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ISSUES OF BIOLOGICAL AND AGRICULTURAL TREATMENT OF MUNICIPAL SEWAGE SLUDGE

Abstract
Increase of sewage sludge production in Poland requires undertaking specific methods for their utilization and disposal. The reason is that sewage sludge, in addition to being rich in organic matter, and biogenic compounds such as nitrogen and phosphorus, which are beneficial from an agricultural point of view, also contain heavy metals, toxic organic pollutants such as persistent organic pollutants and polycyclic aromatic hydrocarbons, inorganic compounds such as silicates and clay, and pathogenic bacteria and other microbial contaminants. This implies problems with further use of such polluted sludge as fertilizer in agriculture. The aim of this paper is to analyze the possibilities and limitations of natural management of sewage sludge, taking into account their effects on the restoration and conservation of organic matter in the soil and the yielding of plants. In addition, the main methods of treatment of polluted sludge before introducing it into the environment are considered.

Key words
sewage sludge, agricultural utilization, pollution, land reclamation methods

Introduction

According to data from the National Waste Management Plan (KPGO) (MP 2010 No 101, item 1183), in 2008, 567.3 thousand tons of dry matter (d.m.) of sewage sludge in municipal sewage treatment plants were produced in Poland. This amount may increase, due to the requirement to regulate our country's sewage economy before 2015, which is the result of Poland's accession to the European Union. The National Urban Wastewater Treatment Program (KPPCK) imposes on each agglomeration in which pollutant effluents are generated equivalent to those generated by 2000 adults (Population Equivalents), that they should be equipped with a sewage collection and treatment system appropriate to local conditions and needs. In addition to improving the quality parameters of the water, a significant effect of KPPCK is to increase the production of sewage sludge. According to data from KPGO, it is estimated that in 2015 the production of sewage sludge in Poland will amount to 642.5 thousand tons d.m. This represents a 62% increase in production compared with 2002 (MP 2010 No 101, item 1183). Based on assumptions and demographic forecasts, the estimated amount of sewage sludge to be generated in Poland by 2018 may amount to 706.6 thousand tons d.m. (MP 2010 No 101, item 1183).

Sewage sludge generated during the sewage and stormwater treatment process in the current practice was most often stored in the area of the treatment plant, as well as exported to and from landfills or incinerated. According to data published in the Statistical Yearbook of Environmental Protection 2004-2009, more than 31% of generated sewage sludge was subject to storage, and 14.5% to temporary storage. Meanwhile, the entry into force of the provisions of the Waste Act of 14 December 2012 (Journal of Laws 2013 item 21) prohibits (from 1 January 2013) the disposal of sewage sludge with the following parameters: content of organic carbon greater than 5% of d.m.; loss on ignition of more than 8% of d.m.; combustion heat exceeding 6 MJ/kg of d.m. As a result, the lack of the possibility of storing municipal sewage sludge results in the need to develop cost-effective and environmentally-friendly methods of disposal. One of these is natural management, which is conducive to the physical and chemical characteristics of sewage sludge rich in organic substances and nitrogen, phosphorus, magnesium, calcium and sulphur. Such a precipitate is therefore characterized by high fertilizer value and can be naturally utilized, among others, to fertilize soils or to reclaim soilless lands [1].

In the remainder of the paper, the possibilities and limitations of natural sewage sludge management have been discussed, taking into account their effects on the restoration and conservation of organic matter in soil and plant yields, and in the case of contaminated sludge, discussing the main methods of treating this before introducing it into the environment.

