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An analysis of the fertilizing potential of selected waste streams – municipal, industrial and agricultural

Introduction

At present, the European Commission (EC) strongly underlines the need to move from the liner economic model to a circular economy (CE) model, in which raw materials are used in the economy as much as possible, and waste is treated as a secondary raw material (Michelini et al. 2017). The CE was officially adopted as the European economic model in 2014, when the first communication on the CE was announced "Towards a Circular Economy: A Zero Waste Program for Europe" (COM no. 398, 2014). It indicated that the change of the system could allow for the reuse of waste and create a new value. However, this would include changes throughout the whole value chain, based on the waste hierarchy that favors waste prevention and discourages waste disposal. The second important document related to the CE was the CE Action Plan, entitled "Closing the loop – An EU action plan for the Circular Economy" (COM no. 614, 2015). It defined a specific set of actions for the transition

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to the CE model, indicating 54 types of activities, and proposed some changes regarding waste management. Subsequently, in 2018, the EC proposed CE monitoring framework (COM no. 29, 2018), which indicated 10 CE indicators divided into 4 groups: production and consumption, waste management, secondary raw materials, competitiveness and innovation. These indicators are subject to constant revision and expansion and are available on the Eurostat website. At present, the new CE Action Plan is in force, as in 2020 the EC presented further communication on the CE implementation in the European Union (EU) entitled "A New Circular Economy Action Plan for a Cleaner and More Competitive Europe" (COM no. 98, 2020). It was clearly stated that the transformation to the CE model should be accelerated, due to the fact that the consumption of materials is expected to double, which could affect an increase in the amount of generated waste per year by 70% by 2050.

The key objective of the transformation to the CE model in EU economy is to achieve resource sustainability (Hobson and Lynch 2016). To enable the transformation from to the CE model, the focus is dedicated to entire product life cycle, from design through production, consumption, waste generation and management (Bianchini et al. 2019). The implementation of sustainable practices of raw materials management (including primary and secondary sources) should reduce the EU's dependence on the import of resources from outside Europe, increase its competitiveness in the market and improve the efficiency of the rational use of resources (European Commission 2018). However, for the transformation process to be effective, all the actors of the economy must be involved in the systematic implementation of changes (Kalmykova et al. 2018) and eco-innovations (Urbaniec 2015). This also applies to the fertilizer sector, which is responsible for providing nutrients for proper farming and thus ensuring a satisfactory amount of food for the society. The fertilizer sector shows many possibilities to actively participate in the transformation toward the CE model through the more sustainable use of fertilizers coming from primary sources and fertilization methods, and use of nutrient-rich waste as substitutes for commercial fertilizers (Smol 2021). In the entire EU, about 2.5 billion Mg of waste is generated (Eurostat 2020a), and a lot of it (including manure, food waste, sewage sludge, and others) can be used for fertilizer purposes. They can provide nutrients valuable for plants, such as nitrogen (N), phosphorus (P), potassium (K) calcium (Ca) and magnesium (Mg). Each of the above-mentioned elements plays an important role in the proper growth and development of plants, therefore, the use of nutrient-rich waste in the production of fertilizer, instead of transfer of waste for landfilling is strongly recommended. However, the use of waste is influenced not only by the presence of elements beneficial for plants, but also by the presence of impurities such as lead (Pb), mercury (Hg) or zinc (Zn) (Górecka and Górecki 2000), which are undesirable in fertilizers and fertilization. Therefore, a detailed analysis of selected waste streams should be made (Włóka et al. 2019), both in terms of their amount, content of nutrients, but also impurities. Waste-based fertilizers that can be used in agriculture are subject to legal regulations, both at the EU and national level (European Commission 2019; Act on fertilizers and fertilization 2007).

This paper presents an overview of waste which, due to the presence of nutrients necessary for plants, can be used as a fertilizer or soil conditioner. The analyzed waste streams were classified according to the group of municipal, industrial or agricultural waste, taking into account their origin and composition. The chemical composition of these waste streams was also presented and analyzed.

1. Materials and methods

This research presents a comprehensive literature review and an analysis of the selected waste streams that can be used in the production of fertilizers. The paper focuses on presenting municipal, industrial and agricultural waste in terms of its possible use in the fertilizer sector.

The selection of literature was based on a review of available publications in full-text databases (Elsevier ScienceDirect, Elsevier Scopus, Google Scholar, Multidisciplinary Digital Publishing Institute – MDPI, BazTech), European statistics (Eurostat), and a review of European law (EUR-Lex). Research was performed using a set of following keywords “circular economy”, “zero waste”, “waste management”, ”municipal waste”, “industrial waste”, “agricultural waste”, “household waste”, “food waste”, “green waste”, “sewage sludge”, “sewage sludge ash”, “digestate”, “biomass ash”, “animal waste”, “plant waste”, “fertilizers”, “waste fertilizers”, “chemical composition of waste”.

The analysis was carried out in order to classify the waste and assign it to specific waste streams that can be used in the fertilizer industry. The following was assigned to municipal

