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Utilization of sewage sludge as an ameliorant for reclamation of technogenically disturbed lands

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Abstract. When rehabilitating technogenically disturbed lands of mining facilities, fertilizers and ameliorants are to be applied due to the lack of organic matter and nutrients required for the restoration of the soil and vegetation layer. The use of unconventional fertilizers (ameliorants) based on sewage sludge is one of the actual directions of land reclamation at mining sites. The purpose of the work is to summarize and analyze up-to-date information on the effectiveness of the use of sewage sludge for the reclamation of technogenically disturbed lands of mining and processing industries. The analysis is based on a review of recent studies aimed at assessing the impact of introduced sediment on soils, plant communities, and rehabilitated areas. The introduction of sewage sludge has a positive effect on the physical and chemical parameters of the soil (optimizes density and aggregation), saturates it with nutrients, i.e. N, P, K, Ca, Mg, and Na, thus improving plant growth indicators. However, it may contain a number of heavy metals and pathogens; therefore, studies of each sediment and conditions of reclaimed areas are necessary.

***Key words*:** sewage sludge; reclamation; disturbed lands; heavy metals; waste; ameliorant; waste utilization

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Introduction. The soil layer is one of the key components of the biosphere, performing several functions to maintain terrestrial ecosystems: providing habitat, preserving biodiversity, regulating the quality of water and air. Intensive soil degradation caused by large-scale work on the development of mineral deposits decreases ecosystem productivity and fertility and violates the interaction of environmental components [18, 27, 29, 40]. The rate of depletion of the soil and, as a consequence, the environment (caused by anthropogenic impact) prevails over the rate of self-restoration. Without proper attention and measures for the reclamation of technogenically disturbed lands, the problem of soil degradation will reach a global level.

The difficulty of restoring technogenically disturbed lands of mining facilities is mainly due to the violation and complete removal of the soil and vegetation layer, which is a source of organic matter necessary for the processes of soil formation and self-healing of the environment. Bare horizons of soils and rocks are not suitable for the formation of plant communities and fertile soil layers.

Human intervention can accelerate the process of restoring the environment by creating Technosols when applying the required organic fertilizers and other nutritional additives. The lack of organic matter is compensated by organic fertilizers, ameliorants, or soil additives.

Problem statement. The increase in the scale of violations and the development of methods for the restoration of soil and vegetation cover led to the search for the most environmentally and

economically successful approaches and technologies in the field of reclamation of technogenically disturbed lands. The use of unconventional fertilizers (ameliorants) formed on the basis of wastewater sludge (WWS) [37] is one of the actual directions in the reclamation of mined lands, i.e., quarries [9, 21], dumps [15, 20], and tailings storage facilities [12].

The possibility of using WWS as organic soil additives has already been proven and is actively used in agriculture in different countries [22]. According to Eurostat, the statistical office of the European Union, as of 2018, Poland applied 20 % of WWS on agricultural land (out of 583.07 thousand tons), Austria applied 21 % (out of 234.481 thousand tons), Sweden applied 39 % (out of 210.9 thousand tons), and Norway applied 44 % (out of 147.6 thousand tons).

Several regulatory documents were developed in the field of agriculture and forestry on the use of WWS as fertilizers and soil additives for the control and regulation of environmentally hazardous sediment components entering the soil (pathogens, heavy metals): Council Directive 86/278/EEC of 12 June 1986, GOST R 17.4.3.07-2001, SanPiN 2.1.7.573-96.

Methodology. The research methods consisted in summarizing and analyzing up-to-date information on the effectiveness of the use of sewage sludge for the reclamation of technogenically disturbed lands of mining and processing industries based on impact assessment on soil and plant complexes of restored or improved territories. For the work, the results of the latest analytical and experimental studies by domestic and foreign specialists on assessing the applicability of WWS as a soil improver were used.

Discussion. Sewage sludge is the final product or waste of biological wastewater treatment, which may differ significantly in its type, chemical composition, and physicochemical properties, depending on the treated wastewater, water treatment system, and treatment processes [5].

