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Review

Sewage Sludge Management and Application in the Form of Sustainable Fertilizer

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Abstract: One of the most pressing environmental problems worldwide is sewage sludge (SS) management. Every year, wastewater volume increases and thus, the amount of SS produced increases as well. The disposal of SS in landfills, as practiced in many countries, is not a sustainable solution. Instead, SS, rich in organic matter and other nutrients, can be used as an alternative soil additive or fertilizer. The properties of these materials depend on their chemical composition and the method of treatment. Experience from a number of countries, such as the US and Europe, has shown that SS can be transformed from a waste into a valuable resource, provided that the final product fulfils the relevant regulatory standards. This review examines the sustainable conversion of SS to sustainable fertilizers, the impact on waste minimization, and the potential benefits in agriculture.

Keywords: sewage sludge; anaerobic digestion; composting; fertilizer; agriculture

1. Introduction

By 2050, global food production must increase by at least 50% to feed the projected population of 9 billion people, while several parts of the world will experience water scarcity. Irrigation of crops with unsuitable or untreated domestic wastewater, practiced in some parts of the planet, leads to soil contamination with pathogens, heavy metal ions, and salinity. A review published by Ungureanu et al. [1] discusses the state of water scarcity and food security issues, agricultural wastewater treatment, and possible risks to humans and the environment. An increase in greenhouse gas emissions causes global warming and climate change. This leads to a deterioration in the quality and general availability of drinking water, threatening food security and human health around the world. Efficient wastewater treatment can produce water suitable for irrigation and may help to reduce scarcity, conserve water resources, and improve food safety.

Wastewater is produced in huge amounts in big cities and is typically treated in wastewater treatment plants (WWTPs) employing biological reactors generating waste sewage sludge (SS). The principal sources of SS at municipal WWTPs are the primary sedimentation basin and the secondary clarifiers. Additional sludge may also come from chemical precipitation, screening, grinding, and filtration [2]. The amount of SS is constantly growing, and it currently constitutes a serious environmental problem. Unfortunately, the uncontrolled disposal of SS on land has been, and remains, the main method of solving this problem in many countries of the world. Another common practice is its disposal in landfills, many of which have reached their capacity and also do not meet the engineering standards. Waste management is directly or indirectly regulated by international conventions, national laws, and codes, as well as other regulatory and technical documentation. Each country has its own SS management system, regulated by domestic legislation, and international conventions regulate the transboundary movement of waste (e.g., the Basel Convention) [3,4]. Some conventions, i.e., the Stockholm Convention on persistent organic pollutants [5], provide detailed recommendations on the management of certain types of waste, but unfortunately, these conventions do not contain clear recommendations on the management of SS.

The European Union (EU) policy is to support the use of SS in agriculture, and the specific requirements are set in the 86/278/EEC directive on the use of biosolids in agriculture [2]. The SS directive requires member states to (1) apply maximum limit values for certain heavy metals in the biosolids and in the soil to which it is applied, (2) pretreat SS, and (3) restrict its use, including the frequency and quantity of application, on certain soils. The European Commission report on the environmental, economic, and social impacts of the use of SS on land [6] states that "if waste is to become a resource that will be returned to the economy as a raw material, then the much higher priority should be given to reuse and recycling." However, SS management poses challenges due to the complexity of its composition and large amounts produced; SS is usually 1–2% of the volume of treated wastewater [7]. Consequently, reuse and recycling are not the main treatment methods, and instead, most waste management authorities either dispose of SS in landfills or use incinerators to reduce the final volume of waste to be managed. Due to legislation restricting its uncontrolled disposal on land, many researchers propose ways to recycle sludge for further reuse as possible environmentally friendly options [8]. The EU circular economy (CE) action plan, adopted by the EU in December 2015, promotes the sustainable management of waste materials. The main goals are aimed at preventing waste disposal, increasing the efficiency of resource and energy use, and promoting the recycling of waste and by-products [9]. Furthermore, landfill disposal is prohibited in many European countries. However, in countries that joined the EU after 2004, the most common method of SS disposal is still the use of landfills. The SS produced in the EU is disposed of as follows [10]: reuse in agriculture (42.4%), incineration (26.9%), landfill (13.6%), and others (17.1%—composting, warehousing, and land reclamation). The extraction of useful components from biodegradable waste serves the goal of waste-free production in the EU and the prevention of greenhouse gas emissions, in accordance with the relevant strategies. Bioeconomy concepts include the sustainable management of organic waste and its processing into value-added products such as animal feed, food, and bioenergy. The use of biodegradable waste from the domestic, industrial, and commercial sectors of the economy is necessary to achieve the sustainability goals towards the development of waste-free industries and the prevention of greenhouse gas emissions. A shift in preferences towards recycling is also observed in the field of wastewater treatment, and WWTPs are turning into producers of secondary resources, namely reclaimed water, nutrients, etc. [11] (Figure 1).