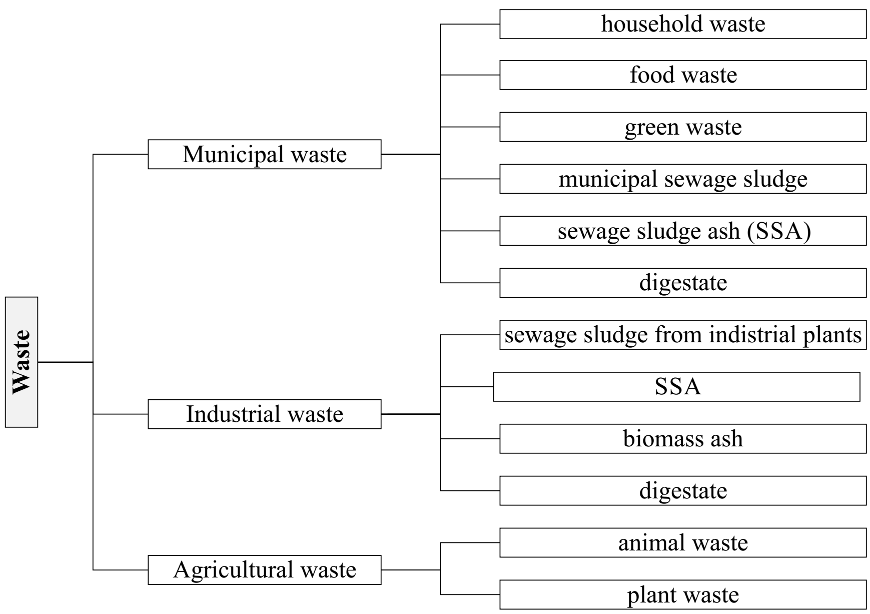

Fig. 1. Classification of waste that can be used in the fertilizer sector (own study based on literature review)

Rys. 1. Klasyfikacja odpadów nadających się do wykorzystania w sektorze nawozowym waste: household waste, food waste, green waste, municipal sewage sludge and digestate. Industrial waste includes: sewage sludge from industrial plants, sewage sludge ash, biomass ash, digestate, while agriculture waste includes animal and plant waste. The classification of waste is presented in Figure 1.

The chemical composition of the most important micronutrients and macronutrients for plants from individual waste streams was analyzed. The descriptive and substantive analysis of the classified waste was conducted. The waste streams were selected for the presence of the main plant nutrients such as N, P and K. Besides the nutrients, the content of heavy metals such as Lead (Pb), Mercury (Hg), Cadmium (Cd) and others was also analyzed.

In the last stage of the work, a SWOT (strengths, weaknesses, opportunities, threats) analysis of the use of fertilizers from waste was performed. This method is one of the most commonly used techniques of market analysis. It enables the identification of strengths (S), weaknesses (W), opportunities (O), threats (T), thanks to which it is possible to define an action and development strategy. The analysis was carried out in 3 steps:

- inside identification – identifying strengths and weaknesses;
- outside identification – identifying opportunities and threats;
- defining the directions of development (Tylińska 2005).

2. Inventory of waste that can be used to produce fertilizers

The potential sources of fertilizer raw materials as macro (N, P, K, Ca, Mg, Na) and micronutrients (Cu, Fe, Mn, Zn) that can be used for fertilization are municipal, industrial and agricultural waste. Characteristics and the chemical composition of municipal waste, which include household waste, food waste, green waste, sewage sludge and digestate, industrial waste such as sewage sludge ashes, ashes from biomass burning and digestate, and plant and animal waste defined as agricultural waste are presented in the following subsections.

2.1. Municipal waste

In the EU, 7–10% of all waste generated is municipal waste (Eurostat 2020b). This is a very specific waste stream due to its complexity, which is why the type of waste management determines the quality of the waste management system in the country. The EC is striving to increase the amount of waste directed for recycling, which is why municipal waste is an area of special interest (Smol et al. 2020a). The following municipal waste is presented in the following subchapters: household waste, food waste, green waste, municipal sewage sludge and digestate. The result below the European average (492 kg per inhabitant) was shown by 14 EU countries (Eurostat 2019). The chemical composition of municipal waste streams, which are presented in the paper that can be used for the production of fertilizers with the partition into micro and macronutrients are presented in Table 1.

Table 1. Chemical composition of individual, municipal waste streams that can be used for the production of fertilizers (mg/kg)

Tabela 1. Skład chemiczny poszczególnych strumieni odpadów komunalnych nadających się do produkcji nawozów [mg/kg]

Parameters	Household waste		Food waste	Compost from green waste		Sewage sludge		Digestate	
								from municipal waste biogas plant	from sewage sludge
Macronutrients (mg/kg)									
N+	15 700	–	31 600	37 470	20 800	298	277	12 501.2	4.2
P+	1 600	–	5 200	6 110	4 900	210	356	14.301	3
K+	14 800	–	9 000	24 500	25 400	272	25	–	3 000
Mg+	1 800	–	1 400	3 070	4 500	4 420	79	3.91	–
Ca+	279.1	0.73	60	–	245	–	540	2.21	–
Micronutrients (mg/kg)									
Mn+	4 500	–	766	–	4550	–	197	2.21	–
Fe+	279.1	0.73	60	–	245	–	540	3.91	–
Cu+	12.44	0.173	31	32.12	35.15	107	438	0.961	1000
Zn+	62.8	0.905	76	177	291	580	1.607	0.631	1890
Cd	0.27	0.0131	<1	1.41	2	1.66	23	0.0011	16
Cr	10.4	–	3	18.52	13.35	28.8	1.592	0.241	–
Hg	–	<0.001	–	–	–	5.5	2	–	–
Pb	7.93	1.65	4	12.8	23.4	20.7	312	0.0251	540
Ni	5.1	0.191	2	10.49	6.66	16.1	960	0.271	85
References	(Hanc et al. 2011)	(Riber et al. 2009)	(Zhang et al. 2007)	(Halik et al. 2004)	(Gondek and Filipek-Mazur 2005)	(Poluszuńska and Ślęzak 2015)	(Tabatabai and Frankenberger 1979)	(Urbanowska and Kotas 2019)	(Sommers 1977)

