Development of the beneficial utilisation of urban sewage sludge using modern analysis methods

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Abstract. The article presents Russian and foreign experience in the recycling of sludge of urban sewage wastewater with the prospect of the beneficial use of both the direct waste and the products of its processing. Special attention is also paid to the problem of recycling of ashes of sewage sludge incineration. The article also considers the possibility of applying modern methods of analysis (such as X-ray fluorescence analysis, spectroscopy, biotesting) to develop a composition of the ash-based soil mixture. The study is realized on the laboratory and experimental base of the accredited Center for the collective use of high-tech equipment of Saint-Petersburg Mining University (as a part of state task for 2018-2019 year).

1. Introduction

One of the most pressing problems in the metropolis is the issue of disposal and recycling of the ever-increasing amount of waste in a limited capacity of the objects of their placement. In particular, the activities of urban sewage treatment plants are not limited only to cleaning of drains; an integral part is also the management of sewage sludge.

In large cities, the volume of urban wastewater is calculated in the millions and the amount of sewage sludge - thousands of cubic meters per day. The reduction of sewage sludge formation and its further transformation into a harmless product are the main tasks assigned to modern technologies.

A feature of sewage sludge as a waste is the presence of organic and mineral phases. The fourth hazard class is usually due to the high content of heavy metals in the sludge [1]. Therefore, most often this waste is deposited in landfills and can not be reused. Available data demonstrate the relevance of this problem and the need to search for new approaches and technologies to involve sewage sludge in economic circulation.

In 2005, the main pathways for the disposal of sewage sludge in European Union was reused in agriculture (52%), incineration (38%) and landfills (10%) (Sewage Sludge Directive 86/278/EEC) [2].

Landfill disposal of sewage sludge is carried out when the waste can not be reused. In the countries where land resources allow disposal sites being formed, this is the main method of waste treatment [3]. After the operation of the landfill is completed, the owner is obliged to reclaim disturbed land in the manner prescribed by the legislation of the Russian Federation. Composts and soils based on sewage sludge can be successfully used for biological remediation as well as to creating green buffer strips [4, 5].
Composting is an aerobic process of bacterial decomposition for the stabilization of organic waste and the production of humus. It is a reliable method of disinfecting sewage sludge and producing useful products such as compost and fertilizer.

In particular, composting technologies available in the Northwestern region of the Russian Federation range from simple open windrow systems with a small effort in terms of process structures to fully enclosed composting plants with accelerated treatment processes, complete enclosure and a high quality treatment of exhaust air. The most feasible for sludge handling are windrow composting and tunnel composting technologies. The operation and maintenance of both methods are relatively simple and only require a basic understanding of the biology and biochemistry of composting [6].

Pyrolysis is one of the most promising areas in the disposal of sewage sludge. It is the thermal decomposition of carbon-containing materials at high temperatures in an inert atmosphere. Pyrolysis products are used in a wide variety of industries and economy. In example, biochar can be used as a fuel or source of phosphorus and nitrogen. Pyrolysis oil after processing may be a source for producing carboxylic acids, paraffin, coke dust, etc. [7].

Due to the presence of high concentrations of phosphorus and nitrogen sewage sludge is a good fertilizer. In agriculture, it is possible to widely use sewage sludge as a valuable fertilizer, turn poor soils into fertile areas and use activated sludge as a protein feed for livestock and poultry.

Netherlands, Spain and Sweden use more than 60% of sludge in agriculture, and Denmark, England and Switzerland use more than 45% for similar purposes. Their experience shows that the negative environmental effects of using sludge in agriculture can be minimized, subject to rules and strict standards [8]. There are also examples of effective fertilization and irrigation using both treated wastewater and sewage sludge [9].

However, sludge used as a fertilizer can be a source of pollution. Until the mid-1980s, collective and state farms actively used the treated sludge as a fertilizer, but in the early 1990s, permissible limit of heavy metals in soil were established and information on the increased content of heavy metals in the urban sewage sludge was made public. All this has led to difficulties in the registration of the waste as fertilizer and this is one of the reasons why in recent years the incineration has become increasingly widespread. Sewage sludge is incinerated if its recovery is impossible or economically impractical, also if the territory for its storage is limited or absent, and in those cases when it is required for sanitary and hygienic reasons [6].