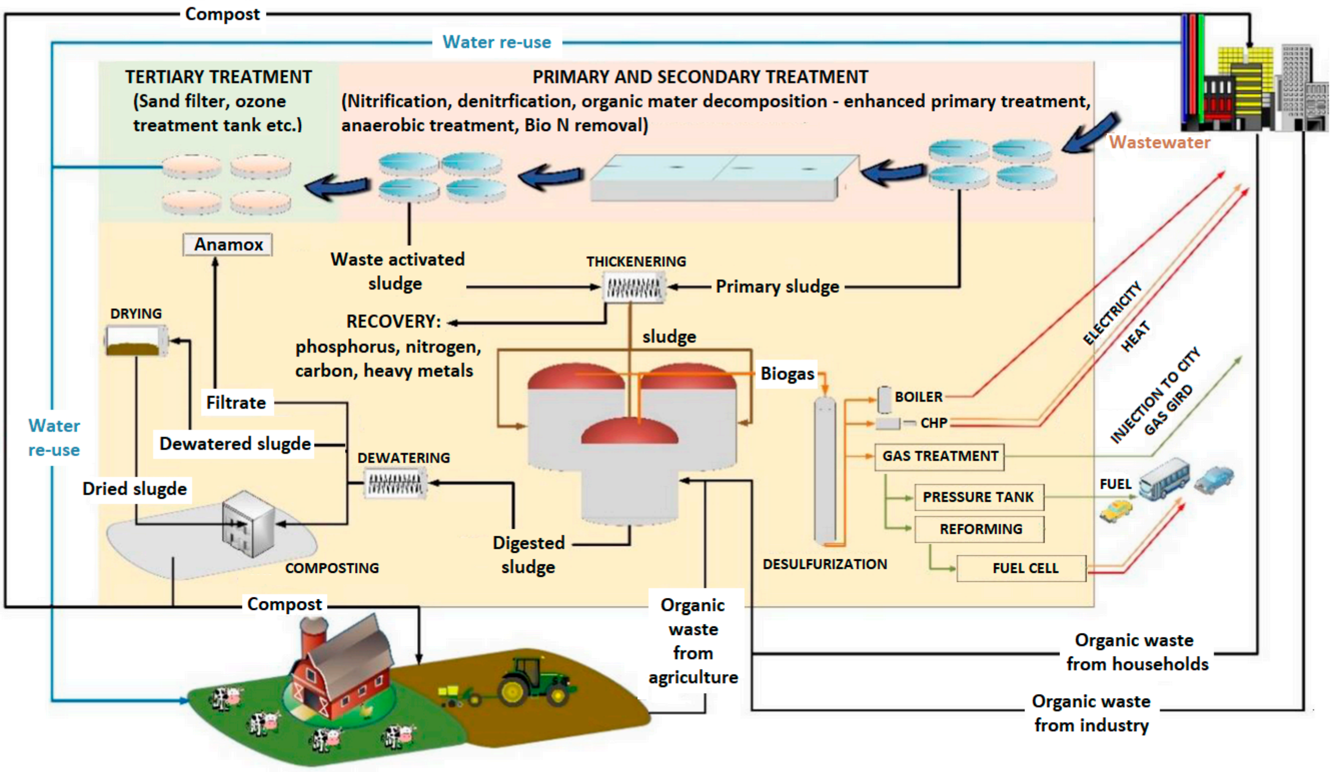

Figure 1. Dehydration of digestate from an anaerobic digester (WWTP) in the concept of a closed bioeconomy. Adapted with permission from [11]. Copyright 2021, MDPI.

2. Sewage Sludge Production and Management

SS includes solids generated at facilities for the mechanical, biological, and physico-chemical treatment of municipal and industrial wastewater and water intended for human consumption (i.e., surface and groundwater) [2]. The biological treatment of wastewater is one of the largest industries in the world, producing millions of tons of SS annually. Biological treatment is the most effective way to treat municipal and some types of industrial wastewater rich in organic load, although is known that certain types of organics either escape the treatment or are poorly degraded, for instance, antibiotics, drugs, pesticides, etc. [12]. The main portion of the organic load is turned into SS [13]. It is known that SS is an organogenic substrate containing biogenic elements (nitrogen, phosphorus, potassium, and their compounds) in concentrations comparable to those of traditional organic fertilizers. Therefore, much attention has always been paid to the rational use of the biological potential of SS. The composition of silt deposits is 40% organic matter and up to 60% mineral component, in terms of dry weight [14]. Moreover, the humic acids and proteins content is high [15]. SS contains trace elements, such as heavy metals, which, inadequate concentrations, are vital for plant development, but in high concentrations, can cause sludge toxicity [16]. Depending on the region's population density and industrial activity, the amount of heavy metals in SS can vary significantly and frequently exceed the maximum allowable concentrations [17,18].