2.1.1. Household waste

Household waste is the main source of municipal waste. In 2016, about 2,538 × 10^6 Mg of waste was generated in the EU, 8.5% of it was waste produced in households. This type of waste is paper, cardboard, plastics, glass, packaging waste, waste that does not fit into standard containers, i.e. bulky waste and biodegradable waste (Bień and Bień 2010). In the case of this waste stream, its selective collection is very important, which is available for example through a door-to-door collection system (European Commission 2018). It is assumed that the selective collection of biodegradable waste, which can be used for fertilization, will be significantly improved. Their composition depends, among others, on the place of their formation and the living standards of the producer of this waste (Hanc et al. 2011). The main methods of processing bio waste are composting and biogas processes with anaerobic digestion. Still, the most popular method is composting, which can increase the availability of plant nutrients (Debosz et al. 2002). Thanks to processing, their volume can be significantly reduced, the material is stabilized and the weeds lose their ability to sprout (Svensson et al. 2004). The distinguishing elements in this waste stream are N – 15,700 mg/kg, P – 1,600 mg/kg, K – 14,800 mg/kg, i.e. the main fertilizing components, but also manganese (Mn) – 4,500 mg/kg, which has an impact on plant root system (Riber et al. 2009). Attention should also be paid to the presence of heavy metals such as Cd, Cr, Pb and Ni, which occur in this type of waste, and their content may be 0.27 mg/kg; 10.4 mg/kg; 7.39 mg/kg; 5.1 mg/kg (Hanc et al. 2011). In connection with the research on the chemical composition of household waste, it is worth mentioning that there is no unambiguous sampling method, which makes it difficult to compare and interpret them in a consistent manner (Dahlén and Lagerkvist 2008).

2.1.2. Food waste

The increase in food waste is mainly due to population growth. The greatest amount of food is wasted in highly developed countries, but nevertheless, about 88 million Mg of food is wasted annually in all EU countries (Polski Instytut Ekonomiczny 2019). Food waste not only has social (malnutrition) and ecological (greenhouse gas emissions) but also economic effects. The raw materials, including water, soil, and energy, are wasted, so the EU is taking action to prevent food waste, such as, for example, developing organic farming (Polski Instytut Ekonomiczny 2019). To maintain an appropriate level of soil fertility, nutrient deficiencies should be supplemented by using appropriate fertilizers. In conventional agriculture, chemical fertilizers are used for this purpose, the production of which requires high energy inputs. An alternative could be fertilizers made from food waste (Chiew et al. 2015). This type of waste is rich in major plant nutrients, such as N (31,600 mg/kg), P (5,200 mg/kg) and K (9,000 mg/kg), however, they may also contain unwanted heavy metals such as Cd (<1 mg/kg), Cr (3 mg/kg), Pb (4 mg/kg) and Ni (2 mg/kg) (Zhang et al. 2007), which come from agriculture, but their amounts may decrease as the waste is subjected to various processes. The most common method of processing food waste is composting (Gao et al. 2017).

2.1.3. Green waste

Green waste is a type of waste generated during the care of urban green areas (gardens, parks, cemeteries, marketplaces) in municipal areas (Dz.U. 2013 item 21. 2020). They can be a source of valuable nutrients for plants, so they should not be seen as a nuisance waste, but a secondary raw material that can be used to produce valuable organic fertilizer to maintain or improve the quality of soil and urban ecosystems (Siuta and Waslak 2000). The main method of their processing is composting, the fertilizing value of such compost depends on many factors, including the quality of the raw material, production technology and maturity of the final product (Madej et al. 2004), which is determined by the C:N value (the C:N value of mature composts should be within 15–20) (Rosen et al. 1993). The main components of municipal green waste compost investigated by J. Halik et al. this is N – 37,470 mg/kg, P – 6,110 mg/kg and K – 24,500 mg/kg, heavy metals that may be present in this type of waste include: Cd – 1.41 mg/kg, Cr – 18.52, Pb – 12.8 mg/kg, Ni – 10.49 mg/kg (Halik et al. 2004). Due to the presence of these undesirable components, it is extremely important to study the chemical composition of the waste to be applied to the soil.

2.2. Industrial Waste

Industry plays a very important role in any developing country, however it is a sector that generates significant amounts of waste, which has a significant impact on the environment (Ahmad et al. 2019). Industrial waste is generated in three main industries: construction (35.7% of generated waste), mining and quarrying (26.3% of generated waste) and production (10.7% of generated waste) (Eurostat 2020c). Waste from the industrial sector that can be used as fertilizer is: sewage sludge from industrial wastewater, sewage sludge ash, ash from biomass burning and digestate. The following subchapters present the characteristics of the above-mentioned wastes, while the chemical composition of industrial waste streams, which are presented in the paper, that can be used for the production of fertilizers with the partition into micro and macronutrients are presented in Table 2.

2.2.1. Sewage sludge

Sewage sludge (SS) is formed during the wastewater treatment process. Due to its organic and mineral composition, which is close to humus, SS can be applied directly to soil (without prior treatment). However the possibility of the direct application of SS depends on its chemical composition, and in a situation where it contains large amounts of heavy metals (limit values of heavy metal concentrations in agricultural sewage sludge: Cd – 20–40 mg/kg; Cu – 1,000–1,750 mg/kg; Ni – 300–400 mg/kg; Pb – 750–1,200 mg/kg; Zn – 2,500–4,000 mg/kg; Hg – 16–25 mg/kg (Council Directive 86/278/EEC)), this method of recovery is not possible (Janosz-Rajczyk 2004). There are some specific conditions to be met for the use of SS in agricultural purposes, as SS doses, which depend on type of soil,

Table 2. The chemical composition of individual, industrial waste streams that can be used for the production of fertilizers (mg/kg)

Tabela 2. Skład chemiczny poszczególnych strumieni odpadów przemysłowych nadających się do produkcji nawozów [mg/kg]

