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Life Cycle Assessment of Eco-Innovative Organo-Mineral Granulated Fertilizer's Production Technology

Maria Bałazińska[*]*, Małgorzata Markowska,*
Agata Blaut, Marcin Głodniok
Central Mining Institute; Katowice, Poland
[*]*corresponding author's e-mail: mbalazinska@gig.eu*

1. Introduction

A number of legal acts, both at the level of the European Union and Polish legislation, as well as the obligations arising from international agreements impose on water and sewage treatment plants the obligation to carry out activities that minimize the negative environmental effect. The most important legal act regulating activities in sewage management is the Council Directive of 21 May 1991 concerning urban wastewater treatment 91/271/EEC (the so-called sewage directive), which aims to protect the environment against the adverse effects of municipal wastewater (EUR-Lex 1991, Rauba 2015). Tailoring actions in the field of processing and use of sewage sludge to the requirements of the Directive (EUR-Lex 1991) is one of the priority tasks in the field of sewage management for Poland (Biegańska 2010). Changes in the perception of the place and role of sewage sludge in water and sewage management began in Poland in the early 2000s, when EU pre-accession funds became available, which were then an important instrument of EU structural policy (Smuda 2014). According to Polish legislation, sewage sludge resulting from wastewater treatment processes is waste code 19 08 05 (Regulation 2014, Regulation 2020). Unlike other waste fractions, their production cannot be prevented and the increase in sewage sludge production in treatment plants is estimated at about 2% per year (Bagreev et.al. 2001). In accordance to statistical data, about 500-600 thousand tonnes of dry matter of sewage sludge is generated annually in Polish wastewater treatment plants (Statistics Poland 2019) with an upward trend.

Therefore, the importance of choosing an ecologically safe and economically and environmentally justified method of sewage sludge management increases.

In accordance to Polish Law, in activities relating to municipal sewage sludge MSS, it is necessary to follow the waste hierarchy – depending on the form in which it appears and its quality, it is required to: 1) prevent the formation of sewage sludge by (among other things) subjecting the sludge to disintegration processes, deep stabilization, hygienization and dehydration or other measures to enable it to lose its waste status; 2) recycle MSS – by organic recycling and mineral recycling with recovery of phosphorus; 3) use MSS recovery methods (including recovery in composting plants, biogas plants or cement kilns), including energy recovery; 4) dispose MSS – sludge in this process may be incinerated in waste incineration plants or waste co-incineration plants, without energy recovery, or landfilled, after treatment, if it meets the requirements specified by law (National Waste Management Plan 2016), which make it practically impossible to store sewage sludge without prior treatment.

Also statistical data about different methods of MSS management confirm that the amount (and percentage) of landfilled sludge has significantly decreased in the last 10 years, while thermal processing and use in agriculture have an upward trend (Fig. 1).

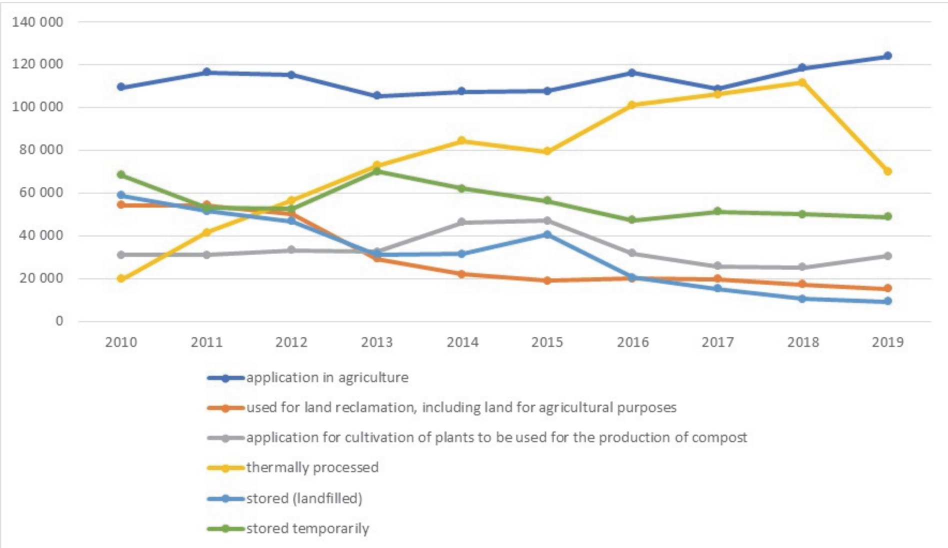

Fig. 1. Management of MSS by different methods in the years 2010-2019 in Poland; Source: own elaboration, based on data from Statistics Poland

Although methods based on incineration and co-incineration are effective and condition a significant reduction in the volume of sewage sludge, its by-product are ashes which can be characterized by a high content of heavy metals

(Wójcik & Masłoń 2019). The presence of heavy metals, as well as other physical and chemical properties largely determine the possibilities and subsequently the choice of an appropriate and effective method of sewage sludge processing and disposal (Act 2007, Regulation 2009, Gawdzik 2013), especially its application in agriculture.

For sludge where the heavy metal content in mg/kg of dry matter of the sludge is no more than the permissible amount (Regulation 2015), their agricultural use is recommended (Kulikowski et.al. 2019).

The need to look for new methods of sludge utilization has led to the development of research in the field of sludge management, which has recently led to municipal sewage sludge being increasingly seen as a raw material or resource, not just waste (Masłoń 2015, Naukawpolsce 2017). Due to the content of protein in its composition, sewage sludge can be used in the production of chelate fertilizers containing trace metals (Liu et. al. 2009). At the same time, the specific characteristics of sludge, in particular the presence of harmful substances and pathogenic organisms, determine the need for an appropriate selection of the method of its management, which will ensure the maximization of the use of valuable components contained in it while minimizing harmful effects on the environment (Wójcik & Masłoń 2019). From the point of view of the circulation of organic matter in nature, enabling the return of sewage sludge to the environment after processing is very valuable. Therefore, developing and implementing more and more modern and eco-innovative solutions for its processing and disposal is necessary.

Eco-innovative solutions (or also eco-innovations) is a term used to describe all forms of innovative activities that contribute to environmental protection, especially those aimed at preventing or reducing adverse environmental impacts and misuse of natural resources (Rennings 2000, European Commission 2007, European Commission 2011). Despite the fact that eco-innovations became the subject of research already in the 1970s, and the term eco-innovations became common in the late 1990s (Jasiński 1997, Bartoszczuk 2016), there are still ongoing discussions in the literature regarding the full definition of this phenomenon and strict criteria explaining its essence (e.g. Rennings 2000, Reid & Miedzinski 2008, Oslo Manual 2008, Kemp & Pearson 2008, Woźniak et al. 2008, Cheng & Shiu 2012, Peng & Liu 2016). There is also a lack of agreement in the scientific literature on whether environmental benefits can be an additional effect of the implemented innovative solution (Carillo-Hermosilla et al. 2010, Urbaniec 2015) or whether they must be the main goal of implementing ecological innovations (Little 2005), as it is the case with the optimization of organic-mineral granular fertilizer.

