2777/086770.
[13] OECD. The bioeconomy to 2030: designing a policy agenda. OECD International Futures Programme. OECD; 2006.
[14] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; COM/2014/0398. Brussels, 2.7.2014. Towards a circular economy: a zero waste programme for Europe. 2020 [accessed 20 September 2020], https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52014DC0398.
[15] McDowall W, Geng Y, Huang B, Barteková E, Bleischwitz R, Türkeli S, et al. Circular economy policies in China and Europe. J Ind Ecol 2017;21(3):651–61. https://doi.org/10.1111/jiec.12597.
[16] European Commission. Implementation of the first circular economy action plan. 2019 [accessed 20 September 2020], https://ec.europa.eu/environment/circular-economy/first_circular_economy_action_plan.html.
[17] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; COM(2020)98. Brussels, 11.3.2020. A new circular economy action plan. For a cleaner and more competitive Europe. 2020 [accessed 20 September 2020], https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN&WT.mc_id=Twitter.
[18] Ubando AT, Felix CB, Chen WH. Biorefineries in circular bioeconomy: a comprehensive review. Bioresour Technol 2020;299:122585. https://doi.org/10.1016/j.biortech.2019.122585.
[19] Batstone DJ, Virdis B. The role of anaerobic digestion in the emerging energy economy. Curr Opin Biotech 2014;27:142–9. https://doi.org/10.1016/j.copbio.2014.01.013.
[20] Wang H, Yang Y, Keller AA, Li X, Feng S, Dong YN, et al. Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa. Appl Energy 2016;184:873–81. https://doi.org/10.1016/j.apenergy.2016.07.061.
[21] Nizami AS, Rehan M, Waqas M, Naqvi M, Ouda OKM, Shahzad K, et al. Waste biorefineries: enabling circular economies in developing countries. Bioresour Technol 2017;241:1101–17. https://doi.org/10.1016/j.biortech.2017.05.097.
[22] Bhatia SK, Joo HS, Yang YH. Biowaste-to-bioenergy using biological methods – a mini-review. Emerg Convers Manage 2018;177:640–60. https://doi.org/10.1016/j.enconman.2018.09.090.
[23] Wainaina S, Awasthi MK, Sarsaiya S, Chen H, Singh E, Kumar, et al. Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. Bioresour Technol 2020:122778. https://doi.org/10.1016/j.biortech.2020.122778.
[24] Singhania RR, Agarwal RA, Kumar RP, Sukumaran RK, editors. Waste to wealth. Springer; 2018. https://doi.org/10.1007/978-981-10-7431-8.
[25] Bastidas-Oyanedel JR, Schmidt JE, editors. Biorefinery: integrated sustainable processes for biomass conversion to biomaterials, biofuels, and fertilizers. Springer; 2019. https://doi.org/10.1007/978-3-030-10961-5.
[26] Kamm B, editor. Microorganisms in biorefineries. Springer; 2015. https://doi.org/10.1007/978-3-662-45209-7.
[27] Ruiz HA, Thomsen MH, Trajano HL, editors. Hydrothermal processing in biorefineries. Springer International Publishing AG; 2017. https://doi.org/10.1007/978-3-319-56457-9.
[28] Bastidas-Oyanedel JR, Schmidt JE. Increasing profits in food waste biorefinery – a techno-economic analysis. Energies 2018;11(6):e1551. https://doi.org/10.3390/en11061551.
[29] Corona A, Ambye-Jensen M, Vega GC, Hauschild MZ, Birkved M. Techno-environmental assessment of the green biorefinery concept: combining process simulation and life cycle assessment at an early design stage. Sci Total Environ 2018;635:100–11. https://doi.org/10.1016/j.scitotenv.2018.03.357.
[30] Zhang H, Lopez PC, Holland C, Lunde A, Ambye-Jensen M, Felby C, et al. The multi-feedstock biorefinery – assessing the compatibility of alternative feedstocks in a 2G wheat straw biorefinery process. GCB Bioenergy 2018;10(12):946–59. https://doi.org/10.1111/gcbb.12557.
[31] Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L. The anaerobic digestion of solid organic waste. Waste Manage 2011;31:1737–44. https://doi.org/10.1016/j.wasman.2011.03.021.
[32] Bujoczek G, Oleszkiewicz J, Sparling R, Cenkowski S. High solid anaerobic digestion of chicken manure. J Agr Eng Res 2000;76:51–60. https://doi.org/10.1006/jaer.2000.0529.