The uncontrolled disposal of untreated SS in the environment, practiced in the past and still in use in many parts of the world, is a serious threat to the environment. Other common practices, such as disposal in landfills and incineration, are environmentally unsound and can be costly [19]. Therefore, alternative options for sludge management have been studied, such as in the production of building materials, biofuels, carbon, and electricity, as well as in agriculture. Efficient use of secondary resources, including SS, benefit many countries, both economically and environmentally. Waste disposal at open landfills is an irrational solution from both an environmental and an economic perspective, and it also contradicts legislative changes. There is a growing incentive to develop cost-effective reuse and recycling options by converting SS and bottom ash into new marketable materials [9]. The main methods of disposal of SS currently used in the EU are waste disposal, tillage, and incineration, which are used to treat almost 90% of the generated SS, as shown in Figure 2 [20]. Depending on the regional socio-economic, and geo-ecological characteristics of the countries, from 10 to 90% of the accumulated SS is used in agricultural production, with an average of 30–40% in the Western Europe, and at least 60% in the US.

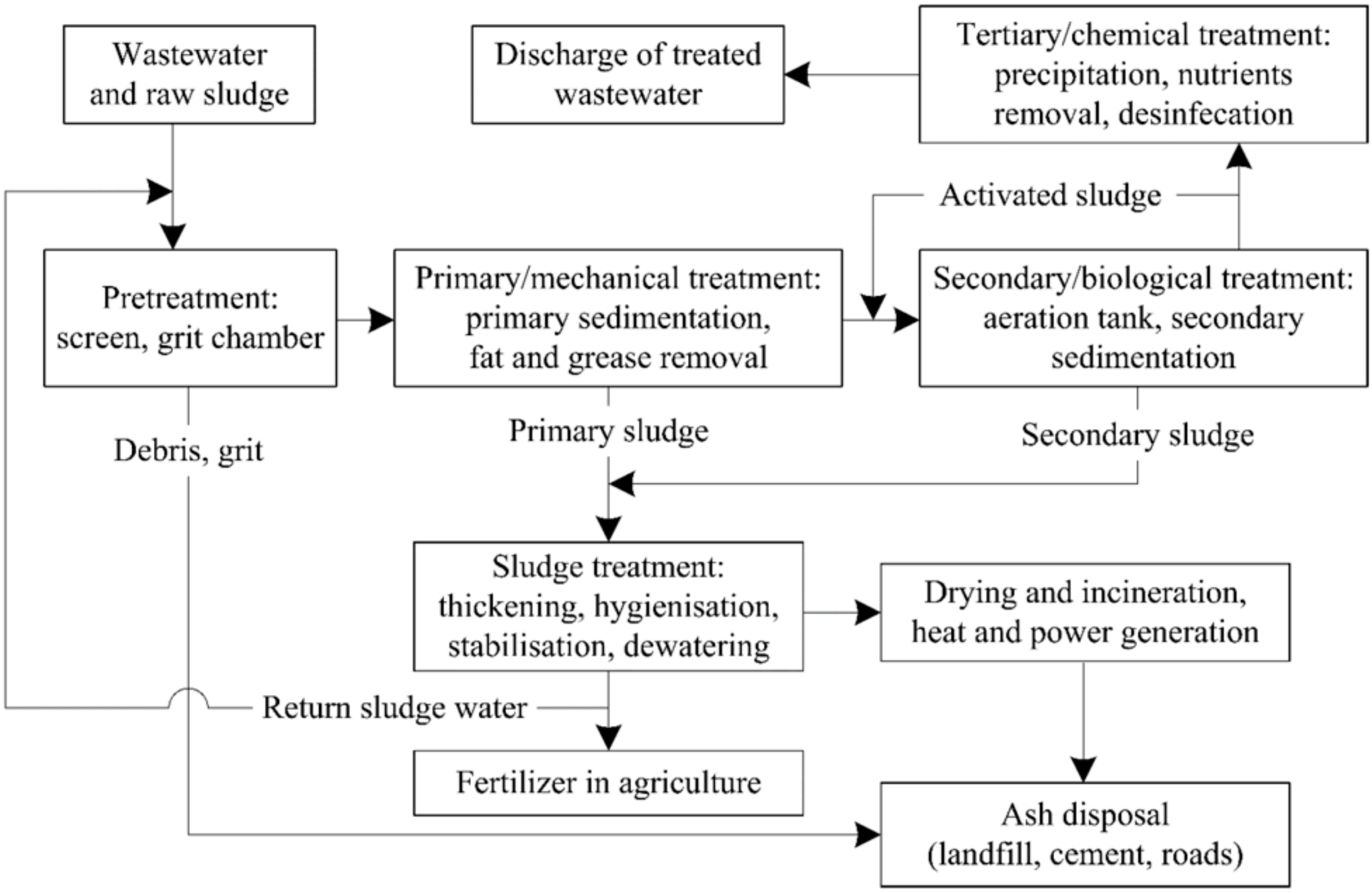

Figure 2. Main processes of wastewater and SS treatment in the EU. Reprinted with permission from [20]. Copyright 2019, MDPI.

Although in developed countries, such as in Europe, the technologies and legislation regarding pollution have long been developed, this is not the case for SS. However, the sustainable management of SS is of great importance as Europe moves towards a CE in line with the European Green Deal [21] and the goal of zero pollution. Figure 3 shows a diagram of the life cycle of SS from its generation at the treatment plant to its definitive treatment [22].