1. The possibilities and constraints for the natural management of municipal sewage sludge

Increased concentrations of heavy metals in sludge, especially from large sewage treatment plants serving multi-thousand urban agglomerations, limit their agricultural use. For this reason, in the last few years the thermal transformation of sludge in incineration plants has been postulated. It is estimated that by 2018 about 60% of sewage sludge will be incinerated. This in turn implies the problem of building new incinerators for sewage sludge, since until now only 9 have been built, serving the largest urban agglomerations such as Warsaw, Kraków, Łódź, Szczecin, Olsztyn, Gdynia, Bydgoszcz, Płock and Kielce. Moreover, it should be noted that the thermal disposal of sewage sludge generates the production of toxic ash, which amounts to 10-12% of the initial sewage sludge weight and leads to emissions of polluted gases, carbon dioxide and methane. Incineration of sewage sludge is also an extremely costly solution, due to the need to remove sludge (about 80% of fresh sludge weight). Thus, the cost of sludge incineration is about 60 EUR/ton of wet mass [2], and in the case of Poland it ranges from 180 to 280 PLN [3]. Drying using the conventional method is very energy-intensive, but the use of solar energy or biogas requires substantial investment [4]. Moreover, during the thermal transformation of sewage sludge, despite the capture of more than 99% of the dust produced by this process, the by-product is also combustion waste and gases, including carbon dioxide [5]. The use of suitable filters reduces the emission of pollutants such as trace elements into the atmosphere, but at the same time shifts the problem of recycling to the captured ashes.

An alternative method of management of municipal sewage sludge, especially for small and medium sewage treatment plants with little or no combustion potential, while producing sludge with moderate or low metal contamination, is their use as a fertilizer for growing crops. Such use of sludge is determined by the acceptable trace elements in both sludge and soil itself. In accordance with the Ordinance of the Minister of the Environment of 13 July 2010 on municipal sewage sludge (Journal of Laws 2010 No. 139 item 924), the maximum dose of sewage sludge that can be used in agriculture per unit of land, meeting the tolerance limit for trace elements, may not exceed 3 tons of d.m./ha/year, and in the case of single use, a 3-year dose of 9 tons of d.m./ha. This method of using sewage sludge determines a safe level of potentially toxic trace elements for the soil, and in addition, shapes the sequestering potential of exogenous organic matter in the soil and also positively affects the growth and yield of crop plants.

1.1. The impact of municipal sewage sludge on restitution and preservation of organic matter in soil

Reducing the supply of crop residues to soil as a result of crop rotation simplifications and the absence of many natural fertilizers in the region results in the decrease of organic matter in soils, which the European Commission has identified as one of the main threats to soil quality in Europe. Thus, an important aspect of the use of sewage sludge for soil fertility is the restoration or conservation of soil organic matter. It is estimated that in the last 30 years the content of humus in the soil has decreased by 40% [6], and the average organic carbon content in the soils of Poland is currently 1.25%. In addition, according to European Commission standards, organic matter content of less than 1.7% precedes desertification of areas, leading to the risk of soil degradation and the need for reclamation to sustain the productive and environmental functions of soils. Also, analyses carried out by the Institute of Crops, Fertilizers and Soil Science - National Research Institute (IUNG-PIB) confirm the negative balance of organic matter on agricultural land in many regions of Poland [7]. Considering the above, the application of fertilizers to environmentally safe sewage sludge seems to be an effective method, not only from an economic point of view but also in the context of the protection of the function of degraded soils or low-quality natural soils. As IUNG-PIB research shows, approximately 3/4 of sewage sludge produced in Poland meets the current criteria for trace elements, providing a potential source of organic soils. These studies were conducted on a representative sample of 60 sludge effluents of different size classes, and the results of these studies were published in 2008 [8]. When controlling the sludge dose and its quality, there is also no risk of polluting groundwater and crop yields with trace elements. Unfortunately, currently acceptable sludge doses (only 3 tons per hectare per year), while effectively protecting the environment, largely limit the potential for soil organic matter enrichment by treating soil with sludge. In addition, it should be emphasized that in sludge there is from 35 to 80% of organic matter, with an average content of about 60%. Results from the 29 municipal sewage treatment plants show that sewage sludge produced there is characterized by properties comparable to that of manure, indicating the potential for agricultural use. At the same time, the distribution of sewage sludge should take place in the soil, as the energy and nutrients released during decomposition will have a positive influence on soil properties and plant growth [9].

