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Use of nutrients from wastewater for the fertilizer industry - approaches towards the implementation of the circular economy (CE)

Marzena Smol[a,*], Christian Adam[b], Oliver Krüger[c]

[a]*Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Wybickiego 7A str., 31-261 Cracow, Poland, Tel. +48 12-617-16-53; email: smol@meeri.pl*
[b]*Bundesanstalt für Materialforschung und - prüfung (BAM), Zweiggelände Adlershof, Richard-Willstätter-Straße 11, 12489 Berlin, Germany, Tel. +49 30 8104-5670; email: christian.adam@bam.de*
[c]*Department of Chemical and Product Safety, Bundesinstitut für Risikobewertung (BfR), Max-Dohrn-Str. 8-10, 10589 Berlin, Germany, Tel. +49 30 18412-27707; email: oliver.krueger@bfr.bund.de*

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ABSTRACT

More sustainable waste management practices are an important element in the transformation towards a circular economy (CE). Activities in this area should be dedicated to all groups of waste, including those generated in the water and sewage sector. This paper presents the characteristics of sewage sludge ash (SSA) coming from Polish municipal waste incineration plants. Due to the high content of nutrients such as phosphorus (8.01% P_2O_5), calcium (5.11% CaO) and magnesium (2.75% MgO), the analyzed SSA may constitute a valuable source of raw materials for the fertilizer industry. Despite the good fertilizing properties of the SSA, in some cases the presence of heavy metals such as cadmium (0.74–1.4 mg/kg dry matter), lead (49.8–99 mg/kg dry matter), mercury (3.93 mg/kg dry matter) and arsenic (4.23–4.43 mg/kg dry matter) and poor bioavailability of P from SSA disqualifies this waste from direct use as a fertilizer. Therefore, it is necessary to look for methods that will allow the municipal SSA to be processed, for example, technologies for the extraction of phosphorus and the production of phosphate fertilizer. This way of SSA management is in the line with the CE assumptions, in which waste becomes a valuable source of secondary raw materials. Fertilizer produced from waste meeting quality, safety and labelling requirements and limits of organic, microbiological and physical contaminants will be able to be traded freely within the European Union (EU) and receive the CE marking. The idea of use of SSA for fertilizer purposes is consistent not only with the objectives of the CE but also with the Polish National Waste Management Plan 2022 and the Municipal Sewage Sludge Strategy 2019–2022, which emphasizes the necessity to maximize the use of biogenic substances contained in wastewater. Therefore, sustainable management of SSA, in particular its storage in a way enabling the recovery of phosphorus, should be promoted.

Keywords: Water; Wastewater; Circular economy (CE); Fertilizer; Sewage sludge (SS); Sewage sludge ash (SSA); Phosphorus (P)

1. Introduction

A circular economy (CE) is one of the priorities of the European Union's (EU) economic policy. The CE strategy assumes that all products, materials and raw materials (RMs) should remain in the economy for as long as possible, and waste production should be minimized [1,2]. The European Commission (EC) underlines in its communications on the circular economy that the transition to CE is necessary to implement the goals of the Europe 2020 strategy for smart, sustainable and inclusive growth [3]. In addition, the EC clearly indicates that the process of transformation towards CE concerns all industries, and the conscious involvement of

* Corresponding author.

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many actors as legislative bodies, scientific units, entrepreneurs, as well as consumers themselves [4].