The implementation of eco-innovation in agriculture is favoured by the European Union's environmentally friendly policy contained in the Europe 2020 strategy, which is based on the premise of intelligent development, based on knowledge and innovation, but also sustainable, consisting in supporting an economy that uses resources efficiently and a more environmentally friendly (Europe 2020, 2010). Since the priority research directions currently carried out in the European Union and in the world are both food security and rational management of natural resources, as well as counteracting climate change, the importance of eco-innovation in the food economy and in the broadly understood agriculture is constantly increasing (Dziedzic &Woźniak 2013).

The paper presents an eco-innovative technological solution for the production of organic-mineral granular fertilizer and its environmental assessment. The scientific aim of the research was to determine the environmental impact of manufactured fertilizer products in the developed technology. The practical aim of the research focused on comparison and selection of the most environmentally friendly fertiliser product.

2. Technology

Organo-mineral granulated fertilizer developed by Central Mining Institute is a mixture of municipal dewatered sewage sludge collected from municipal waste water treatment plant, complying with Polish law requirement, dolomite (50% $CaCO_3$ and 40% $MgCO_3$) provided by JSKM Zielona Góra, lime (96% CaO) from Lhoist, gypsum, ammonium carbonate and microcrystalline cellulose from Rettenmeier–Arbocel. Sewage sludge for fertilizer production contained heavy metals at levels less than: chromium (Cr) 100 mg/kg, cadmium (Cd) 5 mg/kg, nickel (Ni) 60 mg/kg, lead (Pb) 140 mg/kg and mercury (Hg) 2 mg/kg, so well within amount permissible for application in agriculture and for land reclamation for agricultural purposes by Polish Law (Regulation 2015). They were also free from live eggs of intestinal parasites *Ascaria sp. Trichuris sp.*, *Toxacara sp.* bacteria of the genus *Salmonella*. Sewage sludge after dewatering in centrifuges contained 19-20% of dry mass. The final product was in the form of irregular shape non-dusting granulate with diameter 1-6 mm.

Granulation of materials is one of the most significant unit operations applied in many manufacturing processes. It means of forming of grains or granules from a powdery or solid substance of appropriate physicochemical properties, shape and dimensions. The most important advantages of the former include suppression of dusting, avoidance of caking, better behaviour during transport or prevention of segregation in multicomponent materials (Heim 2012). The technology of granulating was applied to produce granular organic fertilizers from dewatered sewage sludge and a few chemicals.

The application for the method was covered by patent protection by the Polish Patent Office as an invention (Głodniok et al. 2017). The planned process of production of the granulate is presented in block scheme at Fig. 2.

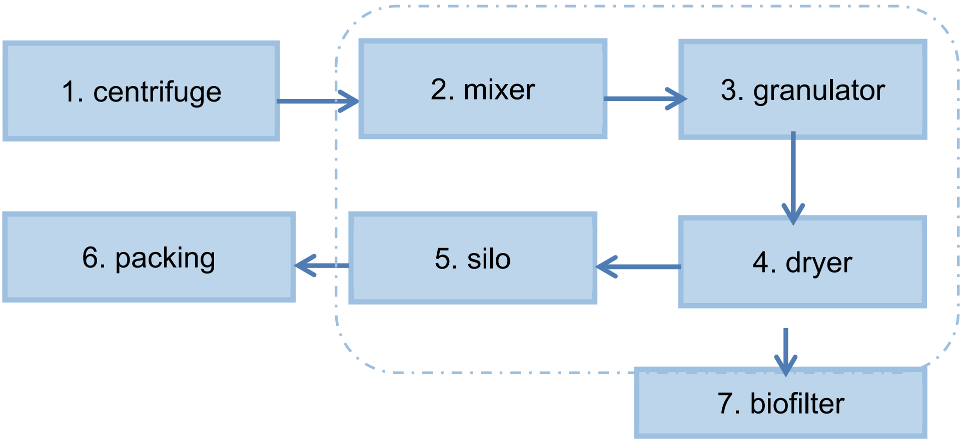

Fig. 2. Block scheme of granulated fertilizer production; Source: own elaboration

Fermented and mechanically dewatered, with a filter press or a centrifuge (1), sewage sludge is gravitationally fed onto a belt conveyor, which transports it to the mixer (2). At the same time, screw conveyors transport proper doses of other components of the granulate: lime, microcrystalline cellulose and dolomite from three separate silos directly to the same mixer. The components are transported to the silos pneumatically from road tankers equipped with compressors.

When the components are mixed in the mixer, a chemical reaction between sewage sludge and lime occurs. From the mixer the product is gravitationally fed into the granulator (3). After granulating, the produced granules of dry matter content of approximately 40-45% are transported to the dryer (4), where, at the temperature 50-80°C they are desiccated until they reach dry matter content of approximately 75-80%. As a result of the reaction, large quantity of ammonia is released, which, together with odours, is exhausted to the biofilter (7). The granules, after desiccation in the dryer, are taken to the silo (5) to cool them before bagger packaging (6). After packaging the fertilizer is stored.

3. Method

The assessment of eco-innovative fertilizer production technology was carried out using the Life Cycle Assessment (LCA) technique, which is the most acceptable method for assessing environmental impact due to the holistic approach, although its complexity is a certain limitation (Kleiber 2011, Heijungs & Guinée, 2012). This technique is known and appreciated by scientific centres around the world (Burchart-Korol et al. 2017a, Burchart-Korol et al. 2017b, Hollberg et al. 2020, Jullien et al. 2019, Morales et al. 2019, Khoo et al. 2019, Zhang et al. 2019, Chen et al. 2019, Fiala et al. 2020, Dal Pozzo et al. 2019, Guinee (Ed.) 2002, Curran (Ed.) 2012, Warshay et al. 2017, Di Maria et al. 2018, Velandia Vargas et al. 2019, Croft et al. 2018). It is also promoted for use by political centres (Federal LCA Commons 2019, EPA 2019, Recommendation 2013/179/EU). The LCA method is a valuable environmental impact assessment tool also applicable in the field of wastewater treatment (Guest et al. 2009, EPA, 2014, Machado et al. 2007, Mouri et al. 2013, Garrido-Baserba et al. 2014, Pintilie et al. 2016, Zawartka 2016).