Sewage sludge containing large amounts of organic matter can be used not only for direct fertilization of soils, but also for the production of vermicompost. Composting of sewage sludge with earthworms (vermicomposting) leads to rapid change of the odorous waste substance in the tuberous fertilizer, rich in plant nutrients. The vermicompost produced in this way is made from organic waste and owes its characteristics to the vital functions of the earthworms that migrate and feed on them [9]. It is particularly advantageous, compared with traditional compost. Vermicompost contains large amounts of enzymes and microorganisms associated with the metabolism of earthworms. Our own research shows that vermicompost contributes to the growth of biomass of plants (e.g. *Salix viminalis*) by about 35%, and biomass of selected grass species on average about 17% [10]. The introduction of such compost to the soil stimulates its biological life, which is particularly important for soils that have lost their self-cleaning ability due to contamination.

Sewage sludge has also been successfully used for the reclamation of toxic waste dumps from zinc and lead smelters. The positive effect of sewage sludge was a result of improved water retention of the top layer of the landfill, reduction of solubility of trace elements (sorption of organic matter, precipitation of insoluble metal compounds by phosphorus introduced with sludge), and fertilization of sludge [11].

1.2. The effect of municipal sewage sludge on crop yield

The use of sludge has a beneficial effect on the improvement of soil fertility and fertility; it contributes to the dynamic growth of the content of organic substances, which are rapidly transformed into soil humus. This is particularly important in the case of degraded soils, as well as light soils, easily permeable, whose fertility and physical properties due to fertilization by sewage sludge radically improve, thereby contributing to increased crop yields. The cumulative application of sludge to winter barley (*Hordeum vulgare* L.) resulted in a significant increase in yield (47%), which is the number of ears obtained from the surface unit. The yield of barley obtained from plots fertilized with sludge was higher than that obtained on mineral fertilized plots. Larger barley yields obtained after fertilization with sewage sludge are attributed to improved soil conditions, by providing an additional organic carbon pool along with the applied sludge. In addition, it was found that the beneficial effect of sludge fertilization is visible only in the second and third year of sludge application [12, 13]. It has also been shown that the regular annual application of sludge has a cumulative effect on the content of nitrogen remaining in the soil that can be mineralized. On the other hand, the long-term effect of a single sewage sludge application is observed only when the organic nitrogen dose is high, because the nitrogen bound in organic compounds has a half-life of about one year. Winter barley plants after cumulative fertilization of sludge also show an increase in dry matter yield, increased total protein content in young leaf tissue (to the emergence stage), and increased grain weight compared with non-fertilized and mineral fertilized plants [12, 13]. Proteins in the plant tissues reserve nitrogen. The observed high concentration of total protein soluble in barley leaf tissue at early stages of development and the post-flowering decrease in protein concentration may be indicative of efficient translocation of the assimilated nitrogen into the growing grain. A similar relationship was observed for total soluble sugars. Fructose, sucrose and fructans are the major water soluble carbohydrates accumulated in winter cereals. Barley plants fertilized with sewage sludge exhibited faster translocation of soluble sugars from leaf tissues to growing grains, when compared with non-fertilized plants and mineral fertilized plants. This data indicates faster physiological development associated with the entry into the generative phase of plants growing on sludge-rich soils.

In alfalfa plants (*Medicago sativa* L. cv. Aragón), growing on soil enriched with sludge increased the photosynthetic yield, contributing to increased plant growth and increased photosynthesis (soluble sugars), as well as increased total protein content in leaves, while increasing the feed quality index [14, 15].

Our own research on the effect of willow sow fertilization on sewage sludge from one of the largest sewage treatment plants in Poland, Group Wastewater Treatment Plant in Łódź, showed a willow biomass increase from 26 to 73% in relation to the increase of the control willow [28]. The best variant of fertilization, resulting in the largest increase of biomass of willow larvae, was a variant of sludge + compost + potassium. Such an aided plantation can yield crops on average of 77.45% bigger, compared with a non-fertilized plantation. In the variant fertilized with sludge and potassium, yields were 23% bigger on average than the variant with sludge only, while calcium supplementation increased biomass by an average of 20%. Simply adding compost increased willow yield by an average of 12%, compared with the sludge variant.