Russia's attempt to adopt foreign combustion experience provided the following results: the volume of the solid phase decreased by only 20% while simultaneously emitting large amounts of gaseous toxic substances and products of combustion into the atmosphere. In this regard, in Russia, as in all other CIS countries, the main way to manage sewage sludge remains its disposal at landfills.

The negative impact that waste has on the environment consists of the alienation of land areas for landfills and the attendant pollution of the atmosphere and water bodies. Thus, it should be noted the need for a more thorough approach to the search for new technologies to involve sewage sludge in the natural economic.

Nowadays, in order to reduce waste generation, State Unitary Enterprise (SUE) «Vodokanal of St. Petersburg» uses incineration of sewage sludge in fluidized bed furnaces. Despite the fact that this technology allows reducing the waste volume by a factor of ten, the annual volumes of the incinerated sewage sludge ash (SSA) are still quite large and amount to about 50 thousand tons.

The study focused on the topical issue of urban sewage sludge utilization with the prospect of using waste in the national economy. The purpose of the study is to assess the possibility of beneficial use of sewage sludge.

The scientific novelty of the study is the establishment of a positive effect, which has the introduction of incinerated sewage sludge ash (SSA) within 20% by weight as a component of the waste-based soil mixture (at the rate of 28.53 t/ha per year), on plant growth (by example Trifolium pratense).
The practical significance of the study is the development of the SSA-based organic-mineral mixture taking into account the possibility of its further use for the improvement of urban areas and land reclamation.

The study was carried out using a set of research methods, including a system analysis of the problem based on studies by Russian and foreign scientists as well as laboratory methods for studying the structure and properties of sewage sludge. The study is realized on the laboratory and experimental base of the accredited Center for the collective use of high-tech equipment of the Saint-Petersburg Mining University.

2. Generation of the data

The South-West wastewater treatment plant is under the jurisdiction of the branch “Water disposal of St. Petersburg” of the State Unitary Enterprise Vodokanal St. Petersburg and put into operation in 2005. The daily volume of urban wastewater is about 330 thousand m³. In 2007, the sludge incineration plant was commissioned; its design capacity is 310 m³ of dry sludge (cake) per day. A cake is a mixture of sediment of primary sedimentation tanks and compacted sludge of aerotanks. Incineration is carried out in fluidized bed furnaces [10]. SSA externally is a brown fine powder. The basic composition of SSA represented by SiO₂, phosphates of Fe and Ca, silicates of certain metals; the heavy metals are concentrated mainly in the fine fraction. Particle size is 1-50 microns; bulk density is 0.68 g/cm³ (at transport humidity).

The most promising ways of beneficial using SSA in agriculture is land reclamation, or as a component in building materials. Nowadays, the growing demand for building material requires an alternative way to obtain it from various sources, including SSA. There are researches on such areas of using SSA as the production of bricks and tiles, raw materials for cement, aggregates for concrete and a component for the synthesis of light materials etc. [9].

However, if the acidic environment affects the waste, the transition of heavy metals into a soluble form and their migration into the environment becomes possible. This is explained by the fact that with an increase in acidity in the soil solution, the amount of free fulvic acids of the active fraction increases. They bind many heavy metals, forming stable complex compounds. Therefore, metals pass into a pseudo-soluble state and become available for plants [11]. For this reason, due to the high content of heavy metals in the SSA of the Vodokanal of St. Petersburg, the supervisory authorities do not recommend the beneficial use of ash, despite the established IV hazard class. The continuous growth of waste generation, which is accompanied by a shortage of free space for its storage, determines both the relevance of the study and the interest of the Vodokanal St. Petersburg in actively addressing the issue of ash disposal.