The LCA collects data and assesses its environmental impact for the analysed product system. The product system is the whole of processes that describe the subject of the study. The quantitative effect of the product system is the so-called functional unit (FU), which is the reference unit in the analysis. According to the methodology (EN ISO 14040: 2006, EN ISO 14044: 2006) LCA analysis is carried out within four stages:

1. Determining the purpose and scope of research,
2. Inventory analysis (Life Cycle Inventory – LCI),
3. Impact Assessment (Life Cycle Impact Assessment – LCIA),
4. Interpretation.

Determining the purpose and scope clearly defines the subject of the study, indicating the product system, its boundaries, as well as the functional unit. LCI collects input and output data describing the product system. Within this stage, calculations are also performed to determine them. Impact Assessment transforms the results of the LCI stage into a unit of impact categories under consideration. Impact categories are selected environmental problems considered in the analysis. The LCIA stage is the heart of the LCA analysis, as it allows us to determine to what extent the product system affects a specific environmental problem. In practice, by entering the LCIA stage, the appropriate method is chosen that guides the user through this stage. On the other hand, conclusions, restrictions and recommendations are formulated as part of the interpretation stage.

The subject analysis was carried out as a comparative analysis, for which, according to the guidelines, system boundaries as well as the functional unit are required to match each other. As part of the research, four cases of mineral-organic fertilizer production technology were compared, which were developed at the Central Mining Institute at the Department of Water Protection. The analysis aims to indicate which technological variant is the most environmentally friendly so that it could be developed in the future and eventually introduced to the fertilizer market. Environmentally friendly should be understood as having the least negative impact on the environment. 1 Mg of fertilizer product was selected as the functional unit.

Material and Energy Flow Analysis – MEFA was used to carry out the LCI stage. MEFA allows establishing an inventory for LCA (Korol et al. 2016, Burchart-Korol et al. 2013, Golak et al. 2011). MEFA collates the flow of materials as well as energy for the analysed system, thus helping to achieve high levels of efficiency. Sankey diagrams are often used to illustrate MEFA. The arrow thickness indicates the size of the material/energy flow. This allows locating particularly large streams, which in turn allows system modification and reduction of energy and materials consumption, and, consequently, also reduction of pollutant emissions (Korol et al. 2016). The MEFA performed for the purposes of this analysis was carried out in the Umberto NXT Universal program.

The method used during the Impact Assessment stage was the ReCiPe 2016 method, both ReCiPe Midpoint and Endpoint (Huijbregts et al. 2016). This method allows the assessment of the environmental impact of the analysed product systems within 18 impact categories, which are then grouped into three damage categories to finally express the overall environmental burden in the form of the so-called ecopoints (Pt). One ecopoint, in turn, expresses the thousandth part of the damage caused by one inhabitant of Europe during a year (Huijbregts et al. 2016, RIVM 2018).

4. Results and discussion

The MEFA analysis was carried out for four alternative solutions for the production of organic and mineral fertilizers. The flow of materials and energy for each of the options is shown in Fig. 3 and Fig. 4. For each production process, the process substrates are located on the left, and the resulting products on the right. This collation also constitutes the results of the LCI stage as input data for the life cycle impact assessment (LCIA).

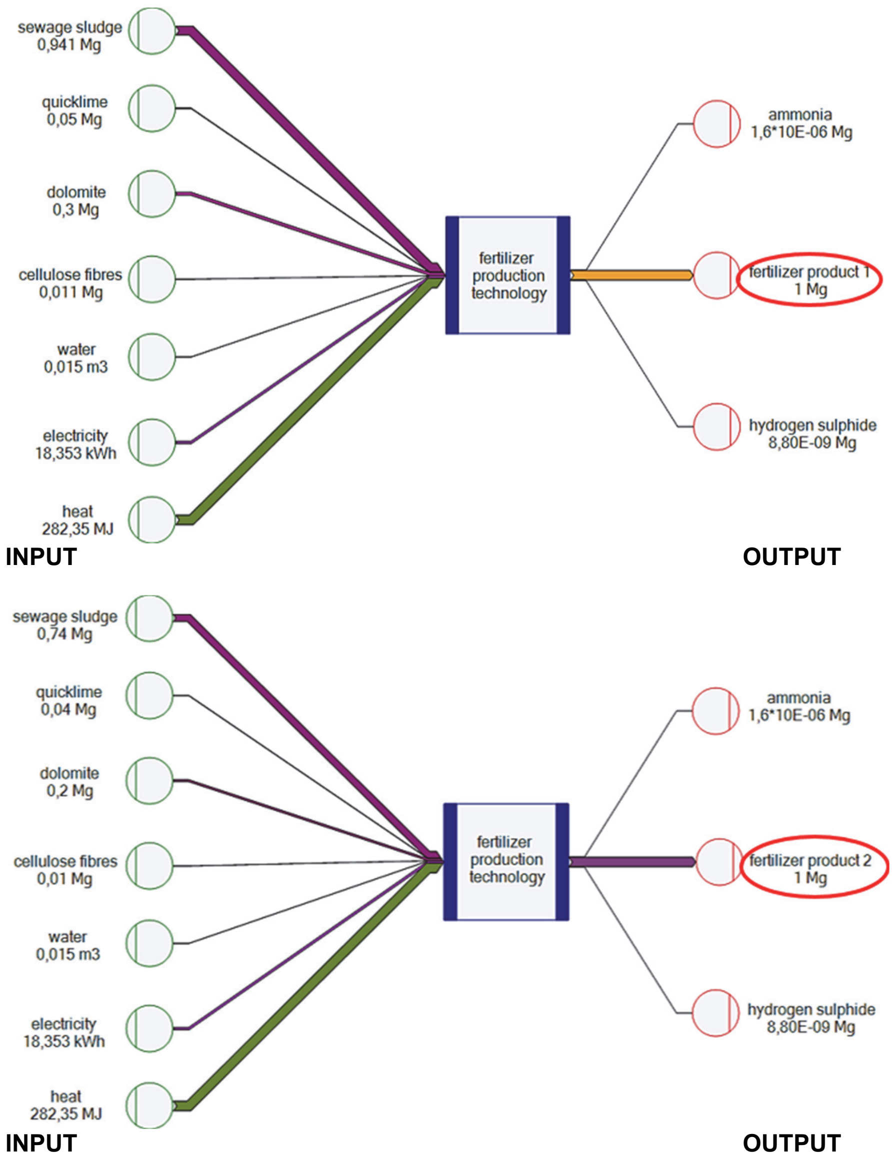

Fig. 3. Material and Energy Flow Analysis (MEFA) of production technology of fertilizer no. 1-2; Source: own elaboration in Umberto NXT Universal

