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Inventory of Wastes Generated in Polish Sewage Sludge Incineration Plants and Their Possible Circular Management Directions

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Abstract: A dynamic development of sewer networks and municipal wastewater treatment plants (WWTPs) leads to the formation a large amounts of municipal sewage sludges (MSSs) which have to be disposed. One of the MSS disposal practices is thermal conversion in mono-incineration plants. Nowadays, there are 11 such installations in Poland, with the total capacity 160,300 Mg d.w. of MSSs per year. This paper presents a comprehensive analysis of wastes generated in Polish MSS mono-incineration plants. As a consequence of MSSs incineration, various types of waste are generated including, for example, bottom and fly ash, dust or solid waste. The most valuable waste is sewage sludge ash (SSA), which can be used in other industries, as fertilizer or construction sectors. In the circular economy (CE) model, SSA should be treated as a secondary source of raw materials, such as phosphates (replacement of nutrients by P-rich ashes in fertilizers) or sand (replacement of sand by ashes in construction materials). Current practices of SSA management include landfilling, recovery at WWTPs or management by external companies (recovery, disposal or collection). To preserve the utility value of SSA, it should be stored selectively, and then directed to raw materials recovery. This creates the possibility of turning waste into a secondary resource, after meeting certain conditions which depend on which product the waste is directed to. Moreover, this waste management practice is recommended in the Polish documents regarding the usage of SSA, and it can strengthen the accomplishment of the European Green Deal, which is the newest roadmap for making the EU's economy sustainable and circular.

Keywords: municipal sewage sludge (MSS); sewage sludge ash (SSA); waste management; circular economy (CE); European Green Deal

1. Introduction

Nowadays, sustainable management of waste generated in municipal and industrial sectors [1] is required as part of the transformation towards a circular economy (CE) in the European Union (EU). It is especially important in the view of the new CE Action Plan adopted by the European Commission (EC) in March 2020 [2], which strongly underlines that the further efforts focused on the waste management are necessary due to annual waste generation being predicted to increase by 70% by 2050. This problem also concerns the management of waste generated in municipal wastewater treatment plants (WWTPs), the amount of which has increased in recent years as a consequence of the dynamic development of sewer networks and treatment facilities. The special interest of CE implementation in wastewater sector is dedicated to the possible use of waste generated in WWTPs as a source of secondary raw materials in other branches of industry. This creates the possibility of turning waste into secondary resources, after meeting certain conditions which depend on which products the waste is directed to.

Management of municipal sewage sludges (MSSs), which are products of wastewater treatment, plays an important role in the technological process of all WWTPs. The main goals of MSS management are:

- Decrease in MSSs' volume (lower sludge volume reduces the costs of its pumping and storage);
- Stabilization of organic substances present in MSSs [3].

One of the technically established and safe methods of MSSs disposal is their incineration in special dedicated installations. In previous years, an increase in the number of facilities for the thermal treatment of MSSs was observed throughout Europe, including, for example, 26 incineration plants in Germany [4] and 11 incineration plants in Poland. The main advantages of the mono-incineration of MSSs include complete destruction of the dangerous organic compounds (as pathogens and endocrine substances) and separation of selected contaminations (as heavy metals and inorganic compounds) [5]. Moreover, the incineration of MSSs reduces the nuisance odour which is experienced in the agricultural. This treatment method crates also an additional benefit: the possible recovery of raw materials [6] and energy [7]. Currently, more than 95% of phosphorus (P), which is a critical raw material (CRM) for the European economy [8] can be recovered from sewage sludge ash (SSA) generated during MSS incineration [9]. Moreover, a significant amount of energy contained in MSSs can be recovered and used to a certain extent to generate district heat and electricity [10].

Poland, entering the EU in 2004, has committed itself to implementing the European legal provisions regarding environmental protection, including waste management. Therefore, the disposal practices of MSSs in Poland have changed in recent years as a consequence of the implementation of the EU regulations, which clearly underline that waste landfilling should be reduced. For many years, MSSs landfilling was the main method of their management. Other methods of MSSs management were usage for agricultural purposes, fertilizing soil and plants (as a valuable source of nitrogen and phosphorus), compost production, as well as the reclamation of degraded areas [11]. The disposal practices of MSSs in Poland in the period 2010–2018 are presented in Figure 1. In recent years, a significant increase in the amount of MSSs directed to the thermal treatment was observed, which reached 234,300 Mg of dry weight (d.w.) in 2018, compared to 2010—66,400 Mg d.w.

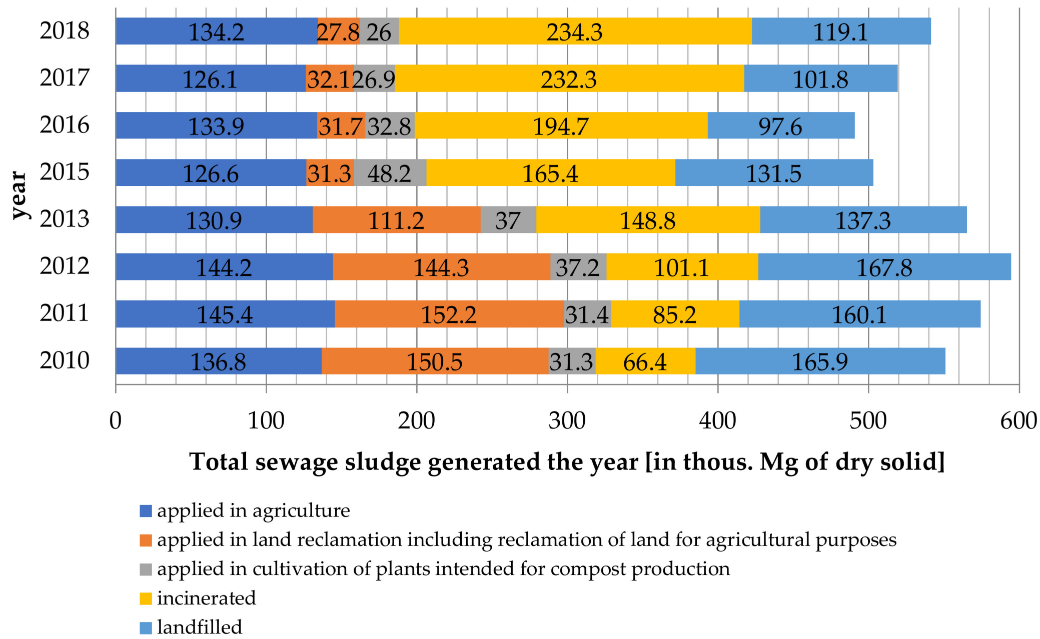

Figure 1. Disposal practices of the municipal sewage sludge (MSS) in Poland in 2010–2018 [11].

An increasing amount of MSSs directed to the combustion is a result of:

- Implementation of Directive 99/31/EC on the landfill of waste (LFD) in 2016 [12], which eliminated the possibility of disposing of completely untreated MSSs in sites other than a hazardous-waste landfill (heat of combustion > 6 MJ/kg); in Poland, thermal conversion was a key alternative to previously used methods of recycling and disposal;
- Modernization of existing MSSs mono-incineration plants in order to incorporate advanced technology designed to reduce the pollution of environment, including air protection;
- Construction of new MSSs mono-incineration plants thanks to implementation of infrastructure using EU co-financing (in 2010, in Poland there were only three MSS mono-incineration plants with the total capacity of 37,300 Mg d.w./year; currently, there are 11 MSS mono-incineration plants, with the total capacity of 160,300 Mg d.w./year) [13].