The origin of WWS. Wastewater entering the treatment facilities is divided into domestic, industrial, and surface (stormwater runoff) [19]; different ratios of incoming water types affect the characteristics of the generated WWS. Characteristic differences can be observed when comparing precipitation from urban water treatment systems, sewage treatment plants of various production facilities, and even with a sharp change in annual or seasonal precipitation distributions.

WWS is formed at wastewater treatment plants in the wastewater treatment system, which is a set of measures to remove pollutants. Depending on the purposes and requirements, the system is completed by devices and structures based on various techniques, e.g., mechanical, biological, and physicochemical treatment. Thus, the totality of water treatment processes is one of the determining factors for the composition and characteristics of the resulting sediment [8].

Upon completion of all stages of water treatment, the sediment is removed from the treatment facilities for processing before storage, disposal, or burial. WWS treatment (compaction, dehydration, stabilization, conditioning, and neutralization) affects its volume, humidity, density, and composition.

Different classifications of WWS consider its origin, as well as stages and types of wastewater treatment. In this paper, the generalized concept of "wastewater sludge" is considered, which implies averaged characteristics of the total mass of raw sludge, excess activated sludge, and its averaged indicators.

Characteristic of WWS. Normally, WWS is solid, semi-solid, or silt-like formations, which in various proportions consist of heavy impurities (sand), crude sediment (mainly suspended solids), and activated sludge (excessive volume of different populations of microorganisms).

Sewage sludge is widely used as fertilizers, ameliorants, and other soil additives, being a major source of organic matter (from 20 to 80 %, ref. Table); it has some nutrients necessary for plants, and can regulate soil regimes [22, 48].

Organic matter plays one of the key roles in the rehabilitation of technogenically disturbed lands, since it affects almost all physical, chemical, and biological properties of the soil, thereby improving

its structure; it increases soil resistance to erosion, promotes nutrient retention, and contains a significant part of plant growth activators [25]. Thus, the presence of a sufficient amount of organic matter determines the ecological efficiency of reclamation measures, the rate of restoration of the soil-plant complex, and the stability of maintaining the productivity of a technogenic ecosystem.

Average composition and characteristics of WWS

Characteristics	Urban wastewater sludge	Source
pH	~ 6.0-7.5	[11, 16, 29, 33, 38, 41]
Electrical conductivity, μS/cm	1.39-2.83	[29,33, 38, 41]
Organic matter, %	26.6-83.5	[11, 16, 32, 33, 41]
C (total), %	No data	–
N (total), %	~ 5-20	[16, 29, 32, 38]
P (P_2O_5), %	~ 2-20	[16, 32, 35]
K (K_2O), mg/kg	No data	–
Mn, mg/kg	No data	–
Zn, mg/kg	~ 500-1000	[14, 16, 32, 33, 41]
Cu, mg/kg	~ 90-800	[11, 14, 32, 33, 41]
Cr, mg/kg	~ 16-288	[11, 14, 16, 33]
Ni, mg/kg	~ 10-140	[11, 14, 16, 33]
Pb, mg/kg	~ 1.5-190	[11, 14, 16, 32]
Cd, mg/kg	~ 0.5-2.0	[11, 14, 16, 32, 33]

According to research, due to high concentrations of P and N, WWS can be classified as phosphorus and nitrogen fertilizers [45]. Field studies and the formation of models of soil-plant complexes proved a significant increase in nitrogen and phosphorus concentrations [14, 16, 27]. In addition, when wastewater is bioremediated, excessive (spent) aquatic plants are formed. Like WWS, they are waste from water treatment systems and can become nitrogen soil additives thanks to a high nitrogen content [24, 30].

When reclaiming technogenically disturbed lands, nitrogen and phosphorus significantly affect the positive dynamics of plant growth: they improve cell growth, metabolic processes, and participate in the formation of the root system [36, 46]. However, due to the heterogeneity of the origin and processes of sediment formation, WWS may also have the opposite results with a decrease in nitrogen concentration, which is shown in the results of a study of quartz industry sludge [48].