One of the key elements in the transition towards CE is to ensure more sustainable waste management practices [5]. Improvement actions in this area should be targeted at all groups of waste [6], including the waste generated in water and sewage sector [7], that is, wastewater, sewage sludge (SS) or sewage sludge ash (SSA) [8–10]. This waste is characterized by a high content of minerals such as phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) [11,12], and therefore is a valuable source of raw materials for the fertilizer industry [13]. Despite the good fertilizing properties of the indicated waste groups, in selected cases the presence of heavy metals [14] such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As) and nickel (Ni) disqualifies this waste from direct application as a fertilizer [15]. Furthermore, the bioavailability of P from SSA might be hampered [16]. Therefore, it is necessary to look for methods that will allow the mentioned waste to be processed, for example, integrated technologies for the recovery of biogenic raw materials and the production of fertilizer [16,17]. The use of waste-based recycling materials in the fertilizer industry is consistent with the objectives of the CE, which emphasizes the need to maximize the use of nutrients contained in various waste streams. The fertilizer industry has an important role to play in the transition towards CE according to the first implementing initiatives of the CE Action Plan proposed by the EC in late 2015. The proposal lays down rules on the making available of CE marked fertilizer products on the market [18] and emphasizes the importance of the fertilizer sector for the implementation of the CE assumptions. In the European countries, interest in the recycling of nutrients and further possibilities of its management for fertilizing purposes has increased in recent years. Municipal wastewater treatment plants (WWTPs) show high potential, where biogenic RMs, such as phosphorus, can be recovered at each stage of the treatment process, that is, from liquid effluent and effluent, from drained sewage sludge, from solid phase from ashes after thermal transformation of municipal sewage sludge sewage systems [19].

The current research presents an assessment of the possibility of using SSA generated in Polish municipal WWTPs as a source of biogenic RMs in the fertilizing products, in the aspect of the legal regulations and the implementation of the CE assumptions in the fertilizer industry. The specific objectives of the present study are (1) to emphasize the importance of use of the waste from wastewater sector as a source of the RMs in the fertilizer industry as one of the key elements in the transformation process towards the CE, (2) to present the results of the chemical characterization of selected waste generated in the wastewater sector – SSA coming from Polish mono-incineration plants, (3) to assess the quality of those waste and compliance with applicable European and national regulations regarding the use of waste materials in the fertilizer products. The structure of the current study is as follows:

- clarify the importance of the use of waste as a source of the RMs in the CE model, with emphasis on the waste generated in wastewater sector,
- research framework and methods used in this paper,
- overview of the implementation of CE assumptions in the fertilizer industry,
- results of the chemical characterization of the SSA from Polish mono-incineration plants,
- assessment of the possibilities to use the different SSAs in fertilizer products concerning legal regulations,
- discussion and conclusions.

2. Research framework

The paper is divided into two parts. The first part presents a summary of the current state of knowledge in the research area showing the importance of more rationale use of waste in the CE model. Special attention is paid to the waste generated in the WWTPs since water is an important carrier of the raw materials (e.g., phosphorus) which can be re-used in other branches of industry, that is, in the fertilizer sector. The review is based on current international literature. The second part of the research includes the chemical characterization of the waste generated in the process of thermal utilization of municipal sewage sludge and the assessment of the use of studied waste samples in fertilizer products, in the aspects of legal regulations and CE implementation.

2.1. Methods used in the previous studies

The literature review has been done with the use of comprehensive analysis of existing data. The selection of primary literature items was proposed based on full-text databases (Elsevier, Scopus, ScienceDirect, Google Scholar, BazTech, EUR-lex) and scientific articles available in a range of peer-reviewed journals. An important source of literature is European and national documents, legal regulations and statistics. The choice of literature was associated with the use of a few keywords: "circular economy", "CE", "waste", "wastewater", "raw materials", "resources", "sewage sludge", "sewage sludge ash", "phosphorus", "fertilizer". 49 (83%) sources on the list of references were published in or after 2014. There were peaks in 2017 and 2018 with 12 (20%) of the sources, and in 2016 with 10 (17%). Only five sources (8%) were published before 2010 and there are no sources published before 2000.

2.2. Laboratory materials and methods

2.2.1. Sample acquisition

Two samples of SSA were obtained from a small compact installation for the thermal utilization of sewage sludge. The respective SS was generated in a municipal WWTP with mechanical and biological wastewater treatment. The WWTP is located in Wielkopolskie Voivodship (Poland). Approximately, 0.5 kg of each sample was collected from the incineration plant and directed to the chemical characterization.

2.2.2. Sample preparation and elemental analysis

The procedure of sample preparation has been described in detail in the previous research [20]. According to the generally accepted methodology, the determination of the mass fractions of selected components and heavy metals present in the SSA has been done with the use of the inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) after microwave-assisted acid digestion. The characterization of the samples coming from Polish incineration plants has been carried out in the laboratory of the German Federal Institute for Materials Research and Testing (BAM) in Berlin (Germany). The current paper presents the average values and relative standard deviations (RSD) of the selected elements, including the most important fertilizer compounds such as calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) and phosphorus (P). The results are given in Table 1 and are expressed in the oxidic forms of the respective elements. Moreover, the contents of iron (Fe), aluminium (Al) and silicon (Si) were determined (Table 1), as well as the contents of selected heavy metals, such as arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), copper (Cu), nickel (Ni), zinc (Zn), chromium (Cr), selenium (Se), cobalt (Co; Table 3).