The experience of SS disposal in Germany, the USA, France, Finland, and several other countries indicates that if there is an effective sludge treatment technology and control over its use, most of the SS (up to 60%) can be used as a fertilizer in agriculture, in urban landscaping, as well as for inland reclamation, reforestation, and other works. The transformation of SS into a new substance or product that meets quality protocols, along with a new level of processing, will provide an opportunity to obtain scarce critical raw materials from secondary raw materials, leading to the successful management of SS waste. Ongoing research and development in the field of SS waste management shows that SS recycling can be used to produce valuable organic substances and plant nutrients that can be used as fertilizers [23–25] or additives to improve soil quality and to increase the fertility and productivity of agricultural land.

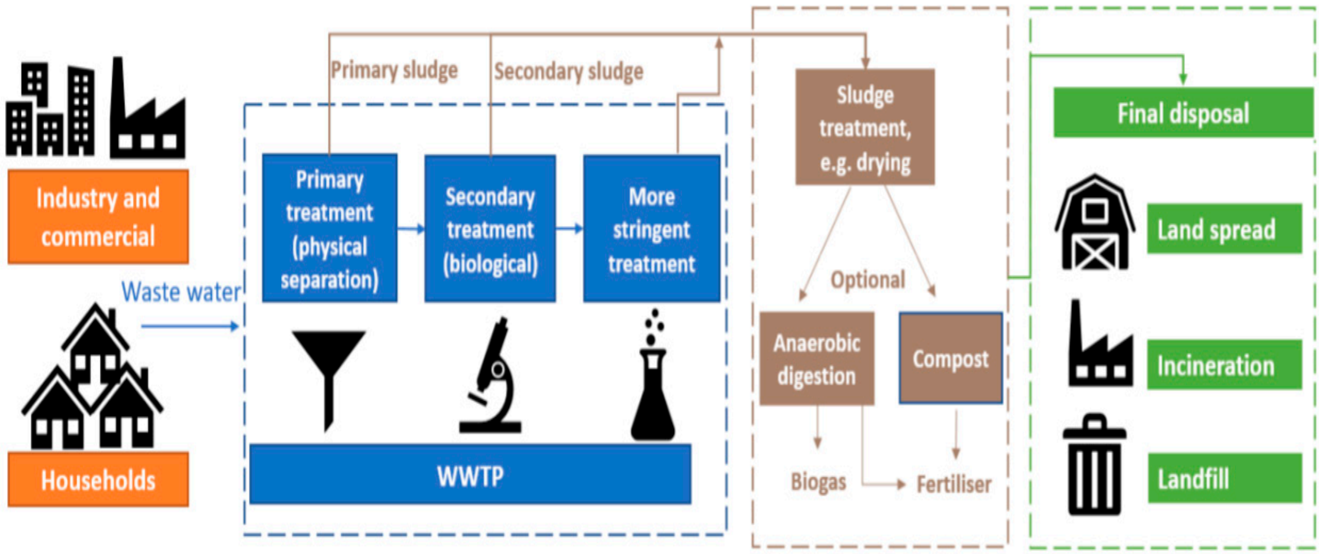

Figure 3. Life cycle of sewage sludge. Reprinted from [22]. Copyright 2021, European Environment Agency.

In the Regulation on the European Waste list (waste code 19 08 05), municipal sludge from WWTP is assessed as safe. However, an exception is described in the article of the Waste Framework Directive 2008/98/EC [26], stating that the sludge is safe only: if the competent authority of an EU Member State considers that the relevant evidence is sufficient to assign the code ANH to this type of waste. Once recovered, the SS must be processed to ensure economical and safe transport and disposal. Depending on the type of plant, primary and secondary sludges are treated separately or together. Co-treatment options include thickening, stabilizing, dewatering, and drying the sludge. Additional and well-established methods for controlling SS include lime treatment, anaerobic digestion (AD), and composting with other organic matter. The final disposal stage is the distribution of sludge over the soil surface, incineration, and disposal. In Europe, there are technologies for extracting phosphorus and, in rare cases, nitrogen. Removal of waste for agricultural purposes usually takes place in the area adjacent to the plant to minimize transport costs.

2.1. Treatment and Disposal Strategies for Sewage Sludge

The SS treatment methods are stabilization (composting, aerobic digestion, treatment with lime, etc.) and dewatering (air drying, vacuum filtering, centrifuging, etc.) [2]. The main objective of SS treatment is to produce biosolids that are safe for agricultural use (i.e., reduction or elimination of pathogens and reduction of fermentability of the final biosolids).

2.1.1. Anaerobic Digestion

AD is the most important SS treatment method. The SS is thickened, digested, and dewatered before it is used for other applications. A useful product of AD is the biogas, consisting of 60–70% CH_4, 30–40% CO_2 and small quantities of H_2, N_2, H_2S and H_2O, which is used for energy production. AD consists of a series of chemical reactions that lead to the decomposition of organic materials in the absence of oxygen [2]. Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. In the case of sludge digesters, this is a very common practice, with the addition of organic waste from the food industry or households as a co-substrate.