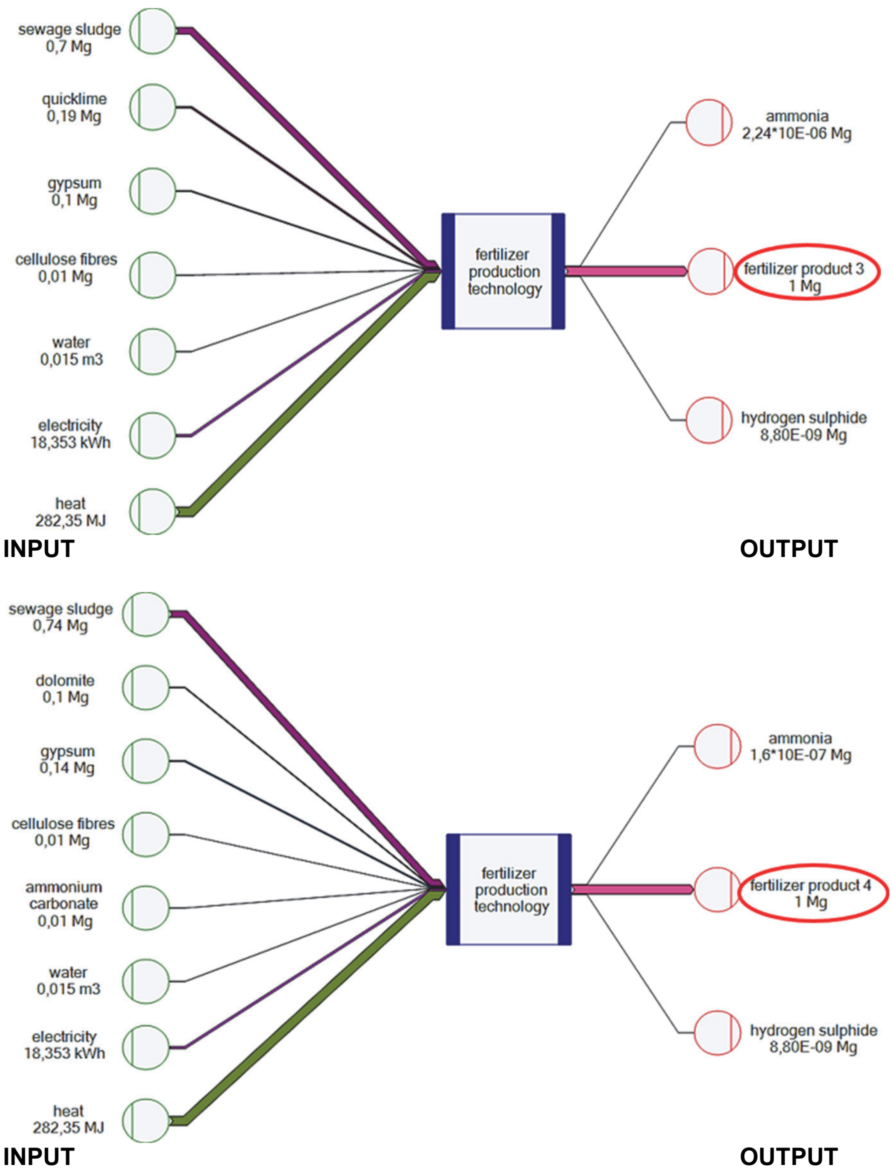

Fig. 4. Material and Energy Flow Analysis (MEFA) of production technology of fertilizer no. 3-4; Source: own elaboration in Umberto NXT Universal

Each of the fertilizer production options considered has the largest mass and energy flow for the sewage sludge used and for heat consumption for the drying process. For each of the analysed alternatives, the amount of heat used is the same. Consequently, there is no less environmental burden resulting from heat consumption for any production technology. In the case of sewage sludge, the thicker arrow in Fig. 3 and Fig.4 means a more environmentally friendly solution, which results from the fact that the sludge is waste which in this system finds useful management. This premise is part of the concepts of the circular economy promoted by the European Union (Circular Economy 2019). According to it, whenever possible, waste should be recycled to minimize the extraction of raw materials from the environment. Therefore, comparing the analysed solutions of the fertilizer production process, the most advantageous option in the field of effective use of sewage sludge is proposal No. 1.

Turning to an actual assessment of the environmental effects of fertilizer production technology presenting the impact on subsequent environmental problems, the results obtained are summarized in Tables 1 and Fig 5-9.

In terms of impact on global warming, the production of fertilizer product No. 4 is the most environmentally friendly. This product is also beneficial in the case of terrestrial acidification or fossil resource scarcity. In the case of marine eutrophication, freshwater and marine ecotoxicity, human non-carcinogenic toxicity, mineral resource scarcity, as well as water consumption, it shows the greatest environmental burden. In turn, the most beneficial fertilizer with regard to the impact on marine eutrophisation is product No. 1. This fertilizer, in turn, generates the largest environmental effect in relation to ionizing radiation, freshwater eutrophisation, or land use. The most environmentally friendly fertilizer in the field of fine particular matter formation, freshwater and marine eutrophication, terrestrial, freshwater as well as marine ecotoxicity, human cancerogenic and non-cancerogenic toxicity, land use and mineral resource scarcity is fertilizer product No. 2. For the largest number of categories, the product Fertilizer No. 3 has the most adverse effect. These categories are: global warming, stratospheric ozone depletion, ozone formation (in terms of impact on both human health and terrestrial ecosystems), fine particular matter formation, terrestrial acidification, terrestrial ecotoxicity, human carcinogenic toxicity and fossil resource scarcity.