3. Fertilizer industry towards circular economy

The use of waste as a source of raw materials in the fertilizer products and an implementation of nutrient recovery technologies are important parts of the transition process from linear economy into a sustainable and therefore well-balanced circular economy [21]. The CE approaches, which have been identified by the European Commission for the fertilizer industry, are presented in Fig. 1.

In 2014, in the first communication on CE "Towards a circular economy: A zero waste programme for Europe", the EC underlined that the resource-efficiency improvements are in demand across a wide range of industrial sectors. The transformation towards CE requires the changes in the development of innovative solutions not only in technologies but also in organization, finance methods and policies. Moreover, social behaviors, attitudes and awareness must be improved in order to create the "recycling society". The EC puts emphasis on two aspects - more efficient use of primary sources and more rationale waste management including the recovery of valuable raw materials and use them again in the economy [1]. In this case, the fertilizer industry has many opportunities of nutrient recovery from the waste generated in other sectors. The usage of waste coming from the WWTPs for fertilizer production is a way to establish the industrials symbiosis (IS), which is indicated as an important part of the CE [22]. The IS focuses on the clustering of activities to prevent by-products from becoming waste [1]. In this context, the waste generated in WWTPs cease to be waste and become valuable secondary raw material in fertilizer industry. The IS is established on the local level and therefore, some of the possibility is the construction of the recovery plant next to the WWTPs and transfer the waste by special technological lines or tracks, without incurring high costs of transport. The recovery installation should be adopted to the special conditions of WWTP and waste stream which is a source of nutrients, so in some cases the recovery installation can be applied at WWTP (e.g., struvite recovery plant) and can be operated by the operator of the WWTP or an external company which is the owner of the recovery installation. Moreover, mobile installations could be also taken under consideration. This can be a solution on rural areas where WWTPs are scattered [23]. In some European countries, centralization on a regional scale might be economic, since high capital investment in recovery plants are necessary.

In 2015, the EC has published the second communication on CE "Closing the loop - An EU action plan for the Circular Economy". The CE Action Plan involves the aspects of nutrients recovery from the water and wastewater sectors [2]. It was underlined, i.a., that the recycled nutrients, that are present in organic waste material, are a distinct and important category of secondary raw materials which can be returned to soils as fertilizer. The EC has also pointed out that a circulation of fertilizer based on recycled nutrients was hampered by the fact that rules as well as quality and environmental standards differ across the Member States. In order to address this situation, the EC proposed a revision of the EU regulation on fertilizer.

In 2016, the mentioned revision has been proposed and "Proposal laying down rules on the making available on the market of CE marked fertilizing products" has been published [18]. Fertilizer produced from waste meeting quality, safety and labelling requirements and limits of organic,

Table 1
Chemical composition of two SSA samples from the same incineration facility (Wielkopolskie Voivodship, Poland) analysed by ICP-OES

Element	Sample I		Sample II	
	% dry weight of sample	RSD (%)	% dry weight of sample	RSD (%)
CaO	4.27	4	5.12	9
K_2O	1.82	4	2.10	2
MgO	2.39	2	2.75	2
Na_2O	1.41	8	2.60	3
P_2O_5	7.41	4	8.01	2
Al	16.2438	2	20.3347	2
Fe	2.0913	2	2.4550	1
Si	23.7645	5	11.4476	11