In addition, it should be emphasized that sludge fertilization improves the plant's resistance to unfavorable environmental conditions such as drought, salinity or low temperature, which is manifested by the increase in free proline concentration in plants (organic chemical compound from the α-amino acids group of organic compounds) [16]. An example of this could be the research of Antolin et al., [12] who observed an increase in free proline concentration in the leaf tissues of young barley plants after the winter period. The low temperatures that were imposed on barley during winter could induce observed changes in proline concentration, but similar changes were not observed in untreated plants. The extent of proline concentration in winter barley leaf tissue was additionally dependent on weather conditions in winter: the more severe the conditions (low temperature, no precipitation), the higher the concentration of free proline. This may indicate a greater resistance of barley plants cultivated on sludge to adverse environmental conditions. Taking into account the fact that fertilization with sludge increases the availability of nitrogen in the soil that is then assimilated by plants, it can be used for proline synthesis, which can be a nitrogen reserve and carbon source for plants [17]. Thus, an increase in the concentration of free proline in the tissues of plants exposed to the above-mentioned stress factors, cultivated on the substrate with the addition of sewage sludge, may indicate that a strategy to survive in winter conditions has been developed, subsequently ensuring that sufficient carbon and nitrogen are supplied to the growing grain. Also, alfalfa plants cultivated on substrates enriched with sewage sludge and subjected to drought stress were characterized by better growth, as well as higher concentrations of free proline and soluble protein compared with control plants (cultivated without sludge). Therefore, the obtained results indicate the increased resistance of alfalfa grown on soils with sewage sludge [14].

An additional aspect of the use of sewage sludge in crop cultivation has been the beneficial effect of high phosphorus content in sediments on reducing the solubility of trace elements and their toxicity in plant tissues. Phosphorus supplementation on chromium-contaminated soils contributed to a significant reduction in the toxicity of this element to the growth and development of rapeseed (*Raphanus sativus* L.) [18].

The impact of environmental stress on plants can induce secondary oxidative stress in their tissues, characterized by an imbalance between the production of reactive oxygen species and their neutralization. Plant cells have an enzymatic and non-enzymatic defense system against the damaging effects of reactive oxygen species on proteins, lipids, and nucleic acids. Alfalfa plants exposed to drought stress showed less oxidative lipid damage when grown on substrate enriched with sewage sludge. [15]. It has been shown that the application of sludge induces the activity of antioxidant enzymes such as ascorbyl peroxidase, catalase, and glutathione reductase, and increases the concentration of ascorbic acid only in root warts, while no significant changes in the activity of the antioxidant system are observed in the root and leaf tissues. The above data may indicate the beneficial effects of sewage sludge present in the substrate on the growth and condition of plants cultivated under conditions of common environmental stresses.

2. Contamination of municipal sewage sludge and methods of their treatment

Sewage sludge, in addition to undesirable trace elements, whose content is regulated by the Ordinance of the Minister of the Environment of July 13, 2010 (Journal of Laws No. 139 item 924) as well as the desired organic substances and fertilizers essential from the fertilizer point of view, may also contain organic impurities. Among these, the most hazardous are considered to be polychlorinated *dibenzo-p*-dioxin (PCDDs) and polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), organochlorine pesticides, phthalates, among others. In accordance with the provisions of the European Union (EU), these compounds are classified as Persistent, Bioaccumulative and Toxic *(PBTs*). They act mutagenically and carcinogenically, causing in animals such diseases as liver damage, precancerous lesions and cancer, e.g. malignant melanoma. The risk associated with the discussed compounds is particularly high due to their ability to accumulate in soil and sewage sludge [19], and it is enhanced by bioaccumulation and biomagnification in aquatic and terrestrial food chains.

Studies conducted over the last few years indicate that sewage sludge contains significant amounts of PCDD/PCDF compounds, ranging between 2.26-1270 ng in the International Toxic Equivalent (I-TEQ)/kg in the United States [20], 19-225 ng I-TEQ/kg in Great Britain [21], 7 - 160 ng I-TEQ/kg in Spain [22] and between 16.85 and 74.56 ng I-TEQ/kg in Poland [23, 24].