Parameters	Sewage sludge		Sewage sludge ash			Ashes from biomass burning		Digestate pulp compost	
						wood chips	no data on the biomass composition	based on glycerine	based on stillage
Macronutrients (mg/kg)									
N+	5 820	298	277	–	–	–	–	1 131	1 191
P+	132	210	356	46 200	–	2 440	–	24 200	23 500
K+	15,20	272	25	10 400	–	45 000	45 000	49 900	58 400
Mg+	46	4 420	79	12 700	–	5 740	18 000	9 100	10 200
Ca+	183	15 800	763	80 100	–	48 200	1 560	35 300	28 500
Micronutrients (mg/kg)									
Mn+	234		540	–	474	1 210	–	–	–
Fe+	–		197	131 000	35 272	2 730	–	–	–
Cu+	213	107	438	553	1503	44.20	342	78.60	69.90
Zn+	456	580	1.61	1 990	2848	420	–	100.20	89.90
Cd	1.70	1.66	23	3.80	15	0.20	10.70	0.16	0.09
Cr	–	28.80	1.60	159	172	21.10	49.10	4.96	4.78
Hg	–	5.50	2	–	7	–	0.157	0.22	0.15
Pb	33.20	20.70	312	258	1 175	18.5	225	0.66	0.65
Ni	27.70	16.10	960	6 360	112	8	32.70	3.80	3.20
Reference	(Krzywy et al. 2004)	(Poluszuńska and Ślęzak 2015)	(Tabatabai and Frankenberger 1979)	(Mattenberger et al. 2008)	(Cheeseman and Virdi 2005)	(Supancic et al. 2014)	(Poluszyńska and Ślęzak 2015)	(Pilarska et al. 2015)	(Pilarska et al. 2015)

[1] Organic nitrogen.

soil quality, SS quality, plant demand for the most important nutrients – N, P, K – the content of these components is variable and depends on the composition of wastewater flowing into the treatment plant and the place of their formation (Chmielowski 2019)) and heavy metal content (Niemiec and Zdeb 2013). The research of Krzywy et al. presents the contents of the above-mentioned nutrients N – 5,820 mg/kg; P – 132 mg/kg; K – 15.20 mg/kg and heavy metals present in sediments such as: Cd – 1.70 mg/kg; Pb – 33.20 mg/kg; Ni – 27.70 mg/kg (Krzywy et al. 2004).

Before applying to soil, sewage sludge can be processed biologically, chemically and thermally. The processing of sewage sludge enables the course of various biological processes in the sludge. The methods of treating sewage sludge are shown in Figure 2 (Chojnacka et al. 2020).

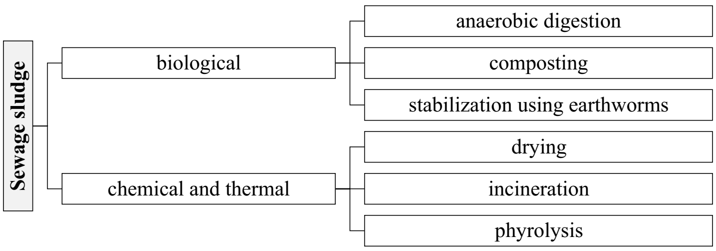

Fig. 2. Sewage sludge treatment methods (Chojnacka et al. 2020)

Rys. 2. Metody przetwarzania osadów ściekowych

2.2.2. Sewage sludge ash (SSA)

In recent years, more and more incineration plants are being built, which is associated with the production of more and more sewage sludge and SSA (Smol 2019). Due to the high phosphorus content in the composition, its potential source may be SSA (Mattenberger et al. 2008), however ashes from sewage sludge may contain pathogens and heavy metals and other pollutants (Kozak et al. 2021), so for this reason they cannot be used directly on the soil (Hudziak et al. 2012). The use of ashes after the incineration of sewage sludge as fertilizer is possible only after reducing the amount of heavy metals, the presence of which in the SSA was examined by Mattenberger et al. (Zn – 1,990 mg/kg; Pb – 258 mg/kg; Cu – 553 mg/kg) (Mattenberger et al. 2008). However, it is worth using ash from sewage sludge as a fertilizer, because they can contain as much as 30% P (Krüger and Adam 2015). This solution is in line with the CE concept (COM no. 398, 2014). The chemical composition of selected samples of SSA is presented in Table 2. The possibility of usage of this waste stream as the source of nutrients in fertilizers is limited to the presence of mono-incineration plans of sewage sludge, which occur in selected countries and regions, as Germany or Poland (Smol et al. 2020b).

2.2.3. Biomass ash

In the context of the recovery of biogenic raw materials, ash from biomass combustion, generated during energy production is an important waste stream. Ash from biomass combustion is indicated as an industrial by-product, it is considered as solid waste. Ashes resulting from biomass combustion are the oldest mineral fertilizers, they can also be used as substances stabilizing sewage sludge (Tan and Lagerkvist 2011). Ash from biomass combustion can also be used in building materials, however, in the context of implementing the principles of circular economy, their agricultural use should be considered first, e.g. through soil application in the form of fertilizers. Factors affecting the possibility of using biomass ashes as fertilizer are primarily the content of nutrients (P_2O_5, K_2O, Na_2O, CaO, MgO) and the content of heavy metals toxic to soil (Poluszyńska and Ślęzak 2015). The characteristics of biomes ashes are presented in Table 3.

Table 3. Nutrients contained in ashes from the combustion specific biomass (Wacławowicz 2011)

Tabela 3. Składniki odżywcze zawarte w popiołach ze spalania konkretnego rodzaju biomasy

Biomass	Fertilizer ingredients			
	P_2O_5 (%)	K_2O (%)	CaO (%)	MgO (%)
Hay pellets	4.30	10.40	18.80	2.70
Oat	11.80	14.80	3.50	4.50
Willow	4	8.90	34.40	0.30
Oak wood	2.20	9.40	40.30	3.50
Triticale straw	4.80	28.80	16.40	1.50
Wood chips from a fluidized bed boiler	1.30	3.60	15.40	6.30

2.2.4. Post-fermentation pulp compost

Composting is a biochemical waste treatment method that serves as a very important role in the aspect of environmental protection. Compost can improve soil properties and increase the yields (Franica et al. 2018). Post-fermentation pulp compost can significantly reduce odor emissions and minimize nitrate (V) leaching into the soil. Foreign research centers conducted digestate pulp tests and compared them with the substrate used for fermentation. Research shows that the pulp contains K, N, Al, Cu, Fe and Zn in the same amount as the starting material, but contains less P, Ca, and Mg (Marcato et al. 2008). During the composting process there may be an increase in the concentration of heavy metals, which is associated with exceeding the permissible standards, despite the earlier appropriate composition.