[33] Ward AJ, Hobbs PJ, Holliman PJ, Jones DL. Optimization of the anaerobic digestion of agricultural resources. Bioresour Technol 2008;99:7928–40. https://doi.org/10.1016/j.biortech.2008.02.044.
[34] Grübel K, Kuglarz M, Wacławek S, Padil V, Cernik M, Varma R. Microwave-assisted sustainable co-digestion of sewage sludge and rapeseed cakes. Energy Convers Manag 2019;199:112012. https://doi.org/10.1016/j.enconman.2019.112012.
[35] Weiland P. Biogas production: current state and perspectives. Appl Microbiol Biotechnol 2010;85(4):849–60. https://doi.org/10.1007/s00253-009-2246-7.
[36] Torrijos M. State of development of biogas production in Europe. Procedia Environ Sci 2016;35:881–9. https://hal.inrae.fr/hal-02636838.
[37] Scarlat N, Dallemand JF, Fahl F. Biogas: developments and perspectives in Europe. Renew Energ 2018;129:457–72. https://doi.org/10.1016/j.renene.2018.03.006.
[38] Tabatabaei M, Ghanavati H, editors. Biogas: fundamentals, process, and operation, 6. Springer; 2018. https://doi.org/10.1007/978-3-319-77335-3.
[39] Atelge MR, Krisa D, Kumar G, Eskicioglu C, Nguyen DD, Chang SW, et al. Biogas production from organic waste: recent progress and perspectives. Waste Biomass Valori 2018:1–22. https://doi.org/10.1007/s12649-018-00546-0.
[40] Wicki L, Wicka A. Bioeconomy sector in Poland and its importance in the economy. Econ Sci Rural Dev 2016;41:219–28.
[41] Statistics Poland. Statistical Information Centre. Statistical Yearbook of the Republic of Poland, Warsaw 2019; Statistical_yearbook_of_the_republic_of_poland. 2019. pdf available at: https://stat.gov.pl/en/topics/statistical-yearbooks/statistical-yearbooks/statistical-yearbook-of-the-republic-of-poland-2019,2,21.html; [accessed 20 September 2020].
[42] Eurostat. European statistics. 2018 [accessed 18 September 2020], http://ec.europa.eu/eurostat.
[43] Ministry of Climate of the Republic of Poland. The 2030 national environmental policy – the development strategy in the area of the environment and water management (PEP2030). 16 July. 2019. The National Environmental Policy 2030 document available at: https://bip.mos.gov.pl/fileadmin/user_upload/bip/strategie_plany_programy/Polityka_Ekologiczna_Panstwa/Polityka%20Ekologiczna%20Pa%C5%84stwa%202030%20ENG_wersja%20internet.pdf; [accessed 20 September 2020], https://www.gov.pl/web/climate/the-2030-national-environmental-policy–the-development-strategy-in-the-area-of-the-environment-and-water-management.
[44] Ministry of Energy of the Republic of Poland (Currently: Ministry of State Assets). Draft: energy policy of Poland until 2040. Environmental impact assessment EPP 2040. 2020. EN_Extract_EPP2040.pdf and Załącznik_ooś_3_Streszczenie_Prognozy_z_wnioskami_(En)_06112019.pdf, available at: https://www.gov.pl/web/aktywa-panstwowe/; [accessed 20 September 2020].
[45] Energy Regulatory Office of the Republic of Poland. Department of Renewable Energy. 2020 [accessed 20 September 2020], www.ure.gov.pl/en.
[46] Igliński B, Piechota G, Iwański P, Skarzatek M, Pilarski G. 15 Years of the Polish agricultural biogas plants: their history, current status, biogas potential and perspectives. Clean Technol Environ Policy 2020;22:281–307. https://doi.org/10.1007/s10098-020-01812-3.

[47] Koryś KA, Latawiec AE, Grotkiewicz K, Kuboń M. The review of biomass potential for agricultural biogas production in Poland. Sustainability 2019;11:6515. https://doi.org/10.3390/su11226515.
[48] Chodkowska-Miszczuk J. Institutional support for biogas enterprises – the local perspective. Quaest Geogr 2019;38(2):137–47. https://doi.org/10.2478/quageo-2019-0018.