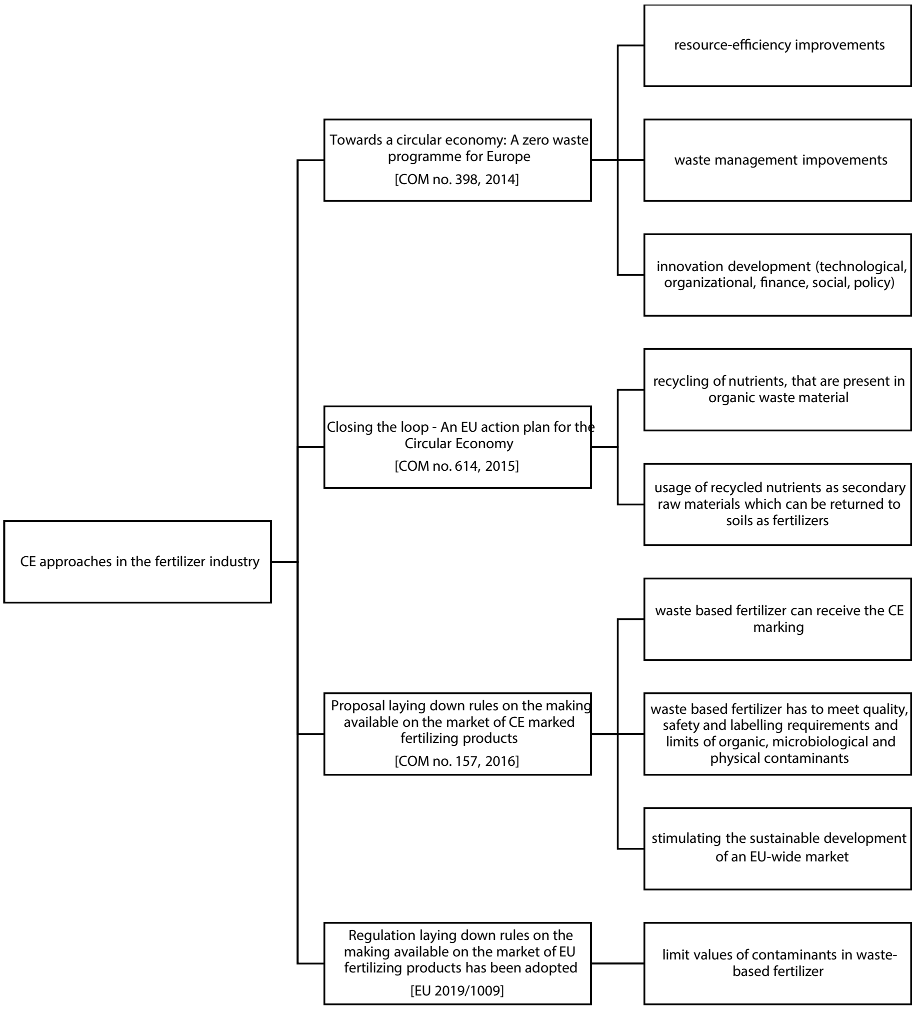

Fig. 1. European Commissions CE approaches for the fertilizer industry.

microbiological and physical contaminants will be able to be traded freely within the EU and receive the CE marking. The main policy objective of the proposal is to incentivize large-scale fertilizer production in the EU from domestic organic or secondary raw materials, according to the assumptions of the CE model, in which waste is transformed into nutrients for crops. The proposal includes the new measures to facilitate the EU-wide recognition of organic and waste-based fertilizer, thus stimulating the sustainable development of an EU-wide market. It was proposed that heavy metals exceeding the below limits must not be present in the CE marked fertilizing product – Cd < 1.5 mg/kg dry matter, Hg < 1 mg/kg dry matter, Ni < 50 mg/kg dry matter, Pb < 120 mg/kg dry matter.

In June 2019, the "Regulation laying down rules on the making available on the market of EU fertilizing products" has been adopted [24]. The conversion of waste into a valuable raw material or product is an important issue from the legal perspective. The newest regulation specifies the conditions when waste, as defined in Directive 2008/98/EC [25], ceases to be waste, if it is contained in a compliant EU fertilizing product. In such situations, the recovery operation should be performed before the material ceases to be waste, and the material needs to be considered to comply with the conditions laid down in Article 6 of that Directive, and therefore to have ceased to be waste from the moment that the EU declaration of conformity was drawn up. Taking into account consultations with many stakeholders connected to the fertilizer sector in Europe, the final limit values of the concentration of heavy metals in the CE marked fertilizing product have been identified as Cd < 2.0 mg/kg dry matter, Hg < 1 mg/kg dry matter, Ni < 90 mg/kg dry matter, Pb < 120 mg/kg dry matter and As < 40 mg/kg dry matter [24].