The presence of nutritional components such as K, Ca, Mg, and Na is a significant advantage of WWS [48]. It should be borne in mind that sewage sludge, due to differences in composition, origin, and characteristics, does not always have high concentrations of nutrients or their presence in general. When restoring poor and infertile soils, it is necessary to take into account the amount of nutrients in the introduced sediment to avoid their deficiency in the soil and subsequent inhibition of normal plant growth and development. The discrepancy in the content of nutrients in urban wastewater sediments is shown in the Table.

There is a discrepancy in the results of the impact of the introduced sediment on the acidity and electrical conductivity of the soil. Experiments set up and carried out on soil-plant sites show a higher [48] and lower [6, 8, 47] acidity of the soil with an increase in the dosage of the deposited sediment, which is also explained by the difference in the sediment and the initial acidity of the soil. Without the introduction of critical volumes of sediment, the soil pH was noted in the range of 6.0-7.5.

The use of sewage sludge as a soil additive also has a significant effect on the change in electrical conductivity, which mainly increases in the studied soils after the application of sediments [5, 14, 48]. When the sediment composition, soil salinity, or processing methods change, the opposite effect may occur: a decrease in electrical conductivity, e.g., during freezing-thawing of WWS, before being introduced into saline soils [13]. A change in conductivity is an indicator of soil salinity, an increase

in the value when sediment is applied may be due to the dissolution of salts from the sediment [28, 42, 45]. Violation of the water-salt regime harms the vital activity of plants; therefore, it is necessary to consider such parameters as acidity and electrical conductivity when designing reclamation.

The results of studies on the use of sewage sludge as soil additives confirm the positive effect on the composition and properties of soils. The introduction of sewage sludge into the soil increases the water content, improves the soil structure, optimizes its regimes, increases the content of organic substances, N, P, and in some cases several other nutrients: K, Ca, Mg, and Na.

The impact of WWS on plant communities. The eco-efficient formation of a soil-plant complex at the rehabilitated mine sites is a complex process leading to long-term self-healing of the environment. The stabilization of ecosystem changes can take tens of years, depending on the state of a technogenic ecosystem. Accelerated vegetation overgrowth is recommended for the speedy restoration and reduction of the negative impact of a disturbed land object. The soil and vegetation cover reduces the negative load by restoring the natural functions of an ecosystem, as well as the buffer properties of the soil cover, prevents erosion processes, and, with successful reclamation, returns the land to economic use.

To assess the impact of WWS on plant communities, methods for assessing the external features and physical dimensions of plant organs are used more frequently. The impact is analyzed both based on visual indicators (plant pigmentation, chlorosis, and necrosis), and measured values of plant growth and development (germination, growth dynamics, stem height, leaf length, flower diameter, and biomass). Biomass is estimated by measuring the whole plant, separately by systems (ground and root) or by plant organs (stems, leaves, roots, etc.). The yield (biomass, yield structure, and the value of plant products) is evaluated to calculate the ecological and economic efficiency of the performed land works and the productivity of the ecosystem. Depending on the plant test objects, these parameters can vary, e.g., length, diameter, and weight of a corn cob [5], oil yield from sunflowers [41], or calorific value in crops used in bioenergy. In addition, photosynthesis analysis and measurements of chlorophyll content are carried out to assess any impact on plant crops [14, 32, 46].

Sewage sludge has a beneficial effect on photosynthesis processes and the content of chlorophyll [14, 32, 34]. When comparing the needles of larch grown on soil with deposited sediment and control soil, there is a significant increase in chlorophyll (when applying 30 and 60 t/ha) [32]. There are no significant differences in the assessment of chlorophyll in sunflower grown on soils fertilized with sediment (15, 30, and 60 t/ha) and regular fertilizer (NPK additive) [34]. Reclamation of lands by WWS with such indicators improves photosynthesis, not inferior to classical fertilizers, which gives both an environmental effect and an economic advantage of the application.