Analysis of the content of nutrients and heavy metals is necessary during the preparation of their appropriate doses, and the chemical composition of the digestate pulp depends mainly on the substrate used (Pilarska et al. 2015). The chemical composition of digestate pulp compost based on glycerine and stillage is presented in Table 2. Thanks to composting, the fertilizer value of digestate pulp increases.

2.3. Agricultural waste

Agriculture includes raising livestock and growing crops, to provide basic food, therefore, every person uses agricultural production resources. The agricultural area used in the EU in 2016 was about 39% of the total EU land area, This is about 173 million hectares of land (Eurostat 2018). This indicates a great potential for the reuse of waste in these areas.

In many EU countries, the area used for agriculture exceeds half of the country, such countries include: Ireland, Denmark, Romania, Hungary, Luxembourg, the Netherlands, France and Spain. Ireland is the country where the agricultural area covers the largest area (64.5%) in relation to the total area of the country. Due to such a high coefficient of agriculture, many countries generate large amounts of waste from this sector, which must be managed in an appropriate manner.

From 2004 to 2016, the amount of agricultural waste generated has decreased significantly, but it is still being produced in large quantities. Due to such a high coefficient of agriculture, many countries generate large amounts of waste from this sector, which must be managed in an appropriate manner. Animal and plant waste generated in the EU in 2004–2016 is presented in Figure 3.

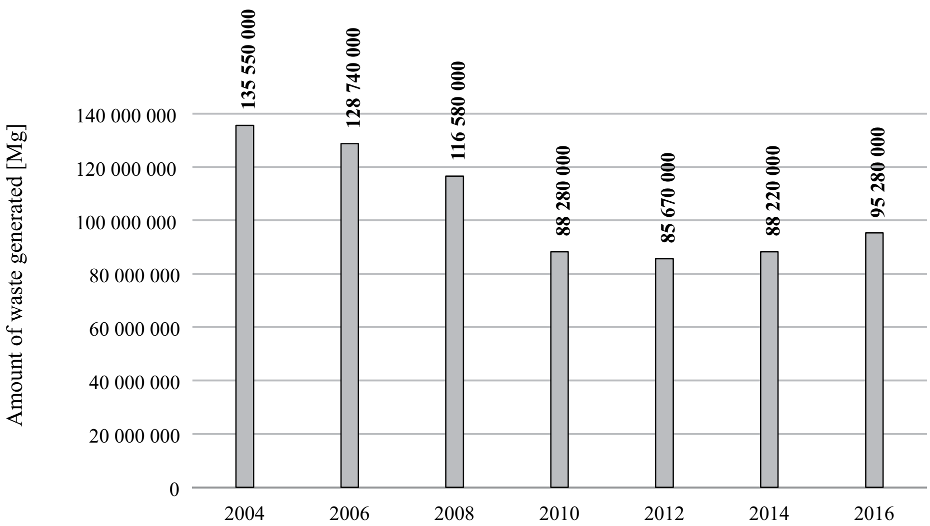

Fig. 3. Animal and plant waste generated in the EU in 2004–2016 (Eurostat 2020a)

Rys. 3. Odpady roślinne i zwierzęce generowane w UE w latach 2004–2016

Such a large amount of agricultural waste should be used as a fertilizer because of the amount of nutrients it contains. The chemical composition of individual agricultural waste streams is presented in Table 4.

Table 4. Chemical composition of individual, agricultural waste streams that can be used for the production of fertilizers (mg/kg)

Tabela 4. Skład chemiczny poszczególnych strumieni odpadów rolniczych nadających się do produkcji nawozów [mg/kg]

Parameters	Animal waste							Plant waste
	manure		pig slurry			cow slurry		compost from mixed plant waste
Macronutrients (mg/kg)								
N+	–	20 900	2 800	3 500[1]	–	3 800[1]	–	20 800
P+	–	21 400	29 500	680[1]	–	750[1]	–	4 900
K+	–	18 700	37 400	1 900[1]	–	3 800[1]	–	25 400
Mg+	–	4 600	14 200	395[1]	–	470[1]	–	4 500
Ca+	–	23 800	51 200	1 570[1]	–	1 750[1]	–	38 600
Micronutrients (mg/kg)								
Mn+	–	314	629	19[1]	–	15[1]	–	245
Fe+	–	1 405	–	120.70[1]	–	87.10[1]	–	–
Cu+	–	411	590	6.35[1]	–	3.15[1]	–	35.15
Zn+	156	419	1 507	31.20[1]	–	18.90[1]	–	291
Cd	1.8	–	–	–	0.24	–	0.019	2
Cr	45.3	–	–	–	1.86	–	1.650	13.35
Hg	0.12	–	–	–	0.07	–	0.030	–
Pb	12.8	–	–	–	3.65	–	4.110	23.40
Ni	1.9	–	–	–	1.20	–	0.700	6.66
Reference	(Ociepa et al. 2007)	(Gondek and Filipek-Mazur 2006)	(Marcato et al. 2008)	(Smurzyńska et al. 2016)	(Ociepa et al. 2007)	(Smurzyńska et al. 2016)	(Ociepa et al. 2007)	(Gondek 2007)

[1] Liquid fraction (mg/dm^3).

2.3.1. Animal waste

All by-products that come from livestock can contain valuable nutrients, and therefore constitute valuable organic fertilizer (Zublena and Barker 1992). Animal waste includes manure and slurry, which have been used as organic fertilizers for years. Manure is a by-product from farm animal excrements that:

- is a natural fertilizer,
- improves the physical and chemical properties of the soil,
- increases water infiltration and nutrient retention (Zhang 2003).