It is worth noticing that the recent investments in the construction and modernization of the MSS incineration plants appear in big Polish cities where the large WWTPs operate, such as Warsaw or Cracow. The incineration solves the problem of MSSs management, especially when the sludge amount is large and it is difficult to transport it, or the transport costs are significant. In the small WWTPs, sludges are removed from the treatment plant instead of incineration as this is more economically justified.

It should be underlined that, during the thermal treatment of MSSs, various waste streams are generated, as bottom ash, fly ash, dust or solid waste [14]. According to the legal requirements, these wastes also must be disposed of [15]. In the context of the possibility of further use of these waste streams as a source of recyclable materials, the quantity and quality of these wastes should be determined, to establish the most sustainable pathways for their management. Despite the fact that selected scientific studies were focused on the characteristics of wastes generated in Polish mono-incineration plants [6,16,17], as well as the possibility of their further usage (e.g., in the construction and fertilizer sectors), to date, no work has been carried out to identify the amount of individual waste groups, and methods for their management. The comprehensive knowledge about the amount and composition of wastes generated in incineration plants is crucial in order to identify, evaluate and select the appropriate resources recovery method [18]. Therefore, the current research presents a detailed inventory of the Polish mono-incineration plants of MSSs and the characteristic of wastes generated in these plants. Moreover, current waste disposal practices and recommended circular management directions, indicated in the Polish and European strategic documents, are presented and discussed.

2. Materials and Methods

This research was divided into three steps. The first step included a detailed review and characteristics of 11 mono-incineration plants of MSSs, located in Poland. The second step focused on an inventory of specific waste streams generated in these plants, with an indication of the current practices of waste management. The last step included an assessment of the possible disposal practices of wastes generated in Polish mono-incineration plants of MSSs, which are in line with the CE model. This step also included the proposition of recommended directions for the further use of wastes generated in these plants.

In the sections below, a detailed description of applied research methods is provided.

2.1. Methods Used in the Literature Review

The comprehensive literature review (desk research) was done based on an overview of the national regulations (Journal of Laws), the European regulations (EUR-lex), the national and international strategic and plannic documents related to waste management (including municipal sewage sludge), the circular economy (CE), the European Green Deal. An important source of information was the reviewed publications published on scientific platforms as Elsevier Scopus, Elsevier ScienceDirect, Google Scholar and Multidisciplinary Digital Publishing Institute (MDPI). The literature review was associated with the use of following keywords: „sewage sludge", „SS", "municipal sewage sludge", „MSS", "incineration", "combustion", „sewage sludge ash", „SSA", „waste", „waste management", "circular economy", "CE", „European Green Deal". An important source of data was also the statistic report published annually by the Central Statistical Office (GUS) and reports published by the analyzed WWTPs. This part of the research was realized in 2020.

2.2. Methods Used in the Wastes Analysis—Mass Flows and Composition

In the present study, the survey method was used to obtain specific information related to the amount and chemical composition of wastes generated in the Polish mono-incineration plants of MSSs. In this research, 11 municipal WWTPs were investigated, located in Warsaw, Cracow, Łódź, Gdańsk, Gdynia, Bydgoszcz, Szczecin, Zielona Góra, Kielce, Olsztyn and Łomża. The localization of the analyzed plants, including their capacity to incinerate MSSs, is presented in Figure 2. The criteria for the selection of these WWTPs was made based on their owning an installation for the thermal conversion of MSSs. The initial questionnaire with the specific questions related to the amount of waste generated during the combustion of MSSs was developed and four experts experienced in the area of sewage sludge management were consulted with. The expert team included two technological scientists and two WWTP managers who represented the analyzed plants. The final version of questionnaire was distributed among 11 mono-incineration plants. The request applications which were sent to WWTP operators (by e-mail and post) included questions about the amount and types (with the indication of specific codes) of waste generated during the MSSs incineration from 2011 to 2018, the characteristics of these wastes, and their disposal methods. The questionnaire was anonymous (no personal data were collected) and all information was obtained in accordance with the General Data Protection Regulation (GDPR). The response rate was equal to 91% (among all 11 incineration plants, only one decided to keep all data confidential). In the process of the thermal treatment of MSSs, various waste streams are generated. According to the Polish legislation, these wastes are classified under the specific codes indicated in Table 1 [14]. The wastes generated in incineration plants include non-hazardous and hazardous wastes. The hazardous wastes are generated during the purification of exhaust gases from gaseous pollutants. Their composition depends on the treatment method applied (dry or wet). Hazardous wastes are always marked with an "*" (asterisk). Non-hazardous wastes do not contain this marking. This part of the research was conducted in the period 2018–2019.

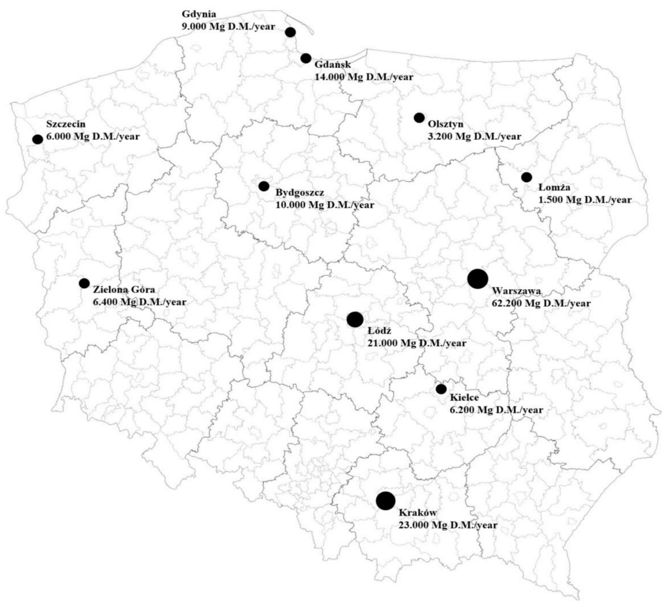

Figure 2. Polish municipal sewage sludge mono-incineration plants (own based on [16]).

Table 1. Wastes generated in mono-incineration plants of MSS (according to Polish legalization) [14].