In studies of the effect of introduced sediment on plant growth, a general trend can be noted. Small concentrations of sediment give better dynamics of plant growth (cereals [48], herbaceous [2, 16, 39], sunflowers [34, 41, 48], and legumes [43]) than control soils, while increasing the amount of added WWS to critical values gives an inhibitory effect and leads to growth inhibition [42, 43, 46]. Similar results of suppressing plant growth after increasing the doses of sediment application can be explained by reaching threshold values without phytotoxic effects [11]. Therefore, a reasonable approach is needed in the use of sediment with the calculation of application doses based on all impact factors.

When rehabilitating technogenically disturbed lands, the roots of plants perform significant functions of fixing a soil layer, improving its structure, and preventing erosion. The addition of sediment improves the root system, contributes to an increase in biomass and the growth of the root system [28, 35].

Soils with introduced sediment give the best results in the productivity of biomass of cereals [2, 21] and shrubs [33]. The biological productivity of soil-plant complexes reflects the state of

soil fertility and its resources. Organic fertilizers (or organic non-traditional additives, such as sewage sludge) can restore the balance of organic and mineral components necessary for plants and thus provide restoration of technogenically disturbed lands [25].

The literature review shows that there were no indicators of diseases, pigment changes, chlorosis, or necrosis in plants from the introduction of WWS into the soil [2, 14].

WWS-treated soils give the best results of plant and biomass growth when 15-45 % of sediment is applied [2, 14, 16]. The optimal dose of application is due to the increased availability of nutrient components for plants in comparison with control sites of untreated soils [16, 41].

Environmental issues of WWS application. Sewage sludge can contain potentially hazardous components: heavy metals [5, 13, 38, 48], organic pollutants, pathogens [5], and other phytotoxic substances [14] that can accumulate in organisms and the environment, preventing the development and regeneration of soil and vegetation areas. To stabilize and reduce the toxicity of the sediment, such measures as composting, thermal exposure (thermal drying, burning, and freezing-thawing), anaerobic digestion, and other methods of processing and neutralization are carried out. However, this does not eliminate the possibility of contamination of the ecosystem with heavy metals that is the main limiting factor in the use of WWS for land works [46, 48].

When introducing WWS with high concentrations of heavy metals (HM) into the soil, there is an increase in the concentrations of Cu and Zn [7, 38], Pb [7, 12, 38], Mn, Cr, Cd [13]. These chemical elements enter the soil solutions, precipitate in the upper soil horizons, migrate to the lower ones, move to the nearby areas, and accumulate in the vegetation cover and living soil organisms. Migration, transformation, and bioaccumulation of HM compounds depend on the chemical composition and reaction of the medium [3, 26], organic matter, soil regimes, and geochemical barriers [4, 6]. Excessive accumulation of HM in soil and plants can lead to disruption of ecosystem functions and negative consequences for living organisms. Despite the presence and even high concentrations of HM in the WWS, no excess of the established concentration standards from a single application of sediment was found [38, 48].

For the rational application of WWS and prevention of soil contamination with metals, each sediment should be evaluated in relation to the improved soil and environmental conditions. A comprehensive study of the chemical composition and physicochemical properties of the introduced WWS and the treated soil with the calculation of guaranteed safe applied doses has to be carried out [19].

There is also a downside to the question. When considering the concentrations of heavy metals in the soil, it should be borne in mind that the lack of some metals can also lead to the oppression or death of plants, since some metals are micronutrients for plants [5, 13]. For example, the presence of copper and magnesium in the soil is necessary for the regulation of photosynthesis and protein transport, zinc affects redox processes. When applying sludge of various origins, the most frequently repeated elements that increase concentrations in the soil are Cu and Zn [5, 7, 38], which can be both an advantage and a disadvantage, depending on their concentrations.

Various plant crops need different amounts of nutrients and have different tolerance to high levels of heavy metals. Therefore, when calculating doses and assessing the safety of WWS application on reclaimed lands, studies of soil and sludge, as well as the monitoring of the vegetation being restored and the necessary optimal conditions for ensuring normal plant growth and development should be carried out.