Also, concentrations of PAHs in sewage sludge range from 3674.1 to 11236.3 µg/kg (values for 5 wastewater treatment plants: Stalowa Góra, Kraśnik, Lublin, Biłgoraj, Zamość) [25]. Other studies by the same author have shown the PAHs value in sewage sludge from 10 sewage treatment plants located in south-eastern Poland ranging from 261.6 to 2000.8 µg/kg [26] and 4700 µg/kg for the sewage treatment plant in Zamość [27].

Our own studies, conducted to assess the effect of sewage sludge (with a concentration of 17 toxic PCDD/PCDF congeners amounting to 3270.07 ng/kg and 29.72 ng TEQ/kg) on soil toxicity measured as Toxic Equivalent (TEQ), showed increased toxic PCDD/PCDF congeners in the surface layer of the soil (0-15 cm). The results also indicate that pollutants are contaminated with PAHs at concentrations ranging from 1400-1800 mg/kg. At the same time, the results of analyses using the Phytotoxkit test showed up to 60% inhibition of root growth of *Lepidum sativum, Sorghum Saccharatum* and *Sinapis alba* at 3 and 9 tons/ha of sludge in accordance with the Regulation of the Minister of the Environment of 13 July 2010 on municipal sewage sludge (Journal of Laws No 137/2010, item 924) [28].

Another limitation for the use of sewage sludge in agriculture is the presence of pathogenic bacteria and eggs of enteric parasites. It is important to remember that the sanitary characteristics of sewage sludge are variable, and are shaped by many factors, such as the standard of living and health of the people in the area, the type of sewage treatment plant and the methods used to process sludge. Sludge management is often on the margins of wastewater treatment processes. Minor amounts of sludge in small treatment plants often lead to the skipping or downplaying of this problem by designers and investors. Sewage sludge, due to its physicochemical composition and particularly high organic content, is inhabited by microfauna and microflora, forming a specific biochemical. It consists of viruses, bacteria, fungi, parasitic invertebrates and their eggs. Among them there are both pathogenic micro-organisms, dangerous for humans, and saprophytic, inert from the sanitary point of view. The current legislation specifies the acceptable number of *Salmonella spp.* and live parasitic eggs of *Ascaris* spp., *Trichuris* spp., and *Toxocara* spp. However, sewage sludge may contain other types and species of bacteria, including pathogenic bacteria, among others: *Escherichia* spp.*, Shigella* spp.*, Pseudomonas aeruginosa, Clostridium perfringens, Bacillus anthracis, Listeria monocytogenes, Vibrio cholerae, Mycobacterium tuberculosis, Streptococcus pyogenes, Proteus vulgaris*. Thus, in the case of the natural use of sludge, it is very important to know the survival time of pathogenic organisms. The necessity for the proper disposal of sludge, from the point of view of sanitary and hygienic issues, before use for agricultural production causes such biological contamination of sludge subjected to technological processes becomes an important and urgent matter.

Considering the above, there is a need to develop an efficient way of treating sewage sludge prior to its introduction into the environment. This will contribute to an increased share of sewage sludge available for agriculture, reducing the environmental impact of its incineration. Knowledge of the effectiveness of individual methods of treating pollutants in sewage sludge is negligible, however, when analyzing the available literature data, specific methods can be distinguished in terms of removing trace elements, stimulating organic pollutants or removing pathogenic bacteria present in sewage sludge (Table 1, 2 and 3).

As far as trace elements are concerned, natural methods have so far been used mainly for the remediation of contaminated soils (Table 1). Phytoevaporation involves the taking of ions of elements such as Hg, As, Se by the plants, and then converting them into volatile compounds that are released into the atmosphere. This method has limited application, due to its low efficiency and secondary atmospheric pollution [29, 30].

Phytoremediation of metals involves the removal of metals from the soil by using plants with the natural ability to collect, accumulate and tolerate large amounts of metals [31, 32]. Some plant species, called hyperaccumulators, accumulate more than 1% of Zn or Ni and more than 0.1% of Cd in dry matter. These plants have a high selectivity in metal extraction, i.e. they do not absorb nickel or copper in high zinc accumulations. An additional advantage of phytoestrus is the ability to recover metals after burning the plants and extracting ash from them. Regarding sewage sludge, research by Lomonte et al. [33] indicated the potential use of the plant *Austrodanthonia caespitosa* to remove mercury from sewage sludge intensified by the use of $(NH_4)_2S_2O_3$ as a chelator. Phytoextraction, however, has so far been limited in practical application to soils and sewage sludge.