Table 1. Impact category indices for fertilizer production technology per functional unit ($kg_{fertilizer\ product}$) – characterization stage according to ReCiPe 2016 Midpoint H/H

Impact category	Unit	Product no.1	Product no.2	Product no.3	Product no.4
Global warming	kg CO_{2eq}	1,16E-01	9,90E-02	2,69E-01	6,38E-02
Stratospheric ozone depletion	kg $CFC11_{eq}$	2,70E-08	2,29E-08	4,18E-08	2,17E-08
Ionizing radiation	kBq $Co\text{-}60_{eq}$	6,15E-02	5,56E-02	5,63E-02	5,64E-02
Ozone formation, Human health	kg NO_{Xeq}	1,67E-04	1,40E-04	2,29E-04	1,25E-04
Fine particulate matter formation	kg $PM2.5_{eq}$	1,10E-04	9,36E-05	1,49E-04	9,77E-05
Ozone formation, Terrestrial ecosystems	kg NO_{Xeq}	1,70E-04	1,43E-04	2,34E-04	1,27E-04
Terrestrial acidification	kg SO_{2eq}	2,74E-04	2,39E-04	3,70E-04	2,35E-04
Freshwater eutrophication	kg P_{eq}	3,71E-05	3,45E-05	3,59E-05	3,63E-05
Marine eutrophication	kg N_{eq}	3,32E-06	3,06E-06	3,19E-06	2,51E-05
Terrestrial ecotoxicity	kg 1,4-DCB	2,26E-01	1,88E-01	4,50E-01	2,02E-01
Freshwater ecotoxicity	kg 1,4-DCB	1,94E-03	1,75E-03	1,85E-03	2,04E-03
Marine ecotoxicity	kg 1,4-DCB	2,79E-03	2,51E-03	2,83E-03	2,90E-03
Human carcinogenic toxicity	kg 1,4-DCB	2,87E-03	2,59E-03	2,91E-03	2,70E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	5,52E-02	4,97E-02	5,51E-02	5,90E-02
Land use	m^2a $crop_{eq}$	6,47E-03	5,86E-03	5,88E-03	5,99E-03
Mineral resource scarcity	kg Cu_{eq}	3,78E-04	3,39E-04	6,35E-04	7,78E-04
Fossil resource scarcity	kg oil_{eq}	2,31E-02	2,06E-02	3,77E-02	2,00E-02
Water consumption	m^3	5,41E-03	5,14E-03	5,25E-03	5,44E-03

(Units: kg CO_{2eq} – kilograms of carbon dioxide equivalents, kg CFC-11_{eq} – kilograms of trichlorofluoromethane equivalents, kg $Co\text{-}60_{eq}$ – kilograms of cobalt-60 equivalents, kg NO_{Xeq} – kilograms of oxides of nitrogen equivalents, kg $PM2.5_{eq}$ – kilograms of particulate matter 2.5 micrometer equivalents, kg SO_{2eq} – kilograms of sulfur dioxide equivalents, kg P_{eq} – kilograms of phosphorus equivalents, kg N_{eq},– kilograms of nitrogen equivalents, kg 1,4-DCB – kilograms of 1,4 dichlorobenzene equivalents, m^2a $crop_{eq}$ – square meters x years of agricultural land use equivalents, kg Cu_{eq} – kilograms of copper equivalents, kg oil_{eq} – kilograms of oil equivalents, m^3 – cubic meters of freshwater)

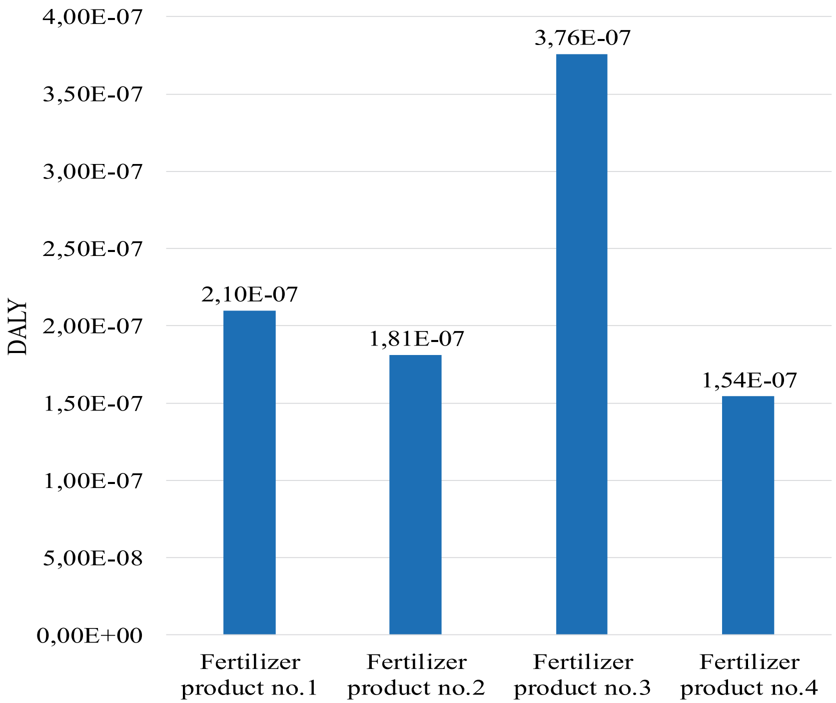

Fig. 5. Human health category indices for fertilizer production technology per functional unit ($kg_{fertilizer\ product}$) – characterization stage according to ReCiPe 2016 Endpoint H/A (Unit: DALY express the sum of shortened years of human life and years of reduced quality as a result of disability)

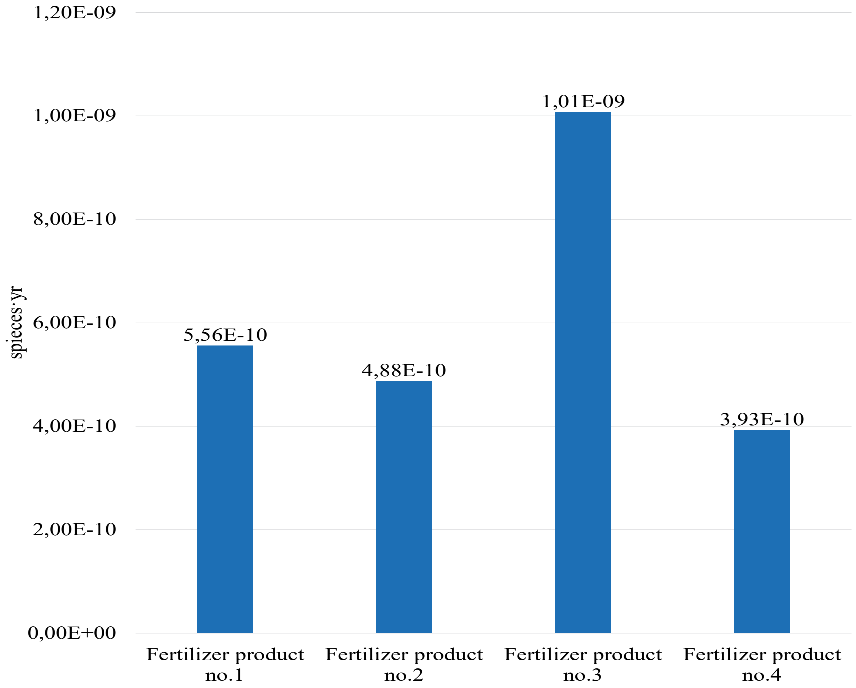

Fig. 6. Ecosystems category indices for fertilizer production technology per functional unit ($kg_{fertilizer\ product}$) – characterization stage according to ReCiPe 2016 Endpoint H/A (Unit: species•yr express loss of species throughout the year)