Although AD has been known for over a century, it has only been studied in depth for various commercial applications in the last three decades [27]. The use of AD for organic fertilizers is challenging due to the long duration of microbial reactions, usually 20–40 days. Each stage of decomposition involves a different consortium of microorganisms, belonging to both bacterial and Archean domains, with varying needs for growth. The physicochemical characteristics of the co-substrates added to the AD bioreactors at the treatment plant significantly influence the co-fermentation and the quality of the digestate. The co-digestion process increases biogas production, as there is a higher degree of volatile solids decomposition [28], resulting in an 82% increase in CH_4 yield, and a 29.5% removal of volatile solids compared to the treatment of SS alone. Digestate obtained after AD requires additional treatment before disposal. The solid fraction obtained after digestion consists of partially decomposed organic matter and a high content of NH_4^+-N and minerals [29]. Regardless of the type of food waste, NH_4^+-N levels in 2540–7200 mg/kg of dry matter and humidity of 70–96% have been reported in different countries [29]. The content of 60–70% NH_3 generates emissions and phytotoxic effect on plants [30]. Therefore, further stabilization through the composting process is required to improve the properties of food SS into a beneficial soil change in an environmentally sustainable manner.

Ting and Lee [31] reported H_2 and CH_4 production from SS using a strain of clostridium. In this work, the authors investigated the formation of H_2 and CH_4 during the AD of pre-treated SS (acidified, alkalized, and frozen/thawed). Yang and Wang [32] provided a critical review of AD sludge handling. H_2 production during sludge fermentation was observed. The primary consumers of H_2 are homoacetogenic bacteria, sulfate-reducing bacteria, and hydrogenotrophic methanogens. Homoacetogenic bacteria are strictly anaerobic and can catalyze acetate formation from H_2 and CO_2, such as *Clostridium thermoaceticum* and *Clostridium aceticum* [33,34]. A biochemical reaction can be described by the following equation:

$$2\,HCO_3^- + H^+ + 4\,H_2 \rightarrow CH_3COO^- + 4\,H_2O \tag{1}$$

Sulfate-reducing bacteria can use H_2 to form sulfides in the presence of sulfate [35], even at extremely low H_2 concentrations (0.02 ppm). The following equation describes the biochemical reaction:

$$SO_4^{2-} + 4\,H_2 + H^+ \rightarrow HS^- + 4\,H_2O \tag{2}$$

Hydrogenotrophic methanogens can use H_2 and CO_2 to form CH_4 [36]. For example, a biochemical reaction is described as the following equation:

$$HCO_3^- + 4\,H_2 + H^+ \rightarrow CH_4 + 3\,H_2O \tag{3}$$

Other H_2 consumption pathways are also observed in the production of propionic, valeric, and caproic acids, and the detailed reactions can be described as follows [37]:

$$C_6H_{12}O_6 + 2\,H_2 \rightarrow 2\,CH_3CH_2COOH + 2\,H_2O \tag{4}$$

$$C_6H_{12}O_6 + 4\,CO_2 + 14\,H_2 \rightarrow 2\,CH_3(CH_2)_3COOH + 10\,H_2O \tag{5}$$

$$C_6H_{12}O_6 + 4\,H_2 \rightarrow CH_3(CH_2)_4COOH + 4\,H_2O \tag{6}$$

AD also contributes to a "short carbon cycle" by removing carbon from the atmosphere. Carbon from organic residues for biogas production continues to be reused in the digestate, returning it to the soil [38]. Biogas and biomethane production as renewable fuel sources is justified in terms of reducing greenhouse gas emissions (CO_2 and CH_4) in agriculture and animal husbandry, as well as for improving the climate by 2050 [39–41]. Europe is the largest producer of biogas and biomethane globally [41]. Globally, more than 1000 M tons of biomethane could be produced by 2040, with average costs reduced by 15% compared to prices in 2018. Thus, digestate as a biofertilizer will increase shortly, contributing to agriculture and lessening the demand for the carbon-intensive production of mineral fertilizers.

2.1.2. Composting

One of the important treatment methods for the use of SS is composting or co-composting with other suitable biodegradable wastes and additives [42,43]. SS composting makes it possible to drastically reduce their volume, and such a technological process is not associated with significant emissions of hazardous substances, compared to incineration, and is acceptable from an environmental point of view. In recent years, compost production has gained wide popularity as a rational method of biowaste disposal due to its environmental friendliness, technological simplicity, and low cost [44–46]. In the process of composting, SS undergoes physical and chemical transformations with the formation of a stable humified final product, which ensures its disinfection and turns it into valuable components. However, the method is effective only at a specific moisture content of SS, and dehydration is required. This method makes it possible to obtain an inert and neutralized final product due to its (1) low cost and simple processing, (2) low energy consumption, and (3) environmental friendliness. During composting, there is a decrease in both organic contaminants and the bioavailability of heavy metals [47,48]. Composting improves sanitary and hygienic indicators due to the death of pathogenic microorganisms, helminth eggs, and fly larvae. Compost disinfection is effectively carried out by adding lime and calcite. The resulting product can be used to improve the structure and fertility of the soil. In this context, composting can be seen as the preferred strategy for the disposal of SS. However, the possible presence of heavy metal ions limits its application due to the impact on human health and environmental pollution [49,50]. Sludge composting is primarily considered an effective treatment method to overcome the problems associated with pathogenic microorganisms and other contaminants in the sludge, and prevents uncontrolled fermentation of organic components [51–53]. However, the latter can (1) interfere with plant growth, (2) cause inconvenience, and (3) be a source of CH_4 emissions [54–56].