The environmental danger of bioaccumulation of heavy metals in plants is an increase in their toxic concentrations at higher trophic levels of living organisms. When assessing the impact of the applied WWS on plant crops grown on treated soils, no negative consequences were recorded during the growth and development of herbaceous [2] and crops [7, 48].

The noted inhibition of plant growth from excessive introduction of WWS may be a reaction to increased concentrations of HM [41]. An increase in the content of heavy metals in various plant organs was recorded in comparison with plants grown on control soil plots without the addition of WWS [43]. These data once again confirm that the use of WWS for land works obliges to control the concentrations of heavy metals in the soil, and do not exclude the environmentally toxic effects of all types of sludge.

Despite the effectiveness of the transformed sewage sludge, its use is most rational in restoration work on technogenically disturbed and forestry land areas. It is recommended to limit their use in agricultural areas due to the potential risk of environmental pollution and to prevent an increase in concentrations of heavy metals in the food industry.

Concerning technogenically disturbed lands and forestry areas, the probability of heavy metal pollution during land reclamation has a smaller scale of consequences for humans, since it does not affect food production and, in case of a risk of an increase in HM concentrations above the values established by regulations, will lead to less environmental damage [41].

One of the planning stages of reclamation of technogenically disturbed lands is the choice of plant crops. When applying WWS with high concentrations of HM, it is recommended to choose plants for phytoremediation to reduce the potential risk of environmental contamination from the applied sludge [34, 46]. With a rational choice of sludge, its application rates, and treatment method, improving the soil by sludge application will not have a phytotoxic effect on the restored soil and vegetation during the reclamation of technogenically disturbed lands.

WWS in the reclamation of technogenically disturbed lands. A significant shortage of organic material is an obstacle to the successful reclamation of technogenically disturbed lands of mining facilities [1, 9, 21]. The standard measures involve the application of fertile (FL) or potentially fertile soil layer (PFL) to the restored areas, but this approach does not always guarantee the environmentally effective formation of a man-made ecosystem. Lack of nutrients and organic matter requires repeated applications of chemical and organic fertilizers, which increases the cost of restoration work. An alternative option is the application of non-traditional fertilizers – sewage sludge, which is an economically available [41, 45] secondary material resource [23].

Agricultural soils and reclaimed mining lands can be improved by applying WWS as soil additives [9, 10], fertilizers [32, 43], or ameliorants, which increase the content of organic matter, such nutrients [23, 31, 44] as phosphorus and nitrogen, as well as some other microcomponents needed by plants. Due to the physical and chemical properties of the soil, sludge can improve the density, aggregation, soil structure, and water-air regime, as well as increase resistance to erosion [1]. According to studies based on agricultural soil enrichment, the application of WWS has a beneficial effect on plant growth and development. There is an acceleration of plant growth, an increase in growth of aboveground biomass and root system, as well as a positive effect on photosynthesis processes and chlorophyll content.

If all the optimal regimes for reclamation works on technogenically disturbed lands are provided, the application of sludge can improve the rate of soil and vegetation cover formation, i.e. the rate of stabilization and restoration of a technogenic ecosystem. This will make it possible to reduce the negative impact of disturbed land on the environment and return the land to economic use as soon as possible.

Examples of positive results on the applicability of WWS on technogenically disturbed mining lands can be found in studies on the restoration of open pits [9, 21], waste dumps [15, 20], gold-mining tailings [12], and on disturbed areas of bauxite deposits [46].

Adding WWS during the reclamation of disturbed mining areas increases the content of organic matter, available phosphorus, copper, and zinc as trace elements necessary for plants [9, 21, 46], but also increases HM content (without exceeding the background values) and reduces the acidity of reclaimed lands [15, 46]. A similar increase in the content of phosphorus and nitrogen was obtained at reclamation sites of gold-mining tailings; however, due to the high concentrations of HM in the reclaimed waste, there was no increase in the concentration of HM after the application of WWS [12].