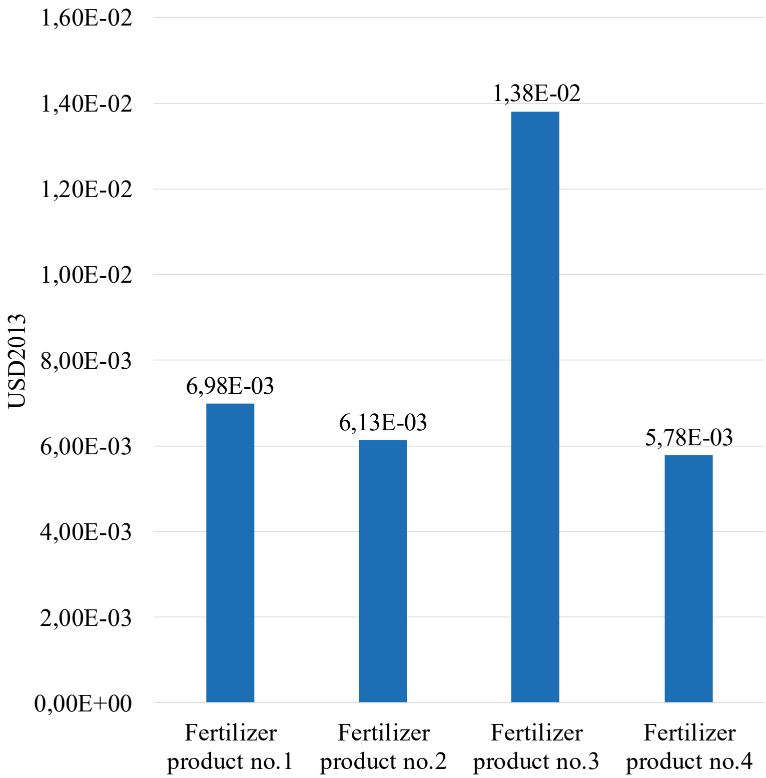

Fig. 7. Resources category indices for fertilizer production technology per functional unit ($kg_{fertilizer\ product}$) – characterization stage according to ReCiPe 2016 Endpoint H/A (Unit: USD2013 – dollars understood as an increase in costs as a result of the need to obtain raw materials from hard-to-reach deposits as a result of using resources from readily available deposits)

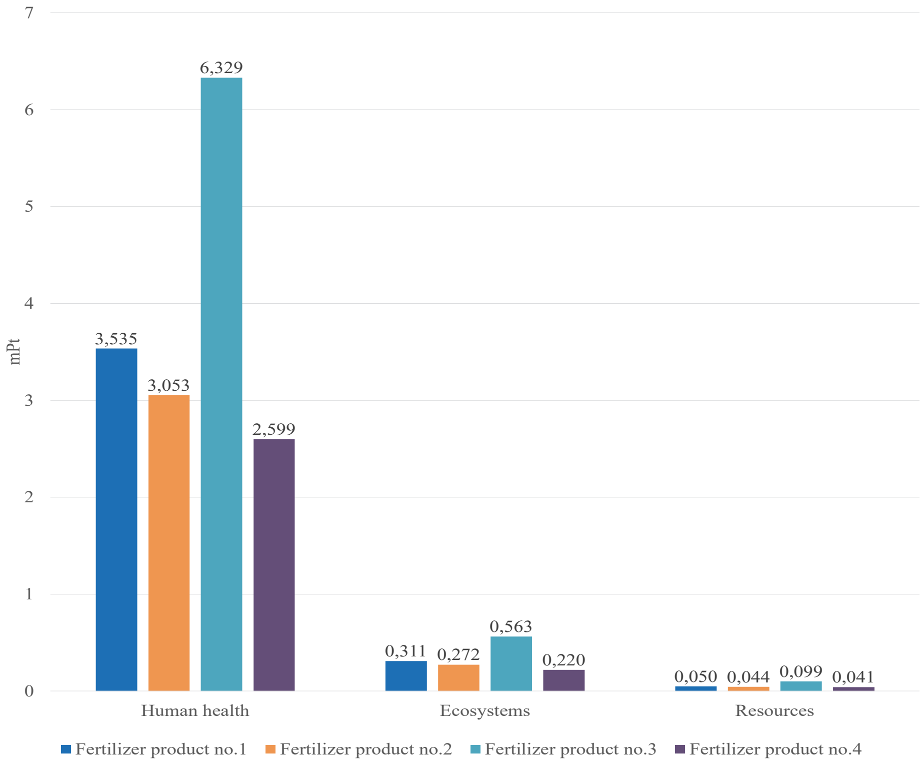

Fig. 8. Damage category indices for fertilizer production technology per functional unit ($kg_{fertizer\ product}$) – weighing stage according to ReCiPe 2016 Endpoint H/A (Unit: mPt – miliekopoint understood as a millionth of the annual environmental damage caused by one inhabitant)