Nowadays in St. Petersburg, according to the Decree of the Government of St. Petersburg N 989 (dated December 11, 2013), about 50,000 t/year of SSA are generated as a result of the activities of three incineration plants and then completely removed to landfills. Vodokanal of St. Petersburg is in charge of the «Volkhonka-2» landfill (currently closed for disposal of waste) and the «Northern» landfill. Placing landfills in close proximity to residential areas is a significant environmental issue. At the same time, the filling volume of the «Northern» landfill amounts to more than 91 percent of the design capacity, which has a negative impact on the environment. The termination of the ash storing in the landfill and possible disposal of already stored waste will not only free up some areas, but also reduce the negative impact of the object on the environment in the future.

3. Results

In order to assess the degree of contamination of ash with heavy metals, it is necessary first of all to establish their content in the sample and compliance with quality standards. In order to assess the degree of contamination of ash with heavy metals, it is necessary first of all to establish their content in the sample and compliance with quality standards [12, 13]. Sampling is performed according to the requirements [14]. On the basis of the obtained data on the ash composition (using the method of x-ray fluorescence analysis with a portable metal analyzer Niton XLt 898), a list of elements was selected
for quantitative analysis in accordance with the atomic absorption spectroscopy method: Pb, Zn, Mn, Fe, Cu, Mo [15]. AAS-7000 spectrometer (Shimadzu, Japan) was used for measurements.

The assessment of the degree of contamination of the sample performed by calculating the concentration ratio \( K \) according to the formula (1):

\[
K = \frac{C}{C_k}
\]

where \( C \) – the element content in the sample, mg/kg;
\( C_k \) – normatively permissible value (MAC or APC) in the medium, mg/kg.

The following exceedances of the relevant standards were recorded: Zn (7.9 APC), Pb (6.3 MPC), Cu (3.7 APC). The results are presented in table 1.

The total pollution indicator \( Z \) was calculated by the formula (2):

\[
Z = \sum K - (n - 1),
\]

where \( n \) – number of elements taken in the calculation.

### Table 1. Content of heavy metals in the SSA

| № | Me | \( C_i \) | MPC \(_i\) | APC \(_i\) | Concentration ratio |
|---|----|----------|----------|----------|-------------------|
| 1 | Zn | 1740     | -        | 220      | 7.9 |
| 2 | Pb | 200      | 32       | -        | 6.3 |
| 3 | Cu | 492      | -        | 132      | 3.7 |
| 4 | Mn | 965      | 1500     | -        | 0.6 |
| 5 | Mo | 16.5     |          |          | Informative |
| 6 | Fe | 270000   |          |          |      |

The indicator is equal to 15.9 (low degree of pollution) [16].

According to the results of the research, the assignment of waste to the IV class of hazard was confirmed using the software “Calculation of the hazard class of waste 2.0” (c) INTEGRAL 2001-2003 [17]. The IV hazard class of waste is also confirmed according to the results of the biotesting of the aqueous extract of waste (using the chlorella alga culture) [18, 17].

In accordance with the research work [19], the calculation of allowable doses of heavy metals in the soil of the Leningrad Region was carried out, taking into account their content in the waste.

Permissible dose \( D_p \) of admission to the soil of a heavy metal according to the formula (3), g/ha:

\[
D_p = (0.8 \cdot \text{MAC (APC)} - B) \cdot M
\]

where 0.8 – a correction factor reducing the normative intake of heavy metals into the soil by 20%;
B – the content of heavy metal in the soil before the introduction of waste (background concentration), g/t;
MAC (APC) – the maximum permissible (approximately permissible) concentration of the metal in the soil according to [12] or [13], g/t;
M – the mass of the arable horizon of the soil in terms of dry matter, t/ha (M = 3000 t/ha).

The average annual dose of waste in the soil in terms of dry matter for 10 years, t/ha, was defined as:

\[
D_a = \frac{D_p}{T \cdot C_{SSA}}
\]

where \( T \) – the maximum total term for depositing waste for the same area, years;
C_{SSA} – the concentration of metal in the ash sample, g/t.

It should be noted that when a useful component is introduced into the soil in the arable horizon, the normative permissible values of heavy metals should not be exceeded:
\[ B + A \leq MAC (APC) \] (5)

where \( F \) – the content of heavy metal in the soil before the introduction of waste (background concentration), mg/kg;

\( A \) – the additional flow of heavy metal into the arable horizon, weighing 3,000 