There are works on impact assessment not only when WWS is applied to reclaimed land, but also a complete replacement of FL and PFL with a method of technogenic soil formation based on mining waste and WWS [17, 21].

The main obstacles to the spread of the method are issues of availability, transportation, application method, and lack of research on the impact of sludge on the environment.

Benefits of using WWS in reclamation:

– low cost of the substrate as a waste of a secondary material resource;

– high concentrations of nitrogen and phosphorus, which potentially refers the sediment to the group of nitrogen, phosphorus fertilizers;

– high content of organic matter required for reclamation of mining waste landfills;

– improvement of soil physical properties, i.e., density and aggregation, which improve soil structure and increase erosion resistance;

– availability of nutrients that plants need: K, Ca, Mg, and Na;

– improvement of conditions for plant growth;

– reduction of chemical fertilizers and similar substrates amount needed in the agricultural industry;

– contribution to ecosystem restoration by accelerating the formation of soil and vegetation cover.

Disadvantages of using WWS in reclamation:

– the need for pre-treatment to dehydrate, stabilize, and improve physical and mechanical properties;

– the presence of Zn, Cu, Cr, Pb, and Ni; to prevent soil contamination with these elements, it is necessary to strictly calculate the dose of each WWS application;

– low acidity of the sludge, which can negatively affect the migration of heavy metals;

– the potential environmental hazards of contaminating organic compounds and pathogenic microflora (in the absence of sludge treatment).

Conclusion. Mining plays one of the key roles in the development of the state, influencing economic, environmental, and social changes. Large-scale mining and processing operations change the terrain and create technogenically disturbed lands, which are out of economic use and harm the components of the environment because of degradation.

The restoration of technogenically disturbed mining lands is carried out by reclamation activities, which include a set of works on the formation of the landscape, territories, and lands for the creation of the ecological system, close to the natural conditions of the area. To reproduce the fertile topsoil, it is necessary to apply organic fertilizers, ameliorants, or soil additives to form soil aggregates, strengthen soil structure and improve the growth conditions of land vegetation.

One of the potential sources of organic matter and nutrients is non-traditional ameliorants – fertilizers formed on the basis of sewage sludge. Sewage sludge is a solid, semi-solid, or sludge-like waste from wastewater treatment (mainly biological), which in different proportions consists of heavy impurities (sand), raw sludge (mainly suspended solids), and activated sludge (excessive numbers of different populations of microorganisms). Sludge can vary significantly in its appearance, chemical

composition, and physical and chemical properties, depending on the treated wastewater, the water treatment system, and its treatment processes. The average composition of the sediment is organic matter ~ 25-80 %, nitrogen ~ 5-20 %, phosphorus ~ 2-20 %, a set of nutrients necessary for plants (K, Ca, Mg, and Na), and heavy metals (Zn, Cu, Cr, Pb, and Ni).

As a soil additive, WWS improves the physical properties of the soil (density and aggregation), which helps the soil to resist erosion processes, and increases the content of nutrients in the soil. This contributes to better growth of vegetation cover of restored areas by influencing the increase in chlorophyll content, improving photosynthesis processes, accelerating growth, and increase in the plant biomass.

The reclamation of technogenically disturbed mining lands will stabilize a technogenic landscape, form a soil and vegetation complex, reduce the negative impact and return the lands to economic use as soon as possible.

Among the shortcomings of the substrate, there is a significant content of heavy metals, the possible presence of pathogenic microflora, radionuclides, and other environmentally unsafe components. The problem of the potential danger of ecosystem contamination by the introduction of sewage sludge is mainly solved by treatment and disinfection. Each sewage sludge should be evaluated for suitability as a soil amender. The applicability assessment should take into account the conditions of the land where the sludge is to be applied. The assessment takes into account: the regional climate, reclaimed areas, restored soils, vegetation cultures of the area, and other factors. All factors are analyzed and taken into account when calculating doses and drawing up a sludge additive plan.

Thus, with a rational approach to mining land reclamation and fertilization, sewage sludge can not only potentially replace some of the applied fertilizers, but also improve the processes of environmental restoration.

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