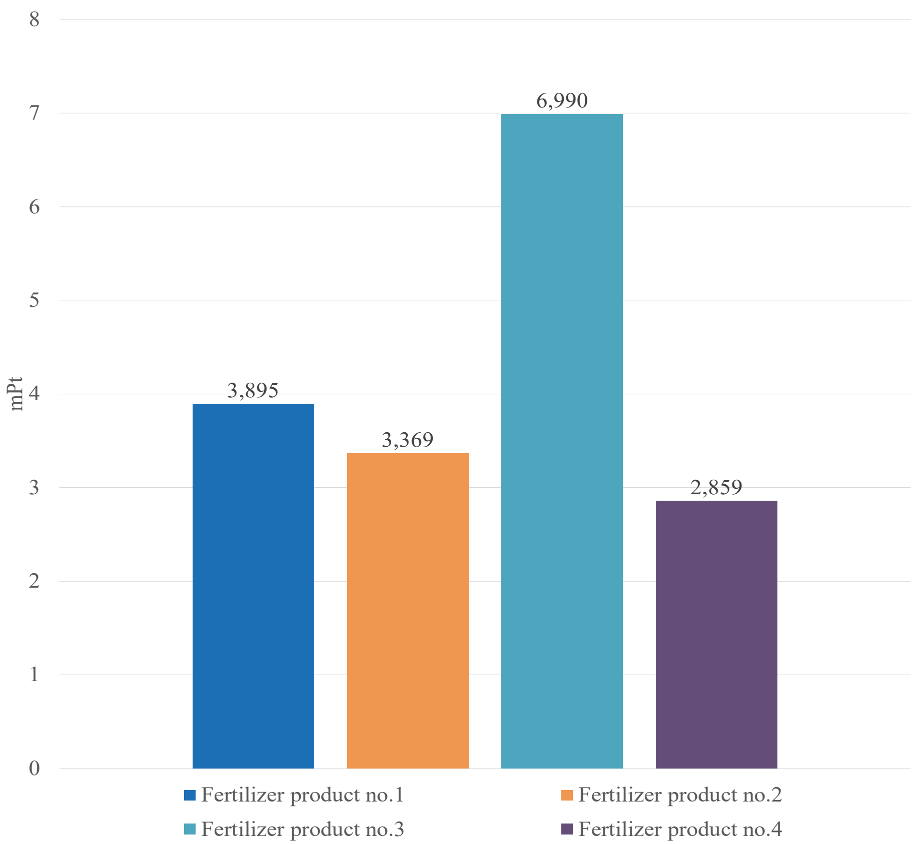

Fig. 9. Total environmental burden for fertilizer production technology per functional unit ($kg_{fertizer\ product}$) – weighing stage according to ReCiPe 2016 Endpoint H/A (Unit: mPt – miliekopoint understood as a millionth of the annual environmental damage caused by one inhabitant)

In the next step, the impact categories were grouped into three damage categories, i.e. human health, ecosystems and resources. Impact category units were converted into general damage category units and then added up. As a result, fertilizer product No. 3 proved to be the most adverse solution in terms of impact on both human health, ecosystems and resources. In turn, the most advantageous solution turned out to be fertilizer product No. 4, which showed the lowest environmental load for each category of damage analysed. After converting the damage category units into ecopoints, the indicator values within each product were summarized to obtain the total load attributed to the specific fertilizer. Product no. 4 was the most environmentally friendly fertilizer, with a total environmental load of 2.859 $mPt/kg_{fretilizer\ product}$. This value is almost two and a half times lower than the value attributed to fertilizer product No. 3, which turned out to be the most environmentally friendly fertilizer. Its total environmental effect was as much as 6.990 $mPt/kg_{fretilizer\ product}$.

With a view to comparing the results obtained with scientific literature data characterizing the fertilizers available on the market, a literature review was carried out. In order for the results of the research presented in this paper to be compared to the results of analyses carried out for other fertilizer products, it is necessary that the assumptions are consistent. The same functional unit, system boundaries and LCIA method are required. Detailed guidelines in this respect are included in EN ISO 14044 (2006). Among the publications, it is problematic to find items presenting the environmental effects of fertilizer products that collectively meet the listed requirements. It is also recommended that the fertilizer be of the same type, and therefore mineral-organic.

J. Lammel (2000) focused his research on mineral fertilizers (urea and ammonium nitrate fertilizers). He led the system boundaries in such a way that it covered both the production process and the use of products. 1 Mg of nitrogen was selected as the functional unit. Consequently, the different functional unit included in the presented paper and in (Lammel 2000) makes it impossible to compare the results. In addition, a fertilizer that is of a different type than the product presented in this paper is analysed.

R. Charles et al. (2006) analysed the wheat production system for bread production, taking into account emissions from fields, but also the production and transport of fertilizers. In this study the intensity of nitrogen, phosphorus and potassium fertilization was optimized using LCA analysis. 1 ha of land, 1 Mg of wheat produced and 1 Mg of wheat containing 13% protein was selected as the functional unit. Various assumptions adopted by the authors in relation to this paper also in this case result in the inability to compare the results.

In turn, T. Nemecek (2011) assessed the impact of agriculture using fertilizers on the natural environment. The system boundaries included both the production process and the use of fertilizers. The functional unit stood for 1 kg of dry matter of cultivated product per 1 ha of land within one year. As a result, a different functional unit makes it impossible to compare the test results with the subject analysis.

However, in the case of Quirós et al. (2015), the impact on the environment of fertilizers was studied, for which the system boundaries included the stage of production, transport to their place of application and cultivation of plants on fertilized land. ReCiPe was chosen as the method for the LCIA stage. Therefore, if the results were presented as unit processes, i.e. listing the environmental effects for the production stage and assuming that the functional unit would correspond to the size selected for analysis presented in this paper, it would be possible to compare the results. Unfortunately, the results of the analysis were not presented as unit processes by the authors. In addition, the functional unit accepted for analysis in the publication is 1 m^2 of fertilized soil. Therefore, it is also a unit different from 1 kg of fertilizer product, the unit which was selected for the purpose of conducting the analysis presented in this paper. Therefore, it is not possible to compare the results to the results of the research presented in (Quirós et al. 2015).

Another publication presenting the results of LCA analyses for fertilizers is Vera-Acevedo et al. 2016. Unfortunately, the assumptions adopted for analysis in that paper also prevent comparison of the test results. In Vera-Acevedo et al. 2016, 1 kg of coffee crops grown on soil fertilized with the analysed fertilizer product was selected as a functional unit. On the other hand, the system boundaries do not take into account the environmental effects associated with growing vegetation in fertilized areas in that paper, which excludes the possibility of compiling results.

In the case of Chen et al. (2018), life cycle assessment of potash fertilizer production in China is presented. The authors selected 1 Mg K_2O production (1.67 KCl fertilizer with a K_2O content of 60.03%) as the functional unit, and the system boundaries covered only the fertilizer production stage. ReCiPe 2008 was used as the method of assessing the life cycle impact on the environment. Therefore, in terms of the direct requirements listed in EN ISO 14044 regarding the possibility of comparing the results of LCA analyses, they are met. Solely different versions of the ReCiPe method used in the calculations may raise doubts (Chen et al. 2018 – ReCiPe 2008, this work – ReCiPe 2016). Both versions, though one older and the other newer, are based on the same principles. The differences are associated with impact categories which do not always overlap or units assigned to them. It is therefore possible to combine results, but to a limited extent. The problem, however, may be the fact that the subject of the study is potassium fertilizer, which does not belong to the group of mineral-organic fertilizers. Therefore, its composition, and thus the environmental effect associated with obtaining other fertilizer components will differ from the one analysed in this paper. For illustrative purposes, however, Table 2 summarizes the results.