[49] IRENA. The International Renewable Energy Agency. 2020 [accessed 15 September 2020], https://www.irena.org/.
[50] EurObserv'ER. Biogas barometer 2017; 2017-Baro-Biogaz-GB. 2020. pdf available at: https://www.eurobserv-er.org/category/all-biogas-barometers/; [accessed 20 September 2020].
[51] European Biogas Association. EBA statistical report 2019: European overview. 2020. published January 2020; https://www.europeanbiogas.eu/category/publications/; [accessed 15 September 2020].
[52] Directive (EU). 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste. Off J Eur Union 2018. L 150/100, 14.6.
[53] Igliński B, Buczkowski R, Cichosz M. Biogas production in Poland–Current state, potential and perspectives. Renew Sust Energ Rev 2015;50:686–95. https://doi.org/10.1016/j.rser.2015.05.013.
[54] Commission notice on technical guidance on the classification of waste. (2018/C 124/01) with annexes. Annex 1: annotated list of waste. Off J Eur Union 2018. C 124/1, 9.4.
[55] Albuquerque JA, de la Fuente C, Ferrer-Costa A, Carrasco L, Cegarra J, Abad M, et al. Assessment of the fertiliser potential of digestates from farm and agroindustrial residues. Biomas Bioenerg 2012;40:181–9. https://doi.org/10.1016/j.biombioe.2012.02.018.
[56] Möller K, Müller T. Effects of anaerobic digestion on digestate nutrient availability and crop growth: a review. Eng Life Sci 2012;12(3):242–57. https://doi.org/10.1002/elsc.201100085.
[57] Chojnacka K, Gorazda K, Witek-Krowiak A, Moustakas K. Recovery of fertilizer nutrients from materials-Contradictions, mistakes and future trends. Renew Sust Energ Rev 2019;110:485–98. https://doi.org/10.1016/j.rser.2019.04.063.
[58] Commission regulation (EU). 2019/1691 of 9 October 2019 amending Annex V to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). Off J Eur Union 2019. L 259/9, 10.10.
[59] Regulation (EC). No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. Off J L 2006;396(30):12.
[60] Fytili D, Zabaniotou A. Utilization of sewage sludge in EU application of old and new methods – a review. Renew Sust Energ Rev 2008;12(1):116–40. https://doi.org/10.1016/j.rser.2006.05.014.
[61] Arthurson V. Proper sanitization of sewage sludge: a critical issue for a sustainable society. Minireview. Appl Environ Microbiol 2008;74:5267–75. https://doi.org/10.1128/AEM.00438-08.
[62] Luukkonen TH, Pehkonen SO. Peracetic acid for conditioning of municipal wastewater sludge: hygienization, odor control, and fertilizing properties. Waste Manag 2020;102:371–9. https://doi.org/10.1016/j.wasman.2019.11.004.
[63] Borowski S, Szopa JS. Experiences with the dual digestion of municipal sewage sludge. Bioresour Technol 2007;98:1199–207. https://doi.org/10.1016/j.biortech.2006.05.017.
[64] Johansen A, Nielsen HB, Hansen CM, Andreasen C, Carlsgart J, Hauggard-Nielsen HB, et al. Survival of weed seeds and animal parasites as affected by anaerobic digestion at meso-and thermophilic conditions. Waste Manage 2013;33(4):807–12. https://doi.org/10.1016/j.wasman.2012.11.001.
[65] Pilarski G, Kyncl M, Stegenta S, Piechota G. Emission of biogas from sewage sludge in psychrophilic conditions. Waste Biomass Valor 2019;11:3579–92. https://doi.org/10.1007/s12649-019-00707-9.
[66] Council Directive. 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (Sewage Sludge Directive). Off J L 2020;181. 04/07/1986; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31986L0278; [accessed 20 September 2020].
[67] Directive. 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Annex II. Recovery operations. Off J Eur Union 2008;L 312/3(22):11.
[68] Manual on waste statistics. A handbook for data collection on waste generation and treatment. Eurostat Methodologies and Working Papers, 2013 Edition. Publications Office of the European Union; 2013.
[69] Suchorab Z, Barnat-Hunek D, Franus M, Lagod G, Pavlik Z. The possibility of utilization of sewage sludge as a filler in production of the lightweight aggregate concrete. Ecol Chem Eng S 2019;S.26:559–70. https://doi.org/10.1515/eces-2019-0041.