In order to improve the management of fertilizer raw materials, some of the European countries introduced the obligatory recovery of selected biogenic raw materials, as phosphorus, which is a critical raw material (CRM) for the European economy due to its economically and strategically extreme importance but has a high-risk associated with its supply. Europe has very limited primary resources of P and is highly dependent on outside providers (88% for phosphate rock and 100% for phosphorus) [26]. Therefore, developed countries have already started identifying some legal and technical solutions in order to increase security of supply of this fertilizer raw material [27]. In 2016, Switzerland implemented the Ordinance on Avoidance and Disposal of Waste, which requires the recovery of phosphorus from wastewater, sewage sludge and SSAs, and the material utilization of P in meat and bone meal as of 2026 [28]. In 2017, in Germany, the national Sewage Sludge Ordinance (AbfKlärV) was also adopted. It makes P recovery from sewage sludge or SSA (if applicable) obligatory in the German WWTPs bigger than 50,000 population equivalents, within the next 12 to 15 years [20]. The recovery of raw materials from waste streams is in line with the adopted CE roadmaps in both of the mentioned countries. In 2016, Germany has published the CE roadmap in the form of "German Resource Efficiency Programme" (ProgRess II). It focuses on the sustainable use and conservation of natural resources, which are defined as all components of nature, including biotic and abiotic resources. In fertilizer law, the Federal Government will create the conditions for the use of recycled materials of proven nutrient content as fertilizer and will lay down requirements for the spreading of sewage sludge [29]. In Switzerland, a transition process towards the CE is presented in the movement programme "Circular Economy Switzerland", which has been published in February 2019. As part of this movement, the Circular Economy Transition (CET) initiative provides the background knowledge and implementation tools to facilitate the transformation towards Circular Economy Switzerland. Swiss companies are world leaders, but they still want to grow and see a lot of environmental benefits in connection with moving to CE. This proves a strong asset for meeting the increasing global demand for both products and services that contribute to the protection and preservation of the raw materials. Swiss companies constantly adapt to a rapidly changing international market and regulatory environment. Anyway, the area of nutrient management and possible recovery of phosphorus is a multi-faceted challenge as nutrient use is subject to a variety of influencing factors comprising policy interventions, consumption trends or technological innovations on different spatial scales [30]. Therefore, one of the Swiss goals is to improve the disposal practices of waste generated in all branches of industry, including water-based waste rich in nutrients. In Poland, a proposal of CE roadmap "Transformation towards a circular economy" has been published by the Ministry of Development (since 2018 Ministry of Entrepreneurship and Technology) in 2016. One of the key issues in the roadmap is the management of raw materials and waste according to CE principles. In the case of nutrients disposal practices, it is necessary to take into account the principles of the sustainable use of both primary and secondary sources of nutrients and directing as much of nutrients-rich waste to recycling as possible. The proposed CE Polish roadmap shows the directions and basic recommendations for the building of a CE in Poland. It is mentioned that the wastewater sector is an important source of nutrients which should be kept in the economy as long as possible [31]. However, there are no specific recommendations regarding this topic in the Polish document.

4. Results of chemical analysis of SSA and discussion

The element mass fractions in SSA could differ significantly for some elements depending on whether the original sewage sludge arises mainly from municipal or industrial sources [20]. The results of chemical characterization of SSA are presented in Table 1. The SSA studied in this paper shows a good fertilizer property, especially in terms of the content of phosphorus, calcium and magnesium. Their contents in SSA in the forms of P_2O_5, CaO and MgO were equal to 8.01%, 5.11% and 2.75%, respectively. It contains also potassium and sodium (up to 2.1% of K_2O and 2.6% of Na_2O), which are valuable nutrients as well. The content of silicon was equal to 23.76%. The studied SSA contains also iron (2.46%) and aluminium (20.33%), which significantly limits the bioavailability of fertilizing phosphorus contained in the ash. Due to the presence of impurities, and in order to increase the availability of phosphorus for plants, new methods for extracting phosphorus from SSA are currently being developed.