In the case of the global warming fertilizer category, product No.3 significantly exceeds the range of values corresponding to the fertilizer described by W. Chen et al. (2018). Product No.4 assumed a value below the range, while fertilizers No.1 and 2 fitted in with the area defined in the literature. Regarding stratospheric ozone depletion and fine particular matter formation, each of the fertilizer products analysed in this paper has a greater negative impact in relation to potassium fertilizer. For terrestrial acidification and marine eutrophication, only product No. 3 exceeds the range of values specified in Chen et al. (2018). The other values correspond to the data area assigned to the potassium fertilizer. In the case of fossil resource scarcity, the range specified by W. Chen et al. (2018) is exceeded by fertilizers No.1 and 3. On the other hand, for water consumption, all data characterizing the analysed fertilizer products fall into the range of values corresponding to potassium fertilizer.

As it has already been mentioned, due to the different types of compared fertilizers, the presented statement is for reference only and cannot be the basis for taking specific environmental decisions.

Table 2. Summary of LCA analysis results for the production stage of fertilizer No. 4 for potassium fertilizer, according to Chen et al. 2018

Impact category	Unit	Fertilizer product no.1	Fertilizer product no.2	Fertilizer product no.3	Fertilizer product no.4	Range of values according to Chen et al.2018 after conversion into the functional unit taken into account in this application (FU=1 kg of fertiliser)	
						min	max
Global warming	kg CO2 eq	1,16E-01	9,90E-02	2,69E-01	6,38E-02	8,44E-02	1,53E-01
Stratospheric ozone depletion	kg CFC11 eq	2,70E-08	2,29E-08	4,18E-08	2,17E-08	2,03E-11	7,78E-11
Fine particulate matter formation	kg PM2.5 eq	1,10E-04	9,36E-05	1,49E-04	9,77E-05	2,19E-05	4,86E-05
Terrestrial acidification	kg SO2 eq	2,74E-04	2,39E-04	3,70E-04	2,35E-04	1,29E-04	2,43E-04
Marine eutrophication	kg N eq	3,32E-06	3,06E-06	3,19E-06	2,51E-05	2,21E-06	5,97E-06
Fossil resource scarcity	kg oil eq	2,31E-02	2,06E-02	3,77E-02	2,00E-02	1,11E-02	2,13E-02
Water consumption	m3	5,41E-03	5,14E-03	5,25E-03	5,44E-03	3,99E-03	5,94E-03

5. Conclusions

After converting the results of the analyses into the same unit (mPt), it was observed that for each damage category, the environmental burden of fertiliser product 4 is the lowest compared to other products. Consequently, the total environmental load of product 4 is also the lowest, and this results in fertilizer No. 4 is the most environmentally friendly among the products considered. This product is also consistent with the definition of eco-innovation adopted by the European Commission as 'innovations aimed at significant and visible progress towards achieving the goal of sustainable development, by limiting the impact on the environment or achieving greater efficiency and responsible use of natural resources, including energy'(European Commission 2007). In this fertilizer, the addition of quicklime was completely abandoned and replaced with gypsum, and as a result the greenhouse effect was significantly reduced. The use of ammonium carbonate in product No. 4 significantly increased its fertilizing properties in terms of nitrogen content. However, this significantly affected the increase in the impact on eutrophication, which is an unfavourable phenomenon for the environment. The addition of ammonium carbonate increased the requirement for easily absorbable nitrogen to the environment. Considering the collected test results, it can be concluded that the most environmentally beneficial product should contain sewage sludge, cellulose, dolomite flour and gypsum. The direction of further product optimization may be the abandonment of dolomite flour due to the fact that grinding dolomite rock is an energy-intensive process that also has a negative impact on the environment.

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Abstract

This paper presents the possibilities of waste management originating from municipal wastewater treatment through the production of mineral-organic fertilizers based on sewage sludge. The original method created for this purpose was used in the study together with the environmental assessment of this method. Therefore, the purpose of this publication is twofold. On the one hand, the first goal of the paper is to draw attention to the need to choose the appropriate method of utilization of sewage sludge, taking into account its characteristics and potentially harmful effects on the environment. The second goal of the paper is to assess the environmental impact of the selected method and demonstrate its eco-innovation.

The first part of the paper is a theoretical introduction to the issues of sewage sludge management, as well as theoretical considerations on the essence of eco-innovation. The second part of the paper presents practical issues of production and application of the organo-mineral granulated fertilizer subjected to research, while the third part – the methodology of the applied Life Cycle Analysis (LCA), including in particular the application of Material and Energy Flow Analysis (MEFA) at the Life Cycle Inventory stage. The fourth section presents the assumptions and results of the conducted research for four alternative solutions for the production of organic-mineral fertilizers. The fifth and final part summarizes the results and contains a number of conclusions and recommendations that should be considered in the context of the possibilities of further product optimization.

Keywords:
organic-mineral fertilizer, sewage sludge, Life Cycle Assessment (LCA), eco-innovation, granulate

Ocena cyklu życia eko-innowacyjnej technologii produkcji nawozu mineralno-organicznego

Streszczenie

W niniejszym artykule przedstawiono możliwości użytkowego wykorzystania odpadów z oczyszczania ścieków komunalnych, poprzez wytwarzanie nawozów mineralno-organicznych na bazie osadów ściekowych autorską metodą oraz ocenę środowiskową tej metody. Tak więc, cel niniejszej publikacji jest dwojaki. Z jednej strony, pierwszym celem artykułu jest zwrócenie uwagi na konieczność doboru odpowiedniej metody utylizacji osadów ściekowych z uwzględnieniem ich charakterystyki oraz potencjalnie szkodliwego oddziaływania na środowisko. Drugim celem artykuły jest ocena wpływu środowiskowego wybranej metody, celem wykazanie jej eko-innowacyjności.

Pierwsza część pracy stanowi wprowadzenie teoretyczne do problematyki zagospodarowania osadów ściekowych, jak również teoretyczne rozważania nad istotą eko-innowacyjności. Druga część pracy przedstawia praktyczne zagadnienia produkcji i zastosowania organo-mineral granulated fertilizer poddanego badaniom, podczas gdy trzecia – metodykę zastosowanej analizy cyklu życia LCA, w tym szczególnie zastosowania analizy Material and Energy Flow Analysis (MEFA) na etapie Life Cycle Inventory. Czwarta sekcja przedstawia założenia i wyniki prowadzonego badania dla czterech alternatywnych rozwiązań technologii produkcji nawozów organiczno-mineralnych. Część piąta i ostatnia podsumowuje wyniki i zawiera szereg wniosków i zaleceń, które należy rozważyć w kontekście możliwości dalszej optymalizacji produktu.

Słowa kluczowe:
nawóz mineralno-organiczny, osady ściekowe, ocena cyklu życia, eko-innowacje, granulat