Chemostabilization of metals consists of their inactivation in soil or sewage sludge by the use of various materials that increase the sorption capacity of the soil/sludge or change the metal form, resulting in reduced bioavailability. The purpose of phasing (immobilization) of metals is to reduce the risk of environmental pollution, but not to clean the soil/sludge. Various materials, such as phosphate fertilizers, lime in various forms, or materials containing iron oxides can be used to stabilize metals [34-37]. Calcium increases soil pH by limiting the mobility of metals, while the use of the other materials mentioned intensifies the adsorption of metals or their precipitation in chemical compounds that are not easily soluble. The advantage of chemically stabilizing metals is their relatively low cost and lack of by-products. In the case of soils, chemostabilization is most often accompanied by phytostabilization, consisting of introducing plants that bind the top layer of the soil and reduce the dispersion of pollutants by erosion and leaching.

It should be added that the solubility and bioavailability of metals after their incorporation with sludge into the soil is affected by the chemical composition of sewage sludge alone. The high content of phosphorus and iron in sewage sludge usually limits the solubility of metals by the precipitation of insoluble metal phosphates or adsorption and metal occlusion to/by amorphous iron compounds [38, 39].

Within the scope of using methods for treating sewage sludge contaminated with organic compounds, microorganisms and higher plants are primarily used (Table 2). Studies on the use of microorganisms capable of degrading chloroorganic impurities have been conducted for over 30 years [40, 41]. Microorganisms perform remedial functions by secreting suitable enzymes (e.g. peroxidase, phosphatase, dioxoxyase, P450 monooxygenase, dehalogenase, nitrilase and nitroreduction) involved in the degradation of organic pollutants. Such enzymes can also be found in plants, fungi, and bacteria colonizing plant roots. This led to a thesis on the interaction of plants and microorganisms in order to completely decompose the pollutant [41-47]. This process is called rhizodegradation, and is defined as the degradation of pollutants in the root zone of plants (rhizosphere). Rhizodegradation is one of the most effective remediation processes. This is due to the interactions between plant roots, root exudates, interglacial soil, and microorganisms that occupy the zone in the rhizosphere. Microorganisms residing in the rhizosphere perform a number of functions, such as protecting the plant against stress caused by too much concentration of the pollutant (through the synthesis of relevant compounds), protection against pathogens, degradation of pollutants (before they affect the growth and development of plants), and chelation of nitrogen and phosphorus compounds easily absorbed by the plant [41, 46, 48-52]. The effectiveness of rhizoradiography depends on the ability of microorganisms to adapt to the concentration of pollutants and the effectiveness of colonization of plant roots [49].

In the case of sanitary pollution, information about the effectiveness of remediation methods is retrospective. In particular, there is no comparison of their suitability to remove individual bacteria or parasites (Table 3), mainly due to the fact that sewage sludge is a very good substrate for the multiplication of various microbial communities. In addition, sewage sludge is easily subject to putrefactive processes. They should therefore be stabilized prior to further use or storage, to reduce or completely destroy pathogens. Hence, the most commonly proposed and used methods include drying, hygienisation and stabilization (Table 3).

Conclusion

To conclude, the analysis of literature data and our own research results related to the use of sewage sludge for soil fertilization indicates great potential for the restitution of organic matter circulation in the soil, and thus the reclamation of poor soil into organic matter, and the possibility of reducing the amount of mineral fertilizers used as a source of nitrogen, phosphorus, and magnesium (cyclic circulation closure of biogenes). The literature data also indicates the potential for using sewage sludge to fertilize plants. In this case, the use of sewage sludge influences grain yield increase (up to 47%), dry matter yield, and increase in total protein content in plant tissues; increased translocation efficiency of water-soluble sugars into grains; increased resistance to adverse and/or harmful environmental conditions (temperature, drought, pollution); reduction of solubility and toxicity of trace elements. In addition, in the case of sewage sludge contaminated with trace elements, organic compounds or microbial contaminants, both global and national studies indicate the possibility of reducing their toxicity by using a number of methods such as phytoremediation, composting, rhizododegradation, drying, hygienisation. These treatments help to treat polluted sludge and thus increase their use in agriculture.