No.	Description	Waste Code
	Non-hazardous waste	
1	Bottom slag and ash, other than those mentioned in 19 01 11	19 01 12
2	Fly ash other than those mentioned in 19 01 13	19 01 14
3	Boiler dust other than those mentioned in 19 01 15	19 01 16
4	Stabilized wastes other than those mentioned in 19 03 04	19 03 05
5	Solidified wastes other than those mentioned in 19 03 06	19 03 07
6	Wastes from waste pyrolysis other than those mentioned in 19 01 17	19 01 18
7	Sands from fluidized beds	19 01 19
8	Wastes not otherwise specified	19 01 99
	Hazardous waste	
8	Solid wastes from gas treatment	19 01 07 *
9	Sludges and other hydrated waste from gas treatment	19 01 06 *
10	Fly ash containing dangerous substances	19 01 13 *
11	Wastes from waste pyrolysis containing dangerous substances	19 01 17 *

3. Results

3.1. Inventory of Polish Mono-Incineration Plants of MSS

Currently, in Poland there are 11 mono-incineration plants of MSSs. Most of these plants were established in recent years with co-financing from EU funds, while the others have been modernized thanks to support from the EU. The characteristics of the analysed plants, including their capacity to incinerate MSSs and used technology for the thermal treatment of sludges is presented in Table 2. In seven plants, the fluidized-bed is used for the combustion of MSSs (Warsaw, Cracow, Łódź, Gdańsk, Gdynia, Bydgoszcz, Kielce), and in four (Szczecin, Zielona Góra, Olsztyn, Łomża) a grate stoker is used. According to the European Committee Reference Document (BREF), the fluidized bed is considered as the Best Available Technology (BAT) for the sewage sludge incineration [19]. In Poland, the most popular technology is the PyrofluidTM technology, which is used in four installations, in Warsaw, Kielce, Łódź and Cracow. This technology shows many advantages, such as the low emission of pollutants into the atmosphere, high combustion efficiency, reliability and work safety, possibility of neutralizing all wastes generated in WWTP (sewage sludge, screenings, fats and sand), safe waste disposal in accordance with the highest environmental standards, maximum reduction in waste. Moreover, during the combustion of MSSs, only ash and residues from chemical exhaust gas treatment are generated. There is a possibility to constantly monitor and control the quality of exhaust gases discharged into the atmosphere due to the location of the WWTP and sludge treatment installation in one place [13]. The total capacity of the incineration plants is equal to 160.300 Mg d.w./year. Therefore, it is alarming that these plants do not fully use their combustion potential, e.g., in 2014, 84,200 Mg of MSSs were incinerated, which accounts for only 52.5% of the total capacity of the incineration plants [13].

Table 2. Characteristics of the Polish MSS mono-incineration plants [19].

No.	Location/Town of the WWTP	Name of the WWTP Equipped with Incineration Plant	Rated Capacity [Thousand Mg d.w./Year]	Used Type of Incineration Furnace
1	Warsaw	Wastewater Treatment Plant „Czajka" (in Polish: Oczyszczalnia Ścieków „Czajka")	62.2	fluidized-bed
2	Cracow	Wastewater Treatment Plant „Płaszów" (in Polish: Oczyszczalnia ścieków „Płaszów")	23.0	fluidized-bed
3	Łódź	Group Wastewater Treatment Plant (in Polish: Grupowa Oczyszczalnia Ścieków)	21.0	fluidized-bed
4	Gdańsk	Wastewater Treatment Plant „Wschód" (in Polish: Oczyszczalnia Ścieków „Wschód")	14.0	fluidized-bed
5	Gdynia	„Dębogórze" Group Treatment Plant (in Polish: Grupowa Oczyszczalnia Ścieków „Dębogórze")	9.0	fluidized-bed
6	Bydgoszcz	Wastewater Treatment Plant „Fordon" (in Polish: Oczyszczalnia Ścieków „Fordon")	7.8	fluidized-bed
7	Szczecin	Wastewater Treatment Plant „Pomorzany" (in Polish: Oczyszczalnia Ścieków „Pomorzany")	6.0	grate stoker
8	Kielce	Wastewater Treatment Plant „Sitkówka" (in Polish: Oczyszczalnia Ścieków „Sitkówka")	6.2	fluidized-bed
9	Olsztyn	Wastewater Treatment Plant „Łyna" (in Polish: Oczyszczalnia Ścieków „Łyna")	3.2	grate stoker
10	Zielona Góra	Wastewater Treatment Plant „Łącza" (in Polish: Oczyszczalnia Ścieków „Łącza")	6.4	grate stoker
11.	Łomża	Łomża Wastewater Treatment Plant (in Polish: Łomżyńska Oczyszczalnia Ścieków)	1.5	grate stoker
		Total	160.3	-

3.1.1. Incineration Plant in Warsaw

The incineration plant located in the Czajka WWTP in Warsaw was launched in 2013 (commissioned on 31 December 2012). The technological line includes preparing sewage sludge for combustion by pre-drying, incineration of technological waste and sewage sludge in two fluidized bed furnaces and three-stage advanced exhaust purification process (multi-cyclone, bag filter, selective catalytic reduction-SCR). Sludge drying ensures that combustion can occur spontaneously without the need for external fuel. External fuel (in the form of natural gas) was only required to start the exploitation of the installation. The high-energy steam generated in the combustion process is a source of heat and electricity, which are used both for the needs of the incineration plant and the entire wastewater and sewage treatment in WWTP Czajka. The thermal treatment process is completely hermetic, while the air containing unpleasant odors is burned in furnaces. The total capacity of the plant is equal to 62,200 Mg d.w./year. The power achieved by an incineration plant can reach 18 MW (17 Mg steam/h). The fuel is waste from municipal wastewater treatment: sewage sludge and screenings, with a content of approximately 25% d.w. and 33% d.w. A polymer compound is used to facilitate the transport of sewage sludge by pipeline from the treatment plant to the incineration plant. The efficiency of the facility is 50–100% and results from the amount of waste directed to the thermal conversion. The technological line also follows for the solidification of ashes and residues from flue gas cleaning [20].

3.1.2. Incineration Plant in Cracow

The incineration plant located in the Płaszów WWTP was launched in 2010. It is the mono-incineration plant for dehydrated sewage sludge, consisting of one technological line, which includes storage and transport system, sludge drying node, thermal utilization node, heat recovery system, waste gas treatment system, monitoring system of process and waste gases, control system and waste solidification node. The total capacity of the plant is 23,000 Mg d.w./year. The achieved capacity of the installation is 0.8 MW. Dehydrated sludge up to 36% d.w. is burned in a fluidized bed furnace. Natural gas is used as an auxiliary fuel. Heat from flue gases is recovered in exchangers and then used for technological needs [21]. The installation in Cracow has only one technological line.

3.1.3. Incineration Plant in Łódź

The incineration plant located in the Group WWTP in Łódź was launched in 2010. Stabilized sewage sludge (approximately 20% d.w., 220 Mg/d) and screenings (approximately 21% d.w., 1.5 Mg/d) are incinerated on two parallel process lines with excess air. The reactor consists of an air chamber with a nozzle bottom for compressing the air and distributing it evenly in the bed, a fluidizing sand bed in which the thermal utilization process takes place, and an evacuation dome with a waste gas discharge pipe. The total capacity of the plant is equal to 21,000 Mg d.w./year. The thermal power of one furnace is 3.95 MW. A fluidized blower that blows heated air into the air chamber works with the reactor. Additional fuel (heating oil, biogas) is fed during start-up and in the event of a decrease in process temperature. The resulting heat energy is recycled to the installation to dry the sludge and heat the fluidizing air in the recuperator. The installation uses a dry waste gas purification system by dedusting them and removing gaseous and heavy metal impurities [22].

3.1.4. Incineration Plant in Gdańsk

The incineration plant in Wschód WWTP in Gdańsk was launched in 2013. Sewage sludge after initial mechanical dewatering with a content of approximately 22% d.w. is transferred to the thermal conversion. After drying in a disc dryer, the sludge (approximately 31.4% DS) is directed to a fluidized-bed furnace, where the temperature in the combustion chamber is >850 °C. Fuel oil is used as an auxiliary fuel. The flue gases is recovered in two exchangers (2.1 and 2.5 MW) and then used for technological needs (to the pre-drying node). The flue gas treatment is carried out using the dry method. A two-stage flue gas cleaning system with bag filters is used. The amount of fly ash generated is about 1 Mg/h in the first filter and 0.36 Mg/h in the second filter. The total capacity of the plant is equal to 14,000 Mg d.w./year [23].