The results of previous research of authors [15,20,23,32–34] and other authors [11,35–41] confirm that the SSA coming from mono-incineration plants show high content of fertilizer components. The results of the chemical composition of the SSA coming from selected WWTPs in Poland are shown in Table 2. The presented results include the ash samples which have been incinerated in the lab conditions (SS taken from

Table 2
Mass fractions of main elements expressed as oxides (%) of SSA samples coming from selected WWTPs in Poland

SSA sample	CaO	K_2O	MgO	Na_2O	P_2O_5	Reference
Krakow	16.51	–	1.86	–	22.86	Gorazda et al. [42]
Gdansk	17,12	1,75	–	–	21,97	Borowski et al. [43]
Czestochowa	15.52	–	2.52	–	28.32	Smol et al. [34]
Tarnow	23.39	–	2.69	–	16.45	Smol et al. [34]
Rzeszow	8.50	–	3.75	–	22.90	Smol et al. [34]
Krakow	14.06	0.70	3.15	0.27	17.86	Gorazda et al. [44]
Kielce	16.38	1.57	4.06	0.38	24.74	Gorazda et al. [44]
Lodz	17.31	1.02	3.72	0.60	19.93	Gorazda et al. [44]
Warszawa	15.26	0.76	2.61	0.34	22.45	Gorazda et al. [44]
Gdynia	16.00	0.86	3.28	0.51	27.94	Gorazda et al. [44]
Bydgoszcz dust	29.00	0.80	3.62	0.35	18.39	Gorazda et al. [44]
Szczecin dust	16.80	1.65	4.61	0.75	22.38	Gorazda et al. [44]

the municipal WWTPs) [34,42] and SSA taken from sewage sludge mono-incineration plants [43,44].

Although the SSA generated in the Polish mono-incineration plants contains amounts of fertilizer raw materials comparable with commercial products, its direct utilization as a phosphate fertilizer in agriculture is not possible due to the Polish regulation on the R10 recovery process [45] that does not allow the direct distribution of SSA on the earth surface. In 2018, the Ministry of Environment published the "Strategy for dealing with municipal sewage sludge for 2019–2022". The Ministry underlines that the fertilizer granules obtained from ashes from the combustion of biomass and municipal sewage sludge have not been used in agriculture so far in Poland, and thus it can be considered as a substance "unknown in fertilization". The chemical composition of ashes is probably variable, and research is needed to clarify the recommendations for their use and to determine the size of the doses. SSA is assumed to be a source of phosphorus, but the form and digestibility of the element originating from this source is not known [46]. There is also a risk that ashes from sewage sludge may have an increased (than in the respective fertilizer ordinances) content of some heavy metals and other pollutants (depending on the origin of the sediments) [47–49]. Due to the lack of information in this area, it is also appropriate to conduct agricultural research to assess the absorption of nutrients and the effect of fertilizer obtained from ashes on soil properties and crop yield under Polish conditions. Therefore, for now, it is not justified to allow uncontrolled introduction of fertilizer obtained from SSA to agriculture. Anyway, the SSA could be a valuable raw material to produce phosphate, potassium and calcium fertilizer. It is possible to produce this kind of fertilizer, and place them on the market, according to the Act on fertilizer and fertilization [50], after having examined their chemical properties, and so in accordance with the procedure in force for mineral fertilizer and soil conditioners and after obtaining permission from the Ministry. The recommended approach is the production of fertilizer as a result of extraction of phosphorus from SSA and its use for the production of mineral fertilizer, rather than the usual granulation of SSA. It is advisable to develop technologies for the extraction of phosphorus from SSA to produce mineral fertilizer [46].