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Table 1. Methods of sewage sludge treatment contaminated with trace elements

Process	Description of method / process	Efficiency of the method in relation to sewage sludge	Literature
Phytoevaporation	Collecting inorganic substances from the soil by plants and releasing them into the atmosphere in volatile form.	Relatively effective with mercury and selenium; Few studies on the effectiveness of sediment treatment.	[29, 30]
Phytoextraction	Use of plants with high biomass production and accumulating high concentrations of heavy metals in ground organs, for the removal of heavy metals and other contaminants from soil. In the process of phytoextraction, we also use hyperaccumulators, i.e. species with natural accumulation capacities, e.g. *Alyssum murale, Alyssum co*rsicum, *Berkheya coddii,* which accumulate Ni.	Limited effectiveness in soils; Tested against nickel, cadmium, zinc; The process is very long.	[31, 32]
Chemostabilization	Use of lime, sorbents and other materials that cause the precipitation and adsorption of elements. Liming causes the reaction to change to a basic level, which limits heavy metal leaching. The addition of sorbents (e.g. organic matter, clay materials, peat or lignite) results in an increase in sorption capacity relative to metal cations, which contributes to their binding. The use of substances rich in phosphorus causes precipitation of lead, and use of substances rich in amorphous iron - adsorption and occlusion of zinc, nickel, and cadmium.	They do not remove elements but lower their solubility	[34, 36-38]

Table 2. Methods of sewage sludge treatment contaminated with trace elements

Process	Description of method / process	Efficiency of the method in relation to sewage sludge	Literature
Phytodegradation/phytotransformation	Breaking down pollutants within plant tissues (mainly grasses and legumes) due to the enzymes produced by the plant.	An effective method for removing, among others, DDT, PCBs, phenols, aromatic and aliphatic hydrocarbons, herbicides (e.g. atrazine) and pesticides; Useful mainly for the remediation of contaminated soils; There is no information on the suitability of sewage sludge alone, but it can be used to remediate soils contaminated with these compounds as a result of sewage sludge.	[44, 45, 50]
Rhizodegradation	A process that utilizes the synergy between soil microorganisms (bacteria, fungi) and plant roots (mainly willow, cane, broadleaf, and *Cucurbitaceae* plants) to degrade pollutants.	An effective method for removing, among others, PAHs, PCBs, dioxins and furans; There is no information on the suitability of sewage	[41-52]

		sludge alone, but it can be used to remediate soils contaminated with these compounds as a result of sewage sludge.	
Bioaugmentation - vaccination with selected bacteria	There is a number of microorganisms involved in the degradation of hydrocarbons, including bacteria such as *Pseudomonas, Arthrobacter, Alcaligenes, Corynebacterium, Flavobacterium, Achromobacter, Micrococcus, Mycobacterium* and *Nocardia*, as well as fungi*Aspergillus ochraceus, Cunninghamella elegans, Phanerochaete chrysosporium, Saccharomyces cerevisiae* and *Syncephalastrum racemosum.* The addition of selected strains of microorganisms provides increased efficiency and speed of degradation, for example, recombinants of bacteria degrading PCBs, which are characterized by increased stability and survival.	Quite effective in soils with PAHs from 2 to 4 rings; Efficiency data in sewage sludge very limited.	[40, 48, 49, 51, 52]
Composting	Composting is a natural, biological method used for the hygienisation of sediments. The final product of the process of mineralization and humification is compost, usually without biological impurities, and rich in organic matter and biogens.	Partly effective against petroleum.	

Table 3. Methods of treatment of sewage sludge contaminated bacteriologically and parasitologically.