[70] Borowski S, Kucner M, Czyżowska A, Berłowska J. Co-digestion of poultry manure and residues from enzymatic saccharification and dewatering of sugar beet pulp. Renew Energ 2016;99:492–500. https://doi.org/10.1016/j.renene.2016.07.046.
[71] Esposito G, Frunzo L, Panico A, Pirozzi F. Enhanced bio-methane production from codigestion of different organic wastes. Environ Technol 2012;33:2733–40. https://doi.org/10.1080/09593330.2012.676077.
[72] Callaghan FJ, Wase DAJ, Thayanithy K, Forster CF. Continuous co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure. Biomass Bioenerg 2002;27:71–7. https://doi.org/10.1016/S0961-9534(01)00057-5.
[73] Shah FA, Mahmood Q, Rashid N, Pervez A, Raja I, Shah MM. Co-digestion, pretreatment and digester design for enhanced methanogenesis. Renew Sust Energ Rev 2015;42:627–42. https://doi.org/10.1016/j.rser.2014.10.053.
[74] Silvestre G, Bonmatí A, Fernández B. Optimisation of sewage sludge anaerobic digestion through co-digestion with OFMSW: effect of collection system and particle size. Waste Manag 2015;43:137–43. https://doi.org/10.1016/j.wasman.2015.06.029.
[75] Nielfa A, Cano R, Fdz-Polanco M. Theoretical methane production generated by the co-digestion of organic fraction municipal solid waste and biological sludge. Biotechnol Rep 2015;5:14–21. https://doi.org/10.1016/j.btre.2014.10.005.
[76] Borowski S. Co-digestion of the hydromechanically separated organic fraction of municipal solid waste with sewage sludge. J Environ Manag 2015;147:87–94. https://doi.org/10.1016/j.jenvman.2014.09.013.
[77] Budych-Gorzna M, Smoczynski M, Oleskowicz-Popiel P. Enhancement of biogas production at the municipal wastewater treatment plant by co-digestion with poultry industry waste. Appl Energy 2016;161:387–94. https://doi.org/10.1016/j.apenergy.2015.10.007.
[78] Peces M, Pozo G, Koch K, Dosta J, Astals S. Exploring the potential of co-fermenting sewage sludge and lipids in a resource recovery scenario. Bioresour Technol 2020;300:122561. https://doi.org/10.1016/j.biortech.2019.122561.
[79] Wang W, Xie L, Chen J, Luo G, Zhou Q. Biohydrogen and methane production by co-digestion of cassava stillage and excess sludge under thermophilic condition. Bioresour Technol 2011;102(4):3833–9. https://doi.org/10.1016/j.biortech.2010.12.012.
[80] Borowski S, Domański J, Weatherley L. Anaerobic co-digestion of swine and poultry manure with municipal sewage sludge. Waste Manag 2014;34:513–21. https://doi.org/10.1016/j.wasman.2013.10.022.
[81] Borowski S, Boniecki P, Kubacki P, Czyzowska A. Food waste co-digestion with slaughterhouse waste and sewage sludge: digestate conditioning and supernatant quality. Waste Manag 2018;74:158–67. https://doi.org/10.1016/j.wasman.2017.12.010.
[82] Borowski S, Kucner M. The use of sugar beet pulp stillage for co-digestion with sewage sludge and poultry manure. Waste Manag Res 2019;37:1025–32. https://doi.org/10.1177/0734242X19838610.
[83] Kratzeisen M, Starcevic N, Martinov M, Maurer C, Müller J. Applicability of biogas digestate as solid fuel. Fuel 2010;89(9):2544–8. https://doi.org/10.1016/j.fuel.2010.02.008.
[84] Project WAVALUE. High added value ecofertilizers from anaerobic digestion effluent wastes. Eco-innovation; 2020 [accessed 20 September 2020], https://ec.europa.eu/environment/eco-innovation/projects/en/projects/wavalue.
[85] Kominko H, Gorazda K, Wzorek Z. The possibility of organo-mineral fertilizer production from sewage sludge. Waste Biomass Valor 2017;8:1781–91. https://doi.org/10.1007/s12649-016-9805-9.
[86] Więckol-Ryk A, Krzemień A, Zawartka P, Głodniok M. Risk assessment of sewage sludge granulation process using HAZOP study. Process Saf Prog 2019:e12089. https://doi.org/10.1002/prs.12089.