3.1.5. Incineration Plant in Gdynia

The incineration plant in Dębogórze Group Treatment Plant in Gdynia was launched in 1997 (formally received in 1995), and thoroughly modernized in 2008. It is a mono-incineration plant for dehydrated sewage sludge, consisting of a system of sludge feeding equipment for drying, apparatus and installations for drying sludge, system of devices feeding sludge for combustion, fluidized bed furnace with equipment, combustion air supply apparatus and installations, installations and installations for the removal and purification of exhaust gases, equipment and the installation of purified exhaust gas cooling exhaust gas before the filter and ash removal system. Sewage sludge before entering the installation is first dehydrated (with the addition of flocculants, in chamber presses) to the content of 24–26% d.w, then dried to 50–70% d.w. of superheated steam at a temperature (at the dryer inlet) of approximately 560 °C. Then, the sewage sludge is completely incinerated in a fluidized bed furnace at a temperature 850 ÷ 900 °C. All ash produced as a result of the combustion process is discharged from the furnace together with flue gas in the form of fly dust. The process is periodically carried out autothermally. The input energy with sewage sludge is about 4 MW. Biogas is used as an additional fuel—an average burner output (for 50 m^3/h) is approximately 300 kW. The average biogas consumption is about 30–50 m^3/h. The total capacity of the ITPO is equal to 9000 Mg d.w./year [24].

3.1.6. Incineration Plant in Bydgoszcz

The incineration plant in Fordon WWTP in Bydgoszcz was launched in 2012. Dehydrated sewage sludge is collected in the sludge buffer from where it is pressure-transported to the sludge bunker. The mixture of sludge stored in the bunker by means of a piston pump is transported to a dryer for the evaporation of water from the sludge. Water vapor generated in the dryer is condensed and discharged to a sewage treatment plant. The dried sludge with a dry matter content of approximately 33% is directed through a feed system to a fluidized bed furnace. The furnace is a cylindrical tank lined inside with refractory lining. At the bottom of it lies a layer of sand. In the central part of the furnace, starter burners have been installed, whose task is to start the furnace and heat the fluidized bed to a temperature of 650 °C, enabling feeding of sludge to the furnace. Compressed air and biogas from sewage treatment plants are supplied to each starter burner. The shape of the combustion chamber space ensures proper mixing of unburned flue gas and secondary air, so that in the most unfavorable operating conditions, the flue gas temperature is at least 850 °C. The combustion of sludge takes place in a fluidized bed produces off-gas and coarse-grained material called slag and furnace ash. The steam produced is used in the sludge drying process, and its excess is directed to the Fordon WWTP. The total capacity of the ITPO is equal to 7800 Mg d.w./year [25].

3.1.7. Incineration Plant in Szczecin

The incineration plant located in the Pomorzany WWTP in Szczecin was launched in 2010. The incineration plant includes the technological line for the drying the sewage sludge and then incineration. The dehydrated sludge tanks are fed to two drying lines—BIOCON low-temperature belt driers—where it is dried to a content of over 90% d.w. The dried sludge is stored in two intermediate tanks, to which dried sludge is also delivered from the Zdroje WWTP. Two boilers with a mechanical grate are provided for burning dried sludge. The heat in the form of steam obtained from combustion of the sludge is directed to the drying installation. The flue gases are cleaned before entering the atmosphere by dosing activated carbon and calcium bicarbonate and separation on electrostatic precipitators. Exhaust emissions to the environment are monitored through on-line probes installed on the exhaust lines of the main combustion products, including carbon dioxide, carbon monoxide, nitrogen oxides, sulfur oxides, total organic carbon, dust. The total capacity of the installation located in the Pomorzany WWTP is equal to 6000 Mg d.w./year [26].

3.1.8. Incineration Plant in Zielona Góra

The incineration plant in Łącza WWTP in Zielona Góra was launched in 2012. It includes the technological line for drying and incineration of the sewage sludge. Drying technology is based on the production of three phases of the material in the dryer (wet, dense plastic, dry). Sludge inside the dryer is in constant motion caused by turbulence caused by a high-speed rotating shaft with blades installed on it inside a cylinder with a heating jacket. When the thin layer of sludge adheres to the cylinder walls, it is possible to perform heat exchange with high thermal efficiency. The drying process is an indirect process and it does not affect the modification of the sludge and in fact the heat treatment consists of the flow of hot process gas and maintaining the product at a temperature of 80 °C ÷ 90 °C. After drying, the sewage sludge is directed to incineration line. The movable furnace grate is equipped with a system for controlling the speed of movement inside the combustion chamber and an oil burner modulating the temperature level to the required values. The installation is equipped with a system for selective non-catalytic reduction of NOx to N_2 particles with a 35% urea solution. During the process in the combustion chamber, the resulting slag is automatically removed from the grate, cooled with water and transferred to a container. Dust from under the cyclone and the bag filter are collected into big-bags and manually transported to the place of temporary storage. The total capacity of the ITPO is equal to 6400 Mg d.w./year, but it is not in operation now [27].

3.1.9. Incineration Plant in Kielce

The incineration plant located in the Sitkówka WWTP in Kielce was launched at the end of 2011. Fluidized bed combustion technology is used, which makes it possible to neutralize both sewage sludge and other process wastes generated during sewage treatment. Sewage sludge, screenings, sand and fats are stored in special silos. The sludge is directed for drying in a disc dryer at a temperature of 215 °C, and then mixed with other waste and jointly transported to a fluidized bed furnace, where it is disposed of at 850 °C. The flue gases are purified by means of a high-performance, two-stage system mechanically through a cyclone and a bag filter, and chemically using reagents. The installation uses a system for the recovery and use of thermal energy from the combustion process, enabling the reduction of the amount of external fuel (light heating oil). The total capacity of the installation in Kielce is equal to 6200 Mg d.w./year [28].

3.1.10. Incineration Plant in Olsztyn

The incineration plant located in the Łyna WWTP in Olsztyn was launched in 2010. It includes sewage sludge dryer and incineration plant. Sewage sludge is first dried in special devices. Later, the dried sludge is processed into granules and in this form goes to the furnace. The incineration plant was designed to completely burn dried sludge with low moisture content up to 20% of the sludge volume. The main elements of the installation are a retention tank with a capacity ensuring a minimum of three days of sludge accumulation, a sludge water evaporation line (drying), a cyclotron for removing process gases, a unit for thermal sludge transformation (furnace) with auxiliary devices (e.g., heat exchanger, reagent dispensers, controlling devices, waste gas treatment installation and bagging device) and waste storage site. The combustion line consists of three sections: combustion section, waste gas purification section and heat recovery section. The heat generated during the burning of the pellets is used to dry another portion of the sludge, which saves on natural gas costs. The final combustion product are slag and ash as well as solid waste from waste gas treatment. The total capacity of the ITPO located in the Łyna WWTP in Olsztyn is equal to 3200 Mg d.w./year [29].