Sustainable use of this waste for soil is necessary, however the long-term use can have a negative impact on soil aggregation (Marcato et al. 2008).

Slurry is pig manure, which due to its properties should be managed in a rational way, because it can pose a threat by contaminating water and soil with pathogenic pathogens. Its chemical properties depend on the animal species, their diet, age, faecal storage, climatic conditions, and the amount of water used. Slurry manure contains valuable macro- and microelements, which cause the proper growth and development of plants. Thanks to nutrients easily absorbed by plants, it has a faster reaction than manure (Marcato et al. 2008). Slurry, due to its properties, is comparable to mineral fertilizers (Smurzyńska et al. 2016). A safer way to use its fertilizing properties is to put the slurry into the composting process. As a result of aeration, you can get a stable and safe fertilizer (Smurzyńska et al. 2016).

Both manure and slurry manure showed a very high content of elements important for plants such as N, P, K, Mg and Ca. Their values for manure were respectively: 20,900 mg/kg; 21,400 mg/kg; 18,700 mg/kg; 4,600 mg/kg and 23,800 mg/kg. Pig slurry values are: 2,800 mg/kg; 29,500 mg/kg; 37,400 mg/kg; 14,200 mg/kg and 51,200 mg/kg. High values of these components and low levels of heavy metals (for example manure: Cd – 1.8 mg/kg; Cr – 45.3 mg/kg; Hg – 0.12 mg/kg; Pb – 12.8 mg/kg; Ni – 1.9 mg/kg (Ociepa et al. 2007)) indicate the potential of animal excrements in soil fertilization.

2.3.2. Plant waste

The main by-product generated on farms during plant production is cereal straw and other arable crops. One possible way of managing them is to refer to the production of fertilizers. The problem with using them as a fertilizer may be enriching biomass with trace elements (Siuta 1999). To improve their physical and chemical properties, they should be composted (Gondek and Filipek-Mazur 2006). During composting, about 50% organic matter is mineralized and the rest is biodegradable with various microorganisms (Sudharsan Varma and Kalamdhad 2015). However, there are difficulties in identifying the correct composition of components due to the variability of their properties over time. The quality parameters of fertilizers from this type of waste are also dynamically changing. Their advantage is the distribution over time of fertilizing activity (Gondek and Filipek-Mazur 2006). The chemical composition of plant waste compost was investigated by Gondek. The main identified nutrients are: N (20,800 mg/kg), P (4,900 mg/kg) and K (25,400 mg/kg), it is precisely because of their large amount that green waste is an attractive raw material that can be successfully used as fertilizer. Like most organic waste, it also contains some amounts of heavy metals such as Cd (2 mg/kg), Cr (13.35 mg/kg), Pb (23.40 mg/kg), Ni (6.66 mg/kg) (Gondek 2007).

3. Discussion

The analysis of the chemical composition and properties of various municipal, industrial and agricultural waste streams has shown that they can successfully be used as a fertilizer or soil conditioner, due to the presence of essential elements (so-called nutrients or biogenic raw materials) which are divided into macro and micronutrients. Macronutrients are the basic nutrients of plants, they are their building material, they are among them (Stanisławska-Glubiak and Korzeniowska 2007):

- N – the main role of this element is participation in the processes of CO_2 binding by plants. The consequence of the deficiency of N is a significant reduction in the amount of yield, as it is the main yield-generating component. An excess of it is also often observed (Piwowar 2013), therefore, plants should be provided with the optimal amount of this nutrient. The degree of use of N by plants is around 50% (Gaj 2013).
- P – this component participates in such processes as photosynthesis, carbohydrate metabolism, respiration and the synthesis of nucleic acids. Due to the appropriate amount of P, plants absorb other components more easily, due to the better developed root system and are more resistant to weather conditions (Piwowar 2013). Plant utilization rate of P is around 25% (Gaj 2013).
- K – water management in the plant is regulated by K, it participates in the biosynthesis process of macromolecular compounds and, similarly to P, in the case of optimal supply of this component to plants, they show greater resistance to adverse weather conditions (Piwowar 2013). The use of K by plants is about 60% (Gaj 2013).
- Mg – this element increases the tissue resistance to degradation, however, its excess influences the absorption of other nutrients, such as Ca, K and Mn, which can lead to many diseases, e.g. bacterial blotch or rot. In order to reduce the possibility of occurrence of this type of disease, Mg nutrition should be properly managed (Huber and Jones 2013).
- Ca – symptoms of Ca deficiency are small yellow-brown spots on the leaves. An excess of this element may cause a deficiency of other nutrients such as, for example, K, Mg, Zn, Fe (Dyśko et al. 2014).

Micronutrients are present in smaller amounts than macronutrients, they are not basic nutrients, but they perform physiological functions, hence they are equally important for plants. They include manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), nickel (Ni). Elements that are not plant nutrients may be harmful to them. The group of elements not desirable by plants includes the so-called heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg) (Stanisławska-Glubiak and Korzeniowska 2007). These elements, even in small amounts, can negatively affect the proper growth and development of plants (Ociepa-Kubicka and Ociepa 2012). It is important to provide the plants with the necessary nutrients in the optimal amount.

In general, the selected waste steams analyzed in the current paper were characterized by a high content of phosphorus, which affects the proper development of the root system, as well as flowering, fruiting and seed formation as well as soil quality (Cieślik and Konieczka 2016). Attention should also be paid to the very high content of iron in the indicated waste groups, which plays an important role in the process of photosynthesis, and its deficiencies may inhibit the synthesis of chlorophyll, carotene and xanthophyll (Brodowska 2019). The calcium contained in the waste promotes the improvement of chemical and physical properties of the soil, regulating its pH, which, in turn, contributes to the storage of a much larger amount of nutrient-absorbable forms of plants (Kalinowski 2018). Magnesium has a positive effect on stimulating root system growth, controlling the conversion of nitrogen into protein and may be responsible for the durability of cell walls (Pikuła 2017). In order for waste to be used for fertilizing purposes, it must meet the conditions that allow it to be placed on the market, this mainly concerns the minimum amount of nutrients and the limit of impurities (Łabętowicz et al. 2019). Particular attention should be paid to the variability in the composition of this type of waste (Chew et al. 2019).