[87] European Commission. Eco-innovation at the heart of EU policies. The Eco-innovation Action Plan (Eco-AP). 2020 [accessed 23 September 2020], https://ec.europa.eu/environment/ecoap/about-action-plan/objectives-methodology_en.
[88] Fricke K, Santen H, Wallmann R, Hüttner A, Dichtl N. Operating problems in anaerobic digestion plants resulting from nitrogen in MSW. Waste Manag 2007;27:30–43. https://doi.org/10.1016/j.wasman.2006.03.003.
[89] Hansen KH, Angelidaki I, Ahring BK. Anaerobic digestion of swine manure: inhibition by ammonia. Water Res 1998;32:5–12. https://doi.org/10.1016/S0043-1354(97)00201-7.
[90] Battistoni P, Pavan P, Cecchi F, Mata-Alvarez J. Phosphate removal in real anaerobic supernatants: modeling and performance of a fluidized bed reactor. Wat Sci Tech 1998;38:275–83. https://doi.org/10.1016/S0273-1223(98)00412-0.
[91] Mavinic DS, Knezevic Z, Anderson BC, Oleszkiewicz JA. Fate of nutrients during anaerobic co-digestion of sludges from a biological phosphorus removal process. Environ Technol 1995;16:1165–73. https://doi.org/10.1080/09593331608616352.
[92] Nie H, Jacobi HF, Strach K, Xu C, Zhou H, Liebetrau J. Mono-fermentation of chicken manure: ammonia inhibition and recirculation of the digestate. Bioresour Technol 2015;178:238–46. https://doi.org/10.1016/j.biortech.2014.09.029.
[93] Britto DT, Kronzucker HJ. NH_4^+ toxicity in higher plants: a critical review. J Plant Physiol 2002;159(6):567–84. https://doi.org/10.1078/0176-1617-0774.
[94] Chen Y, Cheng JJ, Creamer KS. Inhibition of anaerobic digestion process: a review. Bioresour Technol 2008;99:4044–64. https://doi.org/10.1016/j.biortech.2007.01.057.
[95] Bolzonella D, Fatone F, Gottardo M, Frison N. Nutrients recovery from anaerobic digestate of agro-waste: techno-economic assessment of full scale applications. J Environ Manag 2018;216:111–9. https://doi.org/10.1016/j.jenvman.2017.08.026.
[96] Battistoni P, Pavan P, Prisciandaro M, Cecchi F. Struvite crystallization: a feasible and reliable way to fix phosphorus in anaerobic supernatants. Water Res 2000;34:3033–41. https://doi.org/10.1016/S0043-1354(00)00045-2.
[97] Szymańska M, Szara E, Sosulski T, Wąs A, Van Pruissen GW, Cornelissen RL, et al. A bio-refinery concept for N and P recovery—a chance for biogas plant development. Energies 2019;12(1):e155. https://doi.org/10.3390/en12010155.
[98] Doyle JD, Parsons SA. Struvite formation, control and recovery. Water Res 2002;36:3925–40. https://doi.org/10.1016/S0043-1354(02)00126-4.

[99] Törnwall E, Pettersson H, Thorin E, Schwede S. Post-treatment of biogas digestate–An evaluation of ammonium recovery, energy use and sanitation. Energy Procedia 2017;142:957–63. https://doi.org/10.1016/j.egypro.2017.12.153.
[100] De la Rubia MÁ, Walker M, Heaven S, Banks CJ, Borja R. Preliminary trials of in situ ammonia stripping from source segregated domestic food waste digestate using biogas: effect of temperature and flow rate. Bioresour Technol 2010;101 (24):9486–92. https://doi.org/10.1016/j.biortech.2010.07.096.
[101] Ukwuani AT, Tao W. Developing a vacuum thermal stripping – acid absorption process for ammonia recovery from anaerobic digester effluent. Water Res 2016; 106:108–15. https://doi.org/10.1016/j.watres.2016.09.054.
[102] Guštin S, Marinšek-Logar R. Effect of pH, temperature and air flow rate on the continuous ammonia stripping of the anaerobic digestion effluent. Process Saf Environ Prot 2011;89:61–6. https://doi.org/10.1016/j.psep.2010.11.001.
[103] United States Environmental Protection Agency. Office of Water Washington, D.C. Wastewater technology fact sheet. Ammonia stripping. National Service Center for Environmental Publications (NSCEP); 2000. EPA 832-F-00-019, https://nepis.epa.gov/Exe/; [accessed 25 August 2020].