As it was mentioned above, in order to indicate the waste product (SS, SSA and other) as a fertilizer or plant conditioner, one of the most limiting factors, the content of heavy metals, must be determined [51]. The analysed SSAs from Polish incineration plants are carriers not only for valuable nutrients such as calcium, phosphorus, magnesium, potassium and iron but also for considerable amounts of harmful heavy metals. The content of heavy metals in the analysed ash and their maximum levels according to Polish fertilizer regulations is presented in Table 3. The content of heavy metals in fertilizer is standardized in Poland for four elements arsenic (50 mg/kg dry matter), cadmium (50 mg/kg dry matter), lead (140 mg/kg dry matter) and mercury (2 mg/kg dry matter) [52]. The analysed SSA meets the Polish standards for arsenic, cadmium and lead. The content of arsenic was in the range 4.23–4.43 mg/kg dry matter, cadmium 0.74–1.4 mg/kg dry matter and lead 49.8–99 mg/kg dry matter. The content of mercury in ash equals 3.93 mg/kg dry matter. According to the Polish standards, it is not allowed to use the mineral fertilizer with the content of mercury above 2 mg/kg dry matter and therefore, from heavy metals limitation perspective, these samples of SSA cannot be directly used for fertilizer purposes in Poland. Considering the requirements included in the proposal laying down rules on the making available on the market of CE marked fertilizing products, the analyzed SSA meets the limited values of two indicated heavy metals – cadmium and lead. The content

Table 3
Content of heavy metals in SSA from a wastewater treatment plant in Poland compared with heavy metals limiting values that apply to the mineral fertilizer

Element	Sample I	Sample II	Maximum levels according to Polish fertilizer regulations[a]	Maximum levels according to CE fertilizer proposal[b]	Maximum levels according to CE fertilizer regulation[c]
	mg/kg dry matter of sample				
As	4,43	3.23	50	ns.	40
Cd	0.74	1.4	50	1.5	2.0
Pb	99.0	49.8	140	120	120
Hg	3.93	2.46	2	1.9	1.0
Cu	1,016	889	ns.	ns.	ns.
Ni	68.5	82.6	ns.	50	90
Zn	1,338	533	ns.	ns.	ns.
Cr	151	214	ns.	ns.	ns.
Se	0.86	0.95	ns.	ns.	ns.
Co	18.79	21.84	ns.	ns.	ns.

ns – not standardized.
[a]Journal of law 2008, no. 119, item. 765.
[b]COM no. 157, 2016.
[c]EU 2019/1009.

of nickel and mercury in the ash samples do not meet the proposed requirements [18]. According to the current regulation on CE fertilizer products, the SSA meets the limited values for almost all indicated heavy metals. An exception is the exceeded value of mercury [24].

Table 4 shows the solubility of phosphorous in neutral ammonium citrate (P_{nac}) as a parameter indicating its bioavailability. Even though P availability is higher than in some other SSA [32], processing of the ash for increased P bioavailability is recommended. The low loss on ignition indicates that the incineration process was complete. The reason for the slightly negative value is not clear but may be due to oxidation processes during the experiment.

At this moment in Poland, it is forbidden to change the waste status of SSA without treatment, and it is not allowed to dispose SSA by the direct distribution on the earth's surface. However, it is possible to use this waste as a source of fertilizer raw materials in the mixtures of various components, in order to obtain a final fertilizer product meeting the specified requirements [52]. Therefore, SSA can be used as additives to the fertilizer granules having commercial value [53]. Anyway, the granulation of SSA in order to produce fertilizer is not recommended direction of SSA disposal, and the Ministry of Environment propagates the extraction of P from SSA [46]. Moreover, in the National Waste Management Plan 2022 (NWMP 2022), rational management of SSA by its storage in a way enabling the recovery of phosphorus should be promoted. The current NWMP 2022 indicates the directions of activities in the field of waste management based on the waste management hierarchy and being part of the transformation process towards CE [54]. The recovery potential of nutrients from waste generated in wastewater sector in Poland is large and the use of SSA as an alternative raw material could decrease the import of phosphate ore in Poland by about 30,770 t (13% P) which is the equivalent of today's 7% imported amounts [44]. Even though the country could decrease its dependency on the global phosphate rock market through P recovery from waste, P recycling is not a commonly used practice in Poland [55]. The proposed solution for resources and waste management is also in the line with the Resource Efficient Europe vision [56], an integral part of Europe 2020 strategy.