Table 5 presents the list of positive and negative factors regarding the use of waste as fertilizers or soil improvers, which have been identified in the SWOT analysis. The SWOT analysis includes internal factors (strengths and weaknesses) as well as external factors (opportunities and threats) related to the use of various types of waste (municipal, industrial and agricultural) as fertilizers. The most important positive aspects of the usage of waste-based fertilizers are recovering valuable resources and contributing to environmental improvement (Paes et al. 2019). They are very important elements of the implementation of the CE model in the EU, and in the world. In the light of the limited reserves of selected nutrients, as P (Smol 2019), there is high importance to look for alternative sources of plant nutrients (Ylivainio et al. 2021). The application of waste-based fertilizers could be also characterized by lower transport and production or purchase costs (Chojnacka et al. 2020; Supaporn et al. 2013). There are also some weaknesses of use of waste for fertilizer production, as odor, which contributes to a lack of trust in the use of such products by the community. The problem is also uncertain and unstable nutrient content, which has been repeatedly confirmed in research (Nobile et al. 2020; Pacheco et al. 2017; Romanenkov et al. 2019; Vaneeckhaute et al. 2013), while at the same time necessity to comply with certain quality requirements (European Commission 2019/1009).

Due to the EU environmental policy underlining the need for transformation to the CE model, the use of municipal, industrial and agriculture waste in the production of fertilizers is strongly recommended (COM no 98, 2020). Therefore, there is high potential for the further implementation of the CE assumptions in the fertilizer sector.

Table 5. SWOT analysis of the use of waste as a raw material for the production of fertilizers

Tabela 5. Analiza SWOT wykorzystania odpadów jako surowca do produkcji nawozów

SWOT element	Aspect	Description	Reference
Strengths	Recovering valuable resources	The possibility to turn waste streams into valuable resources.	(Paes et al. 2019)
	Contributing to environmental improvement	The use of fertilizers from waste reduces the use of mineral fertilizers, thus reducing their negative impact on the environment.	(Amann et al. 2018; Paes et al. 2019)
	Lower costs	The application of bio-based fertilizers is often characterized by lower transport and production or purchase costs.	(Chojnacka et al. 2020; Supaporn et al. 2013)
	A close-up to the circular economy	Thanks to use waste in the fertilizer sector, the consumption of primary raw materials is limited, which is in line with the CE.	(Wójcik et al. 2017)
	Growing need for sustainable fertilizers	There is a high need for an agricultural product that does not leave any harmful residue or pollutants in the environment and gives organic products.	(Kok et al. 2018; Pahl-Wostl et al. 2003)
	Decreasing amount of insect and pests	Using organic fertilizers, the number of pests and insects in the farm area decrease.	(Chouichom and Yamao 2011)
	Influence on the activity of various physicochemical processes in soil	The use of fertilizer products made from waste affects the activity in the soil environment of processes such as: ◆ stimulation of physicochemical processes that improve the soil's ability to accumulate ingredients available to plants, ◆ increasing the activity of microbiological processes that cause the decomposition of organic compounds into forms available for plants (mineral), ◆ beneficial effect on chemical processes that increase the content of micro- and macro-element forms available to plants.	(Cieślik and Konieczka 2016)

SWOT element	Aspect	Description	Reference
Weaknesses	Unpleasant smell & odor	Very often, waste-based fertilizers have an unpleasant smell, which can be troublesome when using them.	(Bonnichsen and Jacobsen 2020)
	Uncertain and unstable nutrient content	Chemical fertilizers give better results and are more reliable due to certain and stable nutrient content. Moreover, the majority of chemical fertilizers are certified and undergo precise laboratory tests.	(Nobile et al. 2020; Pacheco et al. 2017; Romanenkov et al. 2019; Vaneeckhaute et al. 2013)
	Necessity to comply with certain quality requirements	The usage of waste-based fertilizers require meeting certain quality requirements, and constant maintenance of chemical composition	(European Commission 2019/1009)
Opportunities	Increasing costs of mineral fertilizing agents extraction (e.g. phosphate rock)	Phosphorus fertilizers are mined only from a few phosphate deposits in the world, and the peak of phosphorite extraction is expected in the 2030s, which may cause an increase in the price of phosphorus mineral fertilizers due to higher extraction costs. Waste fertilizers can become an alternative to phosphorus mineral fertilizers.	(Cordell et al. 2009; Rashid et al. 2017; Smol 2019)
	Soil conservation against erosion	Using waste fertilizers can reduce soil erosion.	(Wójcik et al. 2017)
	Development of legal provisions and recommendations	Development of legal provisions and recommendations regarding the usage of waste as a source of secondary raw materials in various branches of industry, including the raw materials sector (CE implementation)	(European Commission 2019/1009; COM no 98, 2020; Smol 2021)
Threats	Risks on the safety and stability of the soil	The often unknown chemical composition of waste-based fertilizers may pose risks on the safety of the consumers and physiochemical and biological stability of the soil.	(Ajmal et al. 2018; Chen et al. 2018; Perdana et al. 2018)
	Hazardous characteristics	The waste-based fertilizers could be hazardous characteristics like corrosively, reactivity, toxicity, flammability and other biological hazards.	(Amann et al. 2018; Savci 2012; U.S. EPA 2019)
	Mutation during fermentation	During the fermentation process of bio-based fertilizers they can mutate which often results in the rise of production and quality control cost	(Ajmal et al. 2018; Waqas et al. 2019)
	Public opinion	Public opinion is an important aspect in the use of waste as fertilizers, as the success of the introduced method depends on the consumers.	(Rashid et al. 2017)

At present, the EC is working on an Integrated Nutrient Management Action Plan (INMAP), which will be a roadmap to address nutrient pollution at the source and increase the sustainability of the livestock sector. The proposed considerations of the INMAP include, in particular, the introduction of requirements for the content of recycled materials in products, which will ultimately prevent the mismatch of supply from the demand for secondary raw materials and ensure a smooth expansion of the recycling sector in the EU (Smol 2021).