[104] Gustavsson DJI. Biological sludge liquor treatment at municipal wastewater treatment plants – a review. VATTEN 2010;66:179–92.
[105] Puigaguta J, Salvado H, Garcia H. Short-term harmful effects of ammonia nitrogen on activated sludge microfauna. Water Res 2005;39:4397–404. https://doi.org/10.1016/j.watres.2005.08.008.
[106] Schmidt I, Sliekers O, Schmid M, Bock E, Fuerst J, Kuenen JG, et al. New concepts of microbial treatment processes for the nitrogen removal in wastewater. FEMS Microbiol Rev 2003;27:481–92. https://doi.org/10.1016/S0168-6445(03)00039-1.
[107] Cheng J, Bergmann BA, Classen JJ, Stomp AM, Howards JW. Nutrient recovery from swine lagoon water by *Spirodela punctata*. Bioresour Technol 2002;81:81–5. https://doi.org/10.1016/S0960-8524(01)00098-0.
[108] Beebe DA, Castle JW, Rodgers Jr JH. Biogeochemical-based design for treating ammonia using constructed wetland systems. Environ Eng Sci 2014;35:396–406. https://doi.org/10.1089/ees.2014.0475.
[109] Li L, Li Y, Biswas DK, Nian Y, Jiang G. Potential of constructed wetlands in treating the eutrophic water: evidence from Taihu Lake of China. Bioresour Technol 2008;99:1656–63. https://doi.org/10.1016/j.biortech.2007.04.001.
[110] Gupta SK, Bux F, editors. Application of microalgae in wastewater treatment. Vol 2: biorefinery approaches of wastewater treatment. Springer Nature Switzerland AG; 2019. https://doi.org/10.1007/978-3-030-13909-4.
[111] Zhang E, Wang B, Wang Q, Zhang S, Zhao B. Ammonia–nitrogen and orthophosphate removal by immobilized *Scenedesmus* sp. isolated from municipal wastewater for potential use in tertiary treatment. Bioresour Technol 2008;99: 3787–93. https://doi.org/10.1016/j.biortech.2007.07.011.
[112] Singh M, Reynolds DL, Das KC. Microalgal system for treatment of effluent from poultry litter anaerobic digestion. Bioresour Technol 2011;102:10841–8. https://doi.org/10.1016/j.biortech.2011.09.037.
[113] Wang H, Xiong H, Hui Z, Zeng X. Mixotrophic cultivation of *Chlorella pyrenoidosa* with diluted primary piggery wastewater to produce lipids. Bioresour Technol 2012;103:215–20. https://doi.org/10.1016/j.biortech.2011.11.020.
[114] Munoz R, Guieysse B. Algal–bacterial processes for the treatment of hazardous contaminants: a review. Water Res 2006;40:2799–815. https://doi.org/10.1016/j.watres.2006.06.011.
[115] Project no. GEKON1/O3/213552/28/2015; acronym BiOdPal. Bioconversion of post-fermentation waste generated by biogas-producing plants: protection of waters and production of the III-rd generation fuel. Poland: National Center for Research and Development and the National Fund for Environmental Protection and Water Management; 2020.
[116] Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment. Consolidated version of 2014. Off J 1991;L 135(30):5.
[117] Jedynak P, Mungunkhuyag K, Burczyk J, Waloszek A, Kędra M, Hałat-Łaś M, et al. Effect of ammonium on growth and photosynthetic activity in selected strains of microalgae dedicated for treatment of effluents from anaerobic fermentation. N Biotechnol 2016;33:S136. https://doi.org/10.1016/j.nbt.2016.06.1194.
[118] Hałat-Łaś M, Kaszycki P, Malec P, Jedynak P, Borowski S. Microbial consortia for treatment of anaerobic sludge digester supernatants generated by a laboratory model fermentation system. N Biotechnol 2016;33:S138. https://doi.org/10.1016/j.nbt.2016.06.1201.
[119] Malec P, Jedynak P, Burczyk J, Borowski S, Kaszycki P, Waloszek A, et al. Effluents from anaerobic digestion as potential media for microalgal culture: evaluation of factors critical for photoautotrophic growth. N Biotechnol 2016;33: S140. https://doi.org/10.1016/j.nbt.2016.06.1207.