3.1.11. Incineration Plant in Łomża

The incineration plant located in the Łomża WWTP was launched in 2008. The installation for sludge mineralization is in operation, following anaerobic digestion of sewage sludge. The mineralization process is carried out in two stages. The first step is a drying the sludge in a low-temperature belt dryer, and a second–co-burning dried sludge and biomass (sawdust sawdust). The flue gases from the process of thermal sludge mineralization are subjected to several stages of purification. In order to limit the emission of odorous substances generated during the drying process, the process was encapsulated and deodorized using a biofilter. Thermal mineralization of dried sludge is carried out in a boiler installation equipped with an afterburning chamber with an earth-burner burner. The basic fuel is a mixture of dried sewage sludge and wood biomass in the proportion of 300 kg/h sludge and approximately 90 kg/h biomass. The incineration plant has an automatic system for the continuous measurement and recording of process parameters and concentrations of emitted pollutants. The total capacity of installation for sludge mineralization located in the Łomża WWTP is equal to 1500 Mg d.w./year [30].

3.2. Inventory of Wastes Generated in Polish Mono-Incineration Plants of MSS

The section presents the amount of specific wastes generated in Polish MSS mono-incineration plants. The presented findings do not include the amount of wastes generated in two facilities as one of the installations was only temporarily operated in 2012–2013 (Zielona Góra), and it is currently not used for the combustion of MSSs (they are directed mainly for fertilizing purposes). On the other hand, data regarding the second installation remained confidential (Łomża). For this plant, the fragmentary data are available from a previous project conducted in the Mineral and Energy Economy Research Institute, Polish Academy of Sciences (MEERI PAS) and publication Smol et al. (2016). The capacity of the installation in Łomża is the lowest among all analyzed incineration plants, and it is equal to 1500 Mg d.w./year. Therefore, the lack of detailed data from this plant does not significantly affect the general view of the situation related to the amount of waste coming from mono-incineration of MSSs in Poland.

The inventory of wastes generated in the Polish mono-incineration plants in 2011–2018 is presented in Table 3. All waste streams presented must be managed. Currently, the WWTPs operators have to pay the costs of transferring and collecting waste to external companies. These costs are particularly high in the case of hazardous waste (marked with *), which, in the case of waste 19 01 07 *, is more than two times higher than 19 01 14, calculated on 1 Mg of collected waste.

The wastes that have a high utility value are bottom and fly ashes (indicated here as SSA) [17], therefore, this waste stream is further analyzed in the current publication. The findings presented in Figure 3 show a significant increase in the amount of SSA generated in the analyzed period of time. In 2011, 8443 Mg of fly ash (19 01 14) and 1.581 Mg of bottom slag and ash (19 01 12) was generated, while in 2018, this amount was equal to 24,510 for fly ash and 24,510 Mg for bottom slag and ash. An inventory of wastes classified under these two codes is of great importance as they can be used in other industries, as cement industry, road construction, civil engineering as well as in advanced ceramic technologies, construction materials or phosphate fertilizers.

Table 3. Inventory of waste generated in the Polish mono-incineration plants.

No.	Technology Used	Waste [Code]	2011	2012	2013	2014	2015	2016	2017	2018
			Waste Generates During the Sewage Sludge Incineration [Mg]							
1	fluidized-bed	fly ash [19 01 14]	0	1785	5427	7371	4001	8420	12,574	10,127
		solidified wastes [19 03 07]	0	4253	5511	3624	460	3122	350	247
		solid wastes from gas treatment [19 01 07 *]	0	412	1524	2049	1075	2298	2778	1576
		sludges and other hydrated waste from gas treatment [19 03 06 *]	0	1559	1380	690	26	995	607	295
2	fluidized-bed	fly ash [19 01 14]	4340	2724	5231	4725	4452	4934	3310	4885
		solid wastes from gas treatment [19 01 07 *]	549	530	780	869	836	871	598	921
3	fluidized-bed	fly ash [19 01 14]	2990	3006	2126	2920	3260	3258	2949	3824
		solid wastes from gas treatment [19 01 07 *]	790	475	238	223	189	163	170	246
4	fluidized-bed	fly ash [19 01 14]	-	-	-	2616	2748	4076	3447	3279
		solid wastes from gas treatment [19 01 07 *]	-	-	-	1328	1734	2190	1951	1838
		stabilized wastes [19 03 05]	-	-	-	1157	109	375	10	58
5	fluidized-bed	fly ash [19 01 14]	1101	1315	1565	1282	1711	1760	1515	1676
6	fluidized-bed	bottom slag and ash [19 01 12]	792	388	435	493	672	1112	601	585
		boiler dust [19 01 16]	1707	1560	2415	1971	1393	1843	1971	2095
7	grate stoker	bottom slag and ash [19 01 12]	455	1011	902	1255	1316	1168	1562	1426
8	grate stoker	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
9	fluidized-bed	fly ash [19 01 14]	12	720	1152	699	699	907	813	719
		solid wastes from gas treatment [19 01 07 *]	26	383	440	236	236	318	247	230
		sands from fluidized beds [19 01 19]	-	-	-	-	106	-	-	-
10	grate stoker	bottom slag and ash [19 01 12]	334	338	122	130	146	323	269	235
		wastes not otherwise specified [19 01 99]	60	-	-	-	-	-	-	-
		solid wastes from gas treatment [19 01 07 *]	-	80	31	41	38	95	60	54
11	grate stoker	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d.: no data.

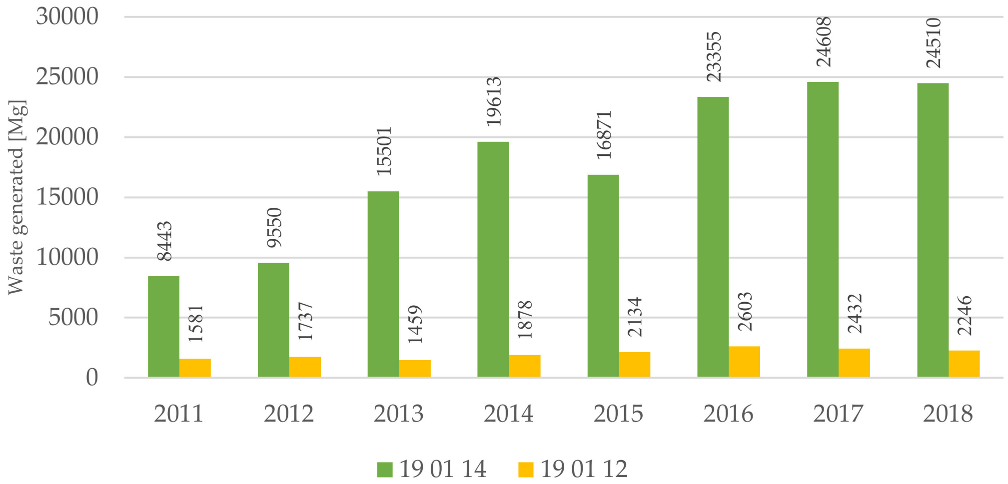

Figure 3. Selected waste streams generated in the Polish mono-incineration plants in 2011–2018.

In Poland, the largest amount of SSA is generated in big cities like Warsaw and Cracow. The most important player is plant in the capital of Poland (Warsaw), which produced more than 10,000 Mg d.w. in 2018 (38% of total SSA generated in all Polish mono-incineration plants). Significant amounts of ash were also produced at plants in Cracow (18% of total SSA produced in Poland), Łódź (14%), Gdańsk (14%) and Gdynia (12%). The share of other individual plants in the total amount of generated wastes does not exceed 10%, and is equal to 6% for Gdynia, 5% for Szczecin, 3% for Kielce, 2% for Bydgoszcz and 1% for Olsztyn.