Cao et al. [57] studied composting additives and fillers to investigate the aerobic properties of the composting process for food waste and residual sludge. Residual sludge, food waste, and bagasse mass ratios of 1:1:1, 2:1:1, and 4:1:1 were used. During composting, changes in nitrogen and phosphorus content in nutrients, microbiota, and metabolic function were observed. It is advantageous to maintain a high reactor temperature when the amount of residual sludge is relatively large and the proportion of residual sludge in the reactor is higher than the content of the original protease. The analysis of the microbial community showed that the 1:1:1 mass ratio promotes the growth and reproduction of beneficial bacteria and the reduction of the number of pathogenic bacteria in the reactor. On the other hand, a reactor with a high proportion of residual sludge encourages the growth of phosphorus-releasing bacteria. The conversion of ammonia and pentose phosphate in a heap of 1:1:1 mass ratio proved to be more favorable for glycolysis and to promoted the pentose phosphate cycle of the heap [57]. Co-composting is an efficient solid waste management method that helps to manage various solid wastes (i.e., poultry waste, animal waste, food waste, agricultural waste, municipal solid waste, industrial sludge, sewage, etc.) and turn them into valuable products, which can increase soil fertility by acting as a soil conditioner. This simple process has the lowest operating costs and is an alternative to expensive fertilizers used to improve the soil. The co-composting process can promote the formation of heavy metal complexes, whose mobility and availability tend to decrease with decreasing toxicity. Biodegradable waste is successfully co-composted with various types of organic waste to produce a higher-quality product. To enhance aeration, achieve the required moisture content, and control the ratio of carbon to nitrogen, the composting of SS is carried out with fillers, such as solid household waste, peat, sawdust, foliage, plant tops, straw, ground bark, and a portion of the finished compost. Optimal conditions for implementing the process are created when the humidity of the mixture of the sediment with the filler is 60–65%, the ratio of carbon to nitrogen is 20–30:1, and the pH of the fermented mass is between 5.5 and 8. The intensity of the process and quality of the resulting compost depend on the conditions created for the vital activity of the microorganisms [58]. Using biochar in compost production helps to reduce the production of gaseous pollutants and to improve the compost quality. In addition, when combined with sensitivity analysis results, emissions of biogenic air pollutants from compost and biochar production, as well as essential issues contributing to undesirable environmental impacts, were identified [59]. Wang et al. [60] reported the use of four different phosphates, as well as a mixture of ferrous sulfate and potassium monophosphate for SS composting. The addition of phosphates contributed to an increase in the temperature and the decomposition of organic matter, as well as to the conservation of nitrogen. Moreover, ferrous sulfate and phosphate show a synergistic effect in reducing nitrogen losses. The content of total phosphorus and mobile phosphorus in the compost with the addition of 1% phosphate was 40.9% and 66.1% higher than in the compost with the control treatment. Sequential extraction with the addition of calcium magnesium phosphate (CMP) makes it possible to reduce the mobility of Cd, Zn, and Cu by 24.2%, 1.7%, and 18.8%, respectively. However, in most cases, lead mobility increased. Seed germination control showed that the compost of all processing methods is favorable for agricultural use. The germination index of treated CMP with monopotassium phosphate (MKP) was 99.9 ± 11.8%, which was the highest among all treatments [60]. Thus, the introduction of phosphate additives provided an increase in the temperature and decomposition of organic matter in the SS during composting. All treatments with phosphate additives showed higher nutrient content and maximum nitrogen retention, as well as an increase in total phosphorus and available phosphorus in the product.

2.1.3. Pyrolysis

One of the promising developing methods for SS treatment is pyrolysis. The pyrolysis method consists of the irreversible chemical change of waste under the influence of temperature, without access to oxygen. Such processing plants require large areas, expensive equipment and, as a result, significant investments; therefore, the processing of sludge by pyrolysis, similar to incineration, is challenging to implement on a large scale [61]. The advantages of the method include the ease of storage and transportation of the resulting products and the fact that the equipment has low power requirements. Compared to direct waste incineration, the advantage of this method lies in its effectiveness in preventing environmental pollution, that is, the release of harmful chemicals into the air. The products resulting from pyrolysis have a high density, drastically reducing the volume of residues subjected to underground storage. The material resulting from pyrolysis exhibit reduced sludge toxicity and can be when used in agriculture [62].