It should be pointed out that in the last years, a growing market demand for the use of waste from the wastewater sector, such as struvite (precipitated from sludge or crystallized from sludge liquor) [57] or ash-based products, as fertilizing products has been observed [24]. It relates to a promising technological progress which is being made in the field of recycling of waste, such as phosphorus recycling from wastewater, sewage sludge or SSA. In more and more European countries, P-recovery technologies are invented and implemented. The full-scale technologies for the recovery of P from waste generated in the wastewater sector (from digestate, liquor and ash) in Europe were upscaled, that is, in Germany, Belgium, United Kingdom, Denmark, Netherlands, France, Italy, and Spain [58]. Most of the technologies mentioned have been analyzed with the use of life cycle assessment and life cycle costing techniques in the P-REX project (Sustainable Sewage Sludge Management Promoting Phosphorus Recycling and Energy Efficiency) which was conducted from 2012–2015. It was underlined that only P-recovery technologies providing marketable raw materials or final products will have a chance for market penetration and replication. In Poland, for now there is no operating nutrients recovery technology. However, there is some progress in this area due to the Jarocin Waterworks Company has signed a contract for carrying out an investment project "Modernization and Extension of WWTP Jarocin", which includes the construction of an installation for the recovery of raw materials, such as nitrogen, phosphorus and biogas, in the municipal WWTP in Cielcza [55].

Table 4
Phosphorus bioavailability (stated as solubility in neutral ammonium citrate P_{nac}) and loss on ignition of SSA samples

Indicator	Sample I		Sample II	
	%	RSD (%)	%	RSD (%)
P_{nac} (phosphorus solubility in neutral ammonium citrate)	42.6	1.2	46.0	1.8
Residual moisture content	0.02	0.8	0.15	66.4
Loss on ignition	–0.3	5.8	1.8	69.4

There is still a very large nutrient recovery potential from water-based waste in all European countries that is not being used for this moment. Due to one of the main fertilizer constituents being phosphate rock and taking into account of Europe's need to import more than 90% of it, domestic P-rich waste could potentially cover about 20–30% of the EU's demand for phosphate fertilizer. An increase in recycling rates and reduction in import dependency for P is considered essential to European agriculture and are mentioned as one of the key objectives for the coming years, next to the publication of the EU Fertilizer Regulation in order to extend its scope to nutrients from secondary sources and organic sources [18]. Due to a lot of fertilizer raw materials are lost throughout the life cycle, and usually get into the water to speed up the eutrophication process, which is an unfavorable phenomenon, it is expected that in coming years, further development and implementation of nutrients recovery technologies in the wastewater sector shall be observed [59]. Currently, more and more research in the area of circular management of by-product of WWTP operation is carried out in the country, for example, conversion of sewage sludge in the processes of combustion, co-combustion [60], gasification [61] and pyrolysis. The research works in area of phosphorus recovery from SSA in Poland were conducted by research team from the Cracow University of Technology and the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences under the project "Environmentally-friendly technology for SSA utilization as a source of fertilizer and construction materials" ("PolFerAsh"). The patented method of phosphorus recovery using acid extraction methods has a chance to be implemented in the future [44].

5. Conclusions

The European countries are currently in the transition period from linear to the circular economy, where the added value of products is kept as long as possible and waste is directed to recovery of valuable resources from it. One of the industries that is particularly taken into account in the CE provisions regarding CE is the fertilizer sector due to the first implementing initiatives of the CE Action Plan was a proposal laying down rules on the making available of CE marked fertilizer products on the market. In this proposal, the recommended direction is the use of waste as source of raw materials for fertilizer products, which is in the line with CE model. Promising fertilizer RMs recovery potential appears in the waste coming from municipal WWTP, as wastewater, sewage sludge or SSA. In the present paper, SSA collected from a Polish mono-incineration plant was studied in order to assess the possibility of use it as a source of RMs in the fertilizer industry. The results show that the SSA has a good fertilizer potential, especially in terms of the content of P_2O_5, CaO and MgO were equal to 8.01%, 5.11% and 2.75%. In Poland, direct utilization of SSA as a phosphate fertilizer in agriculture is not possible due to the legal restrictions. Anyway, the analysed SSA could be a valuable source of the RMs for the substitution of primary resources in the phosphate, potassium and calcium fertilizer. The disposal of waste coming from wastewater sector as a source of biogenic RMs (phosphorus) is recommended direction in Poland. In this context, more rationale usage of water resources (which are under pressure) and more sustainable practices of water-based waste are expected, as a way towards the CE in the water and wastewater sector.

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