The chemical characteristic of SSA produced in selected plants is shown in Table 4. These data come from the operators of the incineration plants. To direct this waste to landfilling, it is necessary to monitor the values of selected indicators, which have been indicated in the Regulation of the Minister of Economy of 16 July 2015 on the acceptance of waste for landfilling [31]. Therefore, these facilities provide and collect data on the quality of waste generated during the incineration of sewage sludge. The results presented in Table 4 show the characteristics of SSA, which can be landfilled as they meet the requirements [31].

Table 4. Chemical composition of SSA generated in the Polish MSS mono-incineration plants.

Element	Warszawa	Cracow	Kielce	Bydgoszcz	Limited Values for Acceptance of Waste for Landfilling [31]
		19 10 14		19 01 12	
			[mg/kg d.w.]		
Arsenic (As)	<1.0	0.03	0.52	<1.00	2
Bar (Ba)	0.56–4.04	0.89	5.330	2.19	100
Cadmium (Cd)	<1.0	0.004	<0.005	<0.01	1
Chromium (Cr)	<0.5	0.168	<0.02	0.25	10
Cooper (Cu)	<0.5	0.02	<0.03	0.26	50
Mercury (Hg)	<0.03	0.005	<0.001	<0.005	0.2
Molybdenum (Mo)	<0.05–12.0	8.2–12.2	4.010	2.02	10
Nickel (Ni)	<0.5	0.049	0.038	<0.1	10
Lead (Pb)	<1.0	0.04	0.567	<0.1	10
Antimony (Sb)	<0.5	0.3	0.537	<0.01	0.7
Selenium (Se)	<0.3–2.03	1.28	0.468	0.03	0.5
Zinc (Zn)	<0.5	0.13	0.660	<0.5	50
Chlorides (Cl^-)	<50–175	50	<50	301	15,000
Fluorides (F^-)	<0.5–141	78	3.730	9.7	150
Sulfur ($SO_4{}^{2-}$)	4280–11,750	6450	<100	>10,000	20,000

The presence of heavy metals such as arsenic, cadmium, lead, mercury and others, in wastes generated in mono-incineration plants [32] depends on the ratio of industrial wastewater in the total amount of treated wastewater. An inventory of industries that can be a sources of emissions of selected heavy metals to the environment includes:

- Cadmium (Cd): electroplating plant, production of dyes, production of batteries, production of paints, production of plastics, production of stabilizers for polymers, chemical industry, plant protection, graphics and printing industries;
- Lead (Pb): production of dye, production of batteries, production of fertilizers, motorization, power industry, plant protection electrochemical industry;
- Chromium (Cr): electroplating plant, tanneries, wood impregnation, textile industry, production of dyes and plastics, graphics and printing industries;
- Cooper (Cu): metallurgy, dyeing, textile industry, production of pesticides and fertilizers;
- Mercury (Hg): production of batteries, production of phosphoric acid, caustic soda, pulp mills industry, production of pesticides and metallic mercury;
- Nickel (Ni): galvanizing industry, paper industry, refinery, steel plant, production of fertilizers;
- Zinc (Zn): production of batteries, production of paints, production of plastics and plastics stabilizers, textile industry, graphics and printing industries [33].

The presence of industrial plants is constantly associated with the functioning of large cities, and therefore pollution generated in these plants can cause increased concentrations of heavy metals in wastes (including SSA), as the analyzed plants are located in large cities, and the incinerated MSSs come from municipal WWTPs that also accept selected industrial wastewater. For this reason, this wastes should be analyzed in detail.

In previous studies conducted on SSA generated in Polish facilities it was shown that SSA is carrier of valuable nutrients [6,9,32], as phosphorus, calcium, potassium or magnesium. The contents of selected nutrients in the SSA generated in the Polish MSSs mono-incineration plants are summarized in Table 5. According to the CE model, SSA should be directed to the recovery of nutrients [34] and production of commercial fertilizers. In recent years, a clear increase in the interest of both scientists and fertilizer companies in the use of secondary nutrient sources for the production of mineral fertilizers is observed.

Table 5. Content of fertilizer raw materials in SSA generated in the Polish MSS mono-incineration plants.

MSS Mono-Incineration Plant	Calcium (Ca)	Potassium (K)	Magnesium (Mg)	Sodium (Na)	Phosphorus (P)	Aluminum (Al)	Iron (Fe)	Reference
	[%]							
Warszawa	10.90	0.63	1.44	-	7.34	7.14	3.76	[34]
Warszawa	10.91	0.63	1.57	0.26	9.80	-	-	[6]
Cracow	10.50	0.53	1.93	-	7.80	2.34	11.34	[34]
Cracow	11.80	-	1.12	-	9.98	-	-	[35]
Cracow	10.05	0.58	1.90	0.20	7.80	-	-	[6]
Łódź	12.37	0.85	2.24	-	8.70	1.37	7.22	[34]
Łódź	12.37	0.85	2.24	0.45	8.70	-	-	[6]
Gdańsk	12.24	1.45	-	-	9.59	-	-	[36]
Gdynia	12.21	0.76	2.41	-	11.3	2.32	9.01	[34]
Gdynia	11.44	0.71	1.98	0.38	12.20	-	-	[6]
Bydgoszcz	20.71	0.67	2.18		8.03	2.94	4.19	[34]
Bydgoszcz	20.73	0.66	2.18	0.26	8.03	-	-	[6]
Szczecin	11.20	1.25	2.67		9.93	4.67	6.01	[34]
Szczecin	12.01	1.37	2.78	0.57	9.77	-	-	[6]
Kielce	12.48	1.34	2.72	0.39	8.29	-	-	[32]
Kielce	11.7	1.30	1.17		10.80	2.26	8.69	[34]
Kielce	11.71	1.30	2.45	0.29	10.80	-	-	[6]
Olsztyn	14.80	1.55	2.70	0.41	9.42	-	-	[32]

4. Disposal Practices of Wastes Generated in Polish Mono-Incineration Plants of MSS

This section provides an overview of wastes disposal practices in the MSSs mono-incineration plants in Poland, which are summarized in Table 6. The disposal practices include landfilling of wastes, recovery in dedicated installations (as stabilization/solidification) or reception and management by an external company (recovery or disposal or collection).

It is worth to noticed that there are two ways of wastes landfilling—transfer of waste to the specially dedicated landfills and co-landfilling with other waste streams generated in the WWTP. To preserve the utility value of selected waste streams, as SSA (e.g., with the possible phosphorus recovery potential), they should be stored selectively. It is particularly important for the SSA that contains large amount of phosphorus and can be directed to P recovery processes [37]. Landfilling of SSA with other wastes makes it impossible to recover this critical raw material [8]. Unfortunately, for many years, most of the ash was landfilled with other waste. This method excludes phosphorus recovery due to the lack of technology for P recovery from mixed wastes. It is worth emphasizing that the plant in Gdynia, for many years, selectively stored SSA in dedicated landfill (protected against groundwater contamination by SSA's leachate) located in the WWTP. From June 2016, SSA is packed in sealed big-bag sacks and stored in the WWTP, on 25,000 m^2 landfill, protected against contamination of groundwater with a layer of the high-density polyethylene (HDPE) geomembrane. The SSA stored in the bags is covered with a layer of soil to avoid the negative effect of UV rays on the material of the bags. SSA is also selectively stored in the plant in Łódź. In the plant in Warsaw, all waste streams are managed through recovery and stabilization in installations in the case of hazardous and non-hazardous waste. Part of the hazardous waste is directed to the disposal. In the plant in Cracow, wastes are collected by external entities for further industrial use. In the facility in Szczecin, SSA is stored in special dedicated containers and successively exported for further use by external companies. Wastes generated in the plant in Gdańsk and in Kielce are also collected by external companies. In the facility in Bydgoszcz, wastes are collected by external companies, and directed to the recovery processes. In the plant in Olsztyn, wastes generated in thermal processing of MSSs are directed to landfilling.