Conclusion

The paper presents an analysis of fertilizer potential of selected waste streams – municipal waste (household waste, food waste, green waste, sewage sludge and digestate), industrial waste (sewage sludge ashes, ashes from biomass burning and digestate), and agricultural waste (plant and animal waste). The analyzed materials contain a significant amounts of both macro and micro nutrients, which indicates the possibility of their usage in the fertilizers production sector. Individual waste groups were characterized by a high content of phosphorus (which influences the proper development of the root system, as well as flowering, fruiting, seed formation and soil quality), iron (which plays an important role in the photosynthesis process), calcium (which helps to improve the chemical and physical properties of the soil by regulating its pH, which in turn contributes to the storage of a much larger amount of nutrients available for plants), and magnesium (which has a positive effect on stimulating the growth of the root system).

It should be underlined is that the use of waste for fertilization purposes is possible after meeting the conditions for admitting such fertilizers to the market, in particular with regard to the minimum amount of nutrients in fertilizing products and pollution limits. Therefore, it is necessary to analyze the physic-chemical composition of waste, especially in terms of the content of heavy metals that are harmful to soil and plants. Overall, the usage of waste-based fertilizers in accordance with applicable regulations and manufacturers' recommendations shows environmental, economic and social benefits, which may contribute to the transformation towards CE in this sector.

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AN ANALYSIS OF THE FERTILIZING POTENTIAL OF SELECTED WASTE STREAMS – MUNICIPAL, INDUSTRIAL AND AGRICULTURAL

Keywords

municipal waste, industrial waste, agricultural waste, fertilizers, circular economy (CE)

Abstract

The circular economy (CE) has been a European Union (EU) priority since 2014, when first official document on the CE was published. Currently, the EU is on the road to the transformation from a linear economy model to the CE model. In 2019, a new strategy was announced – the European Green Deal, the main goal of which is to mobilize the industrial sector for the CE implementation. The CE assumes that the generated waste should be treated as a secondary raw material. The paper presents an analysis of the possibility of using selected groups of waste for the production of fertilizers. Moreover, an identification of strengths and weaknesses, as well as market opportunities and threats related to the use of selected groups of waste as a valuable raw material for the production of fertilizers was conducted. The scope of the work includes characteristics of municipal waste (household waste, food waste, green waste, municipal sewage sludge, digestate), industrial waste (sewage sludge, ashes from biomass combustion, digestate) and agricultural waste (animal waste, plant waste), and a SWOT (strengths and weaknesses, opportunities and threats) analysis. The fertilizer use from waste is determined by the content of nutrients (phosphorus – P, nitrogen, potassium, magnesium, calcium) and the presence of heavy metals unfavorable for plants (zinc, lead, mercury). Due to the possibility of contamination, including heavy metals, before introducing waste into the soil, it should be subjected to a detailed chemical analysis and treatment. The use of waste for the production of fertilizers allows for the reduction of the EU's dependence on the import of nutrients from outside Europe, and is in line with the CE.

ANALIZA POTENCJAŁU NAWOZOWEGO RÓŻNYCH STRUMIENI ODPADÓW KOMUNALNYCH, PRZEMYSŁOWYCH I ROLNICZYCH

Słowa kluczowe

odpady komunalne, odpady przemysłowe, odpady rolnicze, nawozy, gospodarka o obiegu zamkniętym (GOZ)

Streszczenie

Gospodarka o obiegu zamkniętym (GOZ) jest priorytetem Unii Europejskiej (UE) od 2014 r., kiedy opublikowano pierwszy oficjalny dokument nt. GOZ. Obecnie UE jest w procesie transformacji z modelu gospodarki liniowej na GOZ. W 2019 r. ogłoszono nową strategię – Europejski Zielony Ład, której głównym celem jest mobilizacja sektora przemysłowego dla GOZ. Model GOZ zakłada, że wytworzone odpady należy traktować jako surowce wtórne. W pracy przedstawiono analizę możli-

wości wykorzystania wybranych grup odpadów (komunalnych, przemysłowych i rolniczych) na nawozy. Ponadto, dokonano identyfikacji mocnych i słabych stron, a także szans i zagrożeń rynkowych związanych z wykorzystaniem wybranych grup odpadów jako cenny surowiec do produkcji nawozów. Zakres pracy obejmował charakterystykę odpadów komunalnych (odpady z gospodarstw domowych, odpady spożywcze, odpady zielone, osady ściekowe z komunalnych oczyszczalni ścieków, poferment), przemysłowych (osady ściekowe, popioły ze spalania osadów ściekowych, popioły ze spalania biomasy, poferment) oraz odpadów rolniczych (odpady zwierzęce, odpady roślinne), a także analizę SWOT (mocne i słabe strony, szanse i zagrożenia). Kluczowymi czynnikami wpływającymi na możliwość wykorzystania odpadów na cele nawozowe są zawartość składników pokarmowych (fosfor, azot, potas, magnez, wapń) oraz obecność niekorzystnych dla roślin metali ciężkich (cynk, ołów, rtęć). Ze względu na możliwość występowania zanieczyszczeń, w tym metali ciężkich, przed wprowadzeniem odpadów do gleby należy je poddać szczegółowej analizie chemicznej oraz obróbce. Wykorzystanie odpadów do produkcji nawozów pozwala na zmniejszenie uzależnienia UE od importu substancji odżywczych spoza Europy, i jest zgodne z GOZ.