2.2. Application of Treated Sewage Sludge as Fertilizer

Agriculture is the most important sphere of the world economy. In the agro-industrial complex of economically developed and developing countries, considerable attention is paid to increasing crop productivity and developing organic farming in order to improve food quality [63]. The shortage of land suitable for growing crops and other plant species is already becoming a global problem. Reducing the use of chemical fertilizers reduces the impact of chemical effluents on the environment. Organic fertilizers are an essential source of plant nutrition and energy material for microorganisms, as well as the most important means of humus reproduction in arable soils. In the global food market, mineral fertilizers are relevant, but expensive [64].

The use of SS as a soil conditioner and fertilizer is the most environmentally friendly option [65]. The Food and Agriculture Organization (FAO) published *Wastewater Treatment and Use in Agriculture* in 1992, and a short section is dedicated to the agricultural use of SS [2]. Activated sludge is especially rich in nutrients (nitrogen, phosphorus, potassium, and their compounds) and micronutrients (copper, molybdenum, and zinc) [66,67]. The Netherlands, Sweden, and Spain use more than 60% of the sludge for agricultural purposes; Denmark, England and Switzerland use around 45% for the same purposes [68]. Long-term field trials in Sweden studying the spreading SS on agricultural land have been implemented since 1981, showing a general increase in crop yield of about 7%, with no negative effects on plant uptake of heavy metals. In addition, regarding the accumulation of certain organic contaminants in soil upon repeated spreading over time, studies show that the levels in the soil do not pose a risk to the soil ecosystem or humans [69]. Similar trials in Denmark showed that SS does not impede the health and reproduction of earthworms and other soil fauna [69]. There are also examples of effective reclamation of disturbed lands using treated wastewater and SS due to the active impact of waste on the soil formation process [60].

Over the past few years, various methods have been developed for obtaining non-traditional fertilizers from SS. A summary of the application of SS as fertilizer is presented in Table 1.

Table 1. Fertilizers from SS and its uses.

Material	Source	Method for Obtaining Fertilizer	Results Obtained, Fertilizer Effect	References
SS	WWTPs	Undigested sludge and anaerobically digested sludge	The soil quality was improved, SS contributed to the maintenance and improvement.	[23]
SS	-	Treated with a mixture of calcite and dolomite	The particle size distribution of degraded soils was improved.	[70]
Ash from SS incineration	Municipal and agri-food industries	Thermally dried and anaerobically digested	The soil properties were improved, with higher values of organic matter, total potassium, nitrogen, and minerals.	[71–74]
Dehydrated fresh SS	-	Burning	The germination index showed that the composts were safe for agricultural use. The addition of phosphate additives contributed to higher temperatures, decomposition of organic matter, and increased fertilizer efficiency, as well as reduced mobility of heavy metals.	[60]
Sludge from municipal and industrial sewage	WWTPs	Composting using a reactor	The application of pyrolysis products to soils deficient in phosphorus and contaminated with toxic metals effectively reduced the mobility of pollutants and added available phosphorus.	[62]
Digestate	-	AD	A more positive influence was found on the increase in soil organic carbon (SOC). The content of mobile humic substances (MHS) tended to increase in pastures and field crop rotations in soil treated with digestate.	[75]
Dehydrated SS	Municipal WWTPs	Autothermal thermophilic aerobic decomposition (ATAD)	The process produces a sludge that does not rot and does not contain pathogenic microorganisms, parasites, and fungi. The sludge is sanitary, hygienically safe, and contains valuable nutrients. The product has a positive effect on the physical, chemical, and biological properties of soils.	[76]

Table 1. *Cont.*

Material	Source	Method for Obtaining Fertilizer	Results Obtained, Fertilizer Effect	References
SS	-	-	The process significantly increased the yield of barley grain, and improved soil microbiological properties, such as basal respiration, microbial biomass, and the activity of several soil enzymes (urease, dietary protease, phosphatase, and β-glucosidase) that promote nutrient reuse for crops.	[72]
SS	Sewer channels of the city	Air dried, crushed and passed through a 4 mm sieve	The process increased soil pH, organic matter content, EC_e, NPK, Ca + Mg, and trace elements (Fe, Cu, Mn, and Zn). It increased soil productivity, yield, and the quality of wheat. A significant increase in straw yield was noted.	[77]

The content of organic matter, nitrogen, phosphorus, and other macro- and microelements increases in soils when using SS and composts based on them as fertilizers or soils [78,79]. Under the influence of precipitation, as a rule, the acidity of soils decreases and their water capacity increases, which is especially important for soils of light granulometric composition. Soils' thermal, water, and air regimes improve, and their biological activity is increased. It has been experimentally proven that a single application of organic solid biodegradable waste improves the structure and fertility of the soil [80]. The authors have identified some recommendations that should be considered when using land. These are the parameters of soil and solid biological substances, such as the content of nutrients, microelements, and the influence of climate on the sorption mechanism. The addition of biosolids increases carbon (C) uptake of soils by adding organic carbon to the soil and indirectly increasing root biomass. Repeated application of compost not only helps maintain soil quality, but also accelerates carbon sequestration from biodegradable solids and from plant biomass. The influence of heavy metals carried by biological solids on C complexation and inhibition of microbial activity due to the need for C sequestration should also be considered [81]. It has been noted that a significant contribution of organic compounds to the soil occurs through an increase in soil biomass with the addition of biological solids [81]. This is due to an improvement in the soil moisture capacity and a decrease in soil susceptibility to water and wind erosion, as well as an increase in fertility due to an increase in nutrient content. However, the increased content of heavy metals, biogenic elements, and potentially toxic substances in SS necessitates constant monitoring of the composition and characteristics of the sludge and the calculation of permissible application rates, as well as continuous monitoring of the application of digestate to qualitative changes in agricultural land [23].