According to the Polish restrictions [15], hazardous waste must be subjected to the process of neutralization through stabilization and solidification (immobilization), and the remaining wastes generated in the incineration plants can be directed to different methods of disposal. In Polish facilities, hazardous waste is managed in accordance with the requirement of prior processing in order to protect it against uncontrolled release into the environment. These wastes are not currently used for the recovery of raw materials.

Table 6. Waste disposal practices in the Polish MSS mono-incineration plants.

No.	Waste Code	2011	2012	2013	2014	2015	2016	2017	2018
		Waste Disposal Practices							
1	19 01 14 19 03 07	Recovery in installation (solidified) or reception and management by an external company (recovery or disposal or collection)							
	19 01 07 * 19 03 06 *	Recovery in installation (solidified) or reception and management by an external company (recovery or disposal or collection). Part of the hazardous waste was directed to disposal process							
2	19 01 14	Reception and management by an external company (recovery or disposal or collection)							
	19 01 07 *	Reception and management by an external company (recovery or disposal or collection)							
3	19 01 07 *	Reception and management by an external company	57% Landfilling 43% taken by an external company	93% Landfilling 7% taken by an external company	Landfilling				
	19 01 14	Landfilling							
4	19 01 14 19 01 07 * 19 03 05	Reception and management by an external company (recovery or disposal or collection)							
5	19 01 14	Landfilling in heaps, spraying, soil covering					Landfilling in heaps, from 2016 in big bags		
6	19 01 12 19 01 16	Reception and management by an external company (recovery or disposal or collection)							
7	19 01 12	Reception and management by an external company (recovery or disposal or collection)							
8	n.d.	n.d.							
9	19 01 14 19 01 07 * 19 01 19	Reception and management by an external company (recovery or disposal or collection)							
10	19 01 12	Landfilling		Landfilling /sent for recovery	Landfilling		Landfilling/taken by an external company	Landfilling	
	19 01 99	Landfilling	-	-	-	-	-	-	-
	19 01 07 *	-	Landfilling	Landfilling/sent for recovery	Landfilling		Landfilling/taken by an external company	Landfilling	
11	n.d.	n.d.							

5. Circular Management Directions for Wastes Generated in Polish Mono-Incineration Plants of MSS

Waste management in Poland is realized in the line with the Act on waste [15] resulting from Community law (2008/98/EC) [38], and this also applies to sewage sludges and sewage sludge ashes. The management of MSSs is also regulated by specially dedicated strategic documents in Poland. According to the strategy for treatment of municipal sewage sludge in 2019–2022, which was published by the Polish Ministry of Environment, MSSs (unstable or stabilized on/outside the premises of the WWTPs) may be subjected to thermal transformation. This could be realized in the processes of conventional combustion or other thermal processes such as pyrolysis [39], gasification [40] or plasma process (in the case that the substances generated during these processes are then incinerated) co-combustion or hydrothermal methods [41]. The presented technologies of the thermal treatment of MSSs are indicated as promising ways of solving the problem of MSS management [42], which do not meet the requirements for their use on the surface of the earth or the production of compost. The possibility of the MSS incineration depends on their calorific value and the impact on possibly exceeding air emissions standards; however, the obligation to test waste intended for incineration applies only to hazardous waste, and there is no obligation to test all generated waste streams. Investigating waste before accepting it at the incineration plant is important for the operator to avoid exceeding emissions to air [13]. In the WWTPs equipped with incineration installation, the recommended direction is the mono-incineration of MSSs instead of co-incineration. Due to the aluminosilicate chemical composition and amorphous phase structure of the ashes generated during the MSSs mono-incineration, they can be further used in various industries [43] as substitutes in the construction materials or fertilizer products. The possible circular directions for disposal practices of SSA are presented in Figure 4.

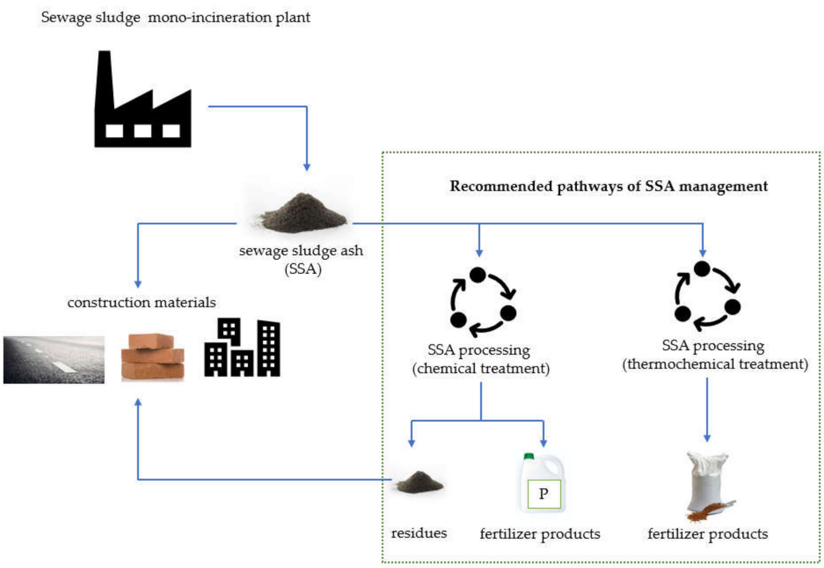

Figure 4. Recommended circular directions for disposal practices of SSA generated in the Polish MSS mono-incineration plants.

Nowadays, the special interest is P recovery from wastes [44] as a consequence of the rapidly depleting natural resources of phosphorus and indication of P resources (phosphate rock and white phosphorus) as the CRMs [45]. Wastes generated in WWTPs are valuable source of this nutrient for plants [46] and phosphorus can be recovered from wastewater, sewage sludge or ashes generated in the mono-incineration plants. The P recovery technologies and the agricultural usefulness of the fertilizers obtained from ashes are not fully recognized in Poland. There is a risk that these phosphorus fertilizers may have an increased content of some heavy metals and other impurities [13]. Despite the fact that a lot of research works in this field in the world were conducted [47,48], in Poland such analysis were usually limited to the development of the P recovery technologies [6,49], without evaluation of the effect of P fertilizers on plants (in field conditions). Therefore, it is appropriate to carry out additional agricultural research to assess the digestibility of nutrients and the impact of SSA-based fertilizers on soil properties and crop yielding [13]. However, as mentioned before, P recovery is only possible from wastes generated in the MSSs mono-incineration plants. Therefore, the rational management of products of thermal transformation of MSSs, in particular the storage of SSA to enable further P recovery, as it is practiced in more and more incineration plants, is indicated as the recommended solution in the National Waste Management Plan, adopted in 2016 [19]. There are several technologies for P recovery from SSA [50], as for example AshDec (thermo-chemical, heavy metal depollution) [46,51], EcoPhos (acidic wet-chemical leaching, heavy metal removal through ion-exchange) [52], ThermPhos (thermo-electric) [53,54], RecoPhos (acidic wet-chemical extraction) [55], PolFerAsh (acidic wet-chemical extraction) [6]. In the Polish Strategy for MSSs management [13], the recommended solution is chemical treatment of SSA instead of its granulation for fertilizer purposes. In the case of chemical treatment and the production of fertilizers, there are still residues after the leaching of P from SSA. The residues can be additionally directed to the construction sector as a substitutes of building materials (Figure 4), and therefore this method can be indicated as a circular solution. In turn, during the thermochemical treatment, SSAs are fully used in the process and there are no additional residues, therefore this solution is fully circular and does not require additional SSA management.

To ensure the safety of crops, uncontrolled release of fertilizers produced from waste into the environment is forbidden. The SSA-based fertilizers must meet the requirements to place such products on the market. The restrictions include the limit values of selected heavy metals, which are listed in Table 7. The content of heavy metals in fertilizer products is dependent on the respective recovery process and the sewage sludge used. Recyclates produced from SSA are free from organic residues and therefore, unlike some recyclates from precipitation processes, no longer contain residues of organic contaminants. These fertilizers are classified as mineral fertilizers. The Polish regulation provides the limit values for four elements in such products—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)—in the mineral fertilizers. In the newest European law, the limit value is also established for nickel.

Table 7. Limiting values of heavy metals that apply to the mineral fertilizer.

Element	Polish Fertilizer Regulations [56]	CE Fertilizer Proposal [57]	EU Fertilizer Regulation [58]
Arsenic (As)	50	ns.	40
Cadmium (Cd)	50	1.5	2.0
Lead (Pb)	140	120	120
Mercury (Hg)	2	1.9	1.0
Cooper (Cu)	ns.	ns.	ns.
Nickel (Ni)	ns.	50	90
Zinc (Zn)	ns.	ns.	ns.
Chromium (Cr)	ns.	ns.	ns.
Selenium (Se)	ns.	ns.	ns.
Cobalt (Co)	ns.	ns.	ns.

ns.—not standardized.

In Poland, the sustainable and circular solutions for P-rich wastes management should be implemented based on the experience of developed countries (such as Germany and Switzerland) which have already introduced the obligatory P recovery from selected wastes (as MSS and SSA) and proposed solutions towards the sustainable management of P resources (primary and secondary) according to the CE model. The further policy directions in this area should include the legal, technical and environmental recommendations next to the economic and social concerns. They have already been presented in the previous paper [59].

Interesting way of management of wastes generated in the incineration plants is the possible use of SSA in construction industry, including brick production, cement production, ceramic and glass production or road constructions. These ways of SSA management were reviewed and summarized in the review publication Smol et al. [60]. The substitution of building materials by several wastes (sludge, ash and other) in commercial products is possible, but after meeting the relevant provisions which concern the construction sector. All building standards in this area should be maintained. However, it should be stressed that substitution in building materials should only be considered when it is not possible to recover raw materials from waste (e.g., for mixed waste or hazardous waste), or specific resources have been already recovered.

As was underlined, the positive aspects of the thermal transformation of sewage sludge that cannot be used for fertilizing purposes includes the possibility of recovering energy from the sludge combustion process and using it for the drying process and potential recovery of P from SSA. These two directions—recovery of energy and raw materials—are in line with the current policy of the European Commission, which presented, in March 2020, a new Circular Economy Action Plan for a cleaner and more competitive Europe [2]. The Commission plans to create an Integrated Nutrient Management Plan, with a view towards ensuring more sustainable [2] application of nutrients (phosphorus, nitrogen) and stimulating the markets for recovered nutrients. Moreover, the revision of directives on wastewater treatment and sewage sludge, and assessment of the natural means of nutrient removal such as algae are also considered. The new CE Action Plan is a part of the European Green Deal strategy which aims to transform the EU into a resource-efficient economy where there are no net emissions of greenhouse gases (until 2050) and where economic growth is decoupled from resource use [61]. It assumes that, in the case where waste cannot be avoided, its economic value must be recovered and its impact on the environment and on climate change avoided or minimized [62]. This emphasizes the possibility of managing wastes generated in the water and sewage sector, both for energy and nutrients recovery, following the disposal of these wastes for construction purposes. The mono-incineration of MSSs brings economic savings because the energy recovered can be used for the plant purposes (as heat or electricity). Moreover, the usage of SSA as a secondary source of P can reduce the negative impact of phosphorus mineral fertilizers (which contribute to eutrophication) and reduce the EU's dependence on this critical raw material [63]. Considering environmental protection, hazardous wastes generated during the incineration of the sewage sludge can be solidified in building materials, which completely removes them from the environment without creating negative effects. Further proposals for legislative reforms in the field of waste will be introduced in the coming years at the European and national levels.

An important aspect of waste management in the CE model [64–66] should be also discussed in the context of MSS incineration. According to the waste management hierarchy [38], wastes should not be directed in the first place to the combustion because, during the thermal conversion, the specific resources are irretrievably lost. However, in the case of mono-incineration of MSSs, there are significant benefits, such as the removal of pathogens during combustion, reduction in the volume of sludges by about 80–90%, as well as the subsequent possibility of P recovery from SSA at a higher level (up to 90–95%) comparing to recovery from wastewater (45–55%) or sewage sludge (50–60%) [67–69]. Waste incineration is an important topic for various environmental debates around the world. In 2017, the European Commission, published the Country Report for Poland [70], in which prepared national and regional waste management plans that would move Poland towards prevention and recycling rather than creating incineration overcapacities were recommended. The EU's approach to waste management is based on the European waste management hierarchy [71] which sets an order of priority when shaping waste policy and managing waste at the operational level: prevention, preparing for reuse, recycling, recovery and, as the least preferred option, disposal (including landfilling and incineration without energy recovery). Due to the fact that installations for the incineration of the MSSs operate in the country and, moreover, they were financed from national and EU funds, it is expected that they will work efficiently and continue their operation. In large cities, it seems to be a rational way to manage the increasing amounts of MSSs that are generated. However, it should be noted here that the transformation process towards the CE should be supported by the recovery of energy and nutrients in these installations and the remaining waste should be managed in sustainable and circular way.

6. Conclusions

The recent investments in the Polish water and sewage sector as the construction and modernization of the MSS incineration plants have contributed to the creation of a significant amount of hazardous and non-hazardous waste streams, such as bottom ash, fly ash, dust or solid waste, which must be managed in accordance with national and European regulations. The development of new international initiatives to improve the quality of the environment, including those aimed at a more rational waste management, forces incinerator operators to seek new methods for managing wastes generated in these facilities. Both at the national and international levels, it is indicated that the main activities should include circular waste management methods, in which wastes are treated as a source of secondary raw materials. Despite the fact that many technological solutions have already been developed in this area (e.g., in the field of phosphorus recovery from ashes), they are not used in Poland. Therefore, further research should be conducted on circular methods of waste management, as well as the targeted transfer of knowledge and technology from more developed regions, such as Germany or Switzerland.

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