Process		Description of method / process	Efficiency of the method and the final effect	Literature
Drying	**1.** Convection drying	It is based on direct contact of the dried sludge with the heat carrier. The drying gas flows over the sludge and the heat is transferred from gas to the dried material. Water evaporating from the sludge goes to the drying gas and is discharged from the device along with it.	Drying removes water to a much greater extent than the best drainage, which causes the sludge to be characterized by: - lower weight and lower transport costs, - lack of pathogenic organisms, - easy to store.	http://ekologia-in-fo.eu/?lang=1&menu=1&menu_select=7&podmenu_select=135
	2. Contact drying	It involves the transfer of heat from the heat carrier to the sludge through the exchange surface (contact). In the contact drying process, the dried material is placed on a heat-treated surface. The evaporated water is removed from the device along with foreign air, penetrating through leaks or by means of a small air stream.		
	3. Radiant drying	It involves the use of electromagnetic radiation or infrared radiation as a source of heat.		
Stabilization	1. Anaerobic stabilization	Organic sediments undergo anaerobic microbiological decomposition into methane and other substances. As a result of the fermentation, stabilization and reduction of sludge volume and biogas production are achieved.	Mezzanine methane fermentation over a period of 30 days yields a significant reduction in pathogenic bacteria and complete destruction of protozoan cysts.	[54]
	2. Aerobic-anaerobic stabilization	The method consists of subjecting sludge to a one-day aerobic stabilization with pure oxygen or air, followed by anaerobic fermentation lasting 12 days. In the first stage, the temperature of the process is raised to 57°C and in stage 2 (thermophilic processing) the temperature of the process reaches 35 ÷55°C.	This method gives complete stabilization of the sludge and a high degree of decontamination.	
Hygienisation	1. Heat treatment - pasteurization	The process involves heating the sludge and maintaining its temperature at a certain level for some time. Pasteurization can be carried out at various points in the technological process: after fermentation or aerobic stabilization, etc.	The methane fermentation applied between stage 1 and 2 removes all pathogenic bacteria. When used after fermentation it is less effective.	[53, 54]
	2. Bernard's active pasteurization method, combined with the production of granular fertilizer	Ammonia gas is introduced into dehydrated sludge - with a dry matter content of 12÷15% s.m - in the amount of 4%. As a result of the exothermic reaction, the sludge temperature rises to about 50°C and the pH reaches 11.6. After 5÷10 minutes neutralization of the alkaline precipitate with phosphoric acid takes place (at 65°C).	Disinfection of pathogenic bacteria. No precise data on the effectiveness of decontamination.	[53, 54]
	3. Chemical treatment - stabilization with lime	Liming is a process of lime interaction on sewage sludge. Lime is used in the form of roasted lime and hydrated lime.	The effect of liming on sewage sludge is intended to increase the pH to the	[53, 54]

		The method is based on the exothermic reaction of calcium oxide with water. In addition, the disinfectant is alkaline sludge solution after introducing the lime (pH above 12).	values at which enzymes are inactivated and there are changes in protein structure. Reduction of pathogens at the level of log 6, stabilization of sludge without risk of further pollution, removal of odor, low investment costs, small area needed for installation, introduction of lime sludge to soil improves its structure, increases soil microbial activity.	
	4. Physical treatment - radiation hygienisation	Application of accelerated electron beams and radiation. Electron beams are used to sterilize liquid sludge, while radiation is used for liquid, dehydrated and dry sludge. (6)	Complete sterilization of sludge.	[53, 54]
	5. Biological treatment - prism and tunnel composting	Process of organic matter decomposition using aerobic bacteria. Composting can be subject to various sludges, i.e. raw, fermented, mixed sludges, dehydrated sludges; they can be stabilized to varying degrees. One of the methods supporting composting is the addition of suitable bacterial strains, so-called biological preparations to accelerate the biodegradation and conversion of organic waste.	Composting can be an effective solution for sediment management in small wastewater treatment plants, replacing both aerobic and anaerobic stabilization processes and the final dehydration and hygienisation of sludge; Low cost of hygienisation; The study found that seven weeks of composting at 60°C gave guarantees of complete elimination of pathogenic organisms; Valuable end product with favorable structure and fertilizer properties.	[53-57]