The role of AD digestate is well known in several studies in which its action as a soil additive increases soil organic matter levels [82–84], as well as its role as a source of nutrients, namely N, P and K [85,86]. However, more knowledge about the agronomic behavior of the digestate as a source of nitrogen for crops is needed. Low-cost and technologically simple processing of the AD product for solid–liquid separation is widely used, which makes it possible to obtain two fractions with different characteristics. The liquid fraction contains most of the total digestate nitrogen, with values around 87% [87]; 61% is in the available mineral form (i.e., $N\text{-}NH_4$) [88]. The liquid phase can substitute for N-mineral fertilizers, and the solid fraction can be offered as an NP-organic fertilizer. The study results showed that the solid phase might have a different ability to allocate nitrogen to crops, depending on the ratio between their mineral and organic forms of nitrogen. Nitrogen input into crops is affected not only by its content in mineral nitrogen, but also by its distribution between mineral and organic states, which causes differences in the balance between immobilization/mineralization. The digestate used in the fertilization of vegetable crops showed a positive effect. The digestate not only contributed to an increase in soil organic matter, but also to an increase in soil pH, which helps to improve conditions for the growth of crops. However, the digestate has limitations. After the AD of biowaste, the composition of the digestate becomes more stable compared to the initial mixture. The solid fraction of the digestate is characterized by a high content of organic forms of nitrogen, which also have low mineralization. The final nitrogen input to crops is also deteriorated due to soil immobilization and the release of mineral nitrogen due to the digestate. For autumn-winter vegetable crops, fertilizing with digestate is recommended to be carried out simultaneously with the introduction of mineral forms of nitrogen. The content of organic nitrogen (ON) in the digestate in regards to total nitrogen (total Kjeldahl nitrogen (TKN)) can be used as an index to assess the efficiency of nitrogen use by a crop. To maintain the production of biomass as a mineral nitrogen fertilizer (85 kg of nitrogen per hectare (kg N/ha)), the authors suggested: (1) at a ON/TKN ratio of about 0.65, 170 kg N/ha digestate plus 25 kg N/ha should be applied to the soil; (2) at a ON/TKN ratio above 0.80, 85 kg N/ha digestate plus 60 kg N/ha mineral N should be applied. In both cases, the digestate had a positive effect as an organic additive and reduced the consumption of mineral nitrogen fertilizers, while simultaneously creating an additional energy source through biogas. The liquid fraction contains large amounts of biologically stable organic carbon due to the retention of stable compounds during AD. The high biological stability measured for the liquid phase is similar to that of composts, confirming good soil improvement properties. Thus, AD produces a biologically stable and valuable fertilizer—digestate, which can be used as an alternative to mineral fertilizers in crop production. However, the massive use of digestate can (1) provoke public dissatisfaction due to an unpleasant odor, and (2) cause environmental problems associated with nitrate leaching and ammonia emissions into the atmosphere. Comprehensive field experiments are needed to support the evidence for the use of digestate in agriculture and to facilitate its proper management. Tambone et al. [88] carried out studies on replacing mineral nitrogen fertilizers (urea) with digestate and its processing products for corn silage. The digestate and the liquid fraction of the digestate were applied to the soil with pre-sowing and top-dressing fertilizers, compared to urea, using both surface and subsoil application, during the sowing seasons. AD products can replace urea without reducing yields, except for the surface application of fertilizers derived from AD. Digestate and its derived products, due to the high biological stability acquired during AD, significantly reduced the effect of olfactometry when applied to the soil, with 82–88% fewer odors than those found in untreated biomass. The ammonia emission data, as expected, showed that the correct use of digestate and its derived products requires their application to the soil to avoid the evaporation of ammonia into the air and preserve the value of the fertilizer. Its underground application reduced ammonia emissions by 69% and 77% compared to surface application.

3. Conclusions

The literature review shows that SS constitutes a pressing environmental problem which requires sustainable solutions and investments. The circular economy (CE), which dominates the current trends in sustainability, offers new ways to deal with SS, not as a waste, but as a resource. SS is rich in organic matter, nitrogen, phosphorous, and other nutrients, and following treatment, it can be transformed from a problem to a solution in the form of soil additives and fertilizers. There are a number of treatment methods available, such as composting and AD, each with its own advantages and disadvantages. The quality of the treated SS depends on several factors, including the odor, presence of toxic organic compounds and heavy metals. These may limit the use of the treated SS in agriculture, i.e., for edible crops, but there are other potential uses for this waste as a soil additive, for instance, in silviculture or the rehabilitation of mine sites. Moreover, regulations determine the uses of the treated SS, and there are a variety of approaches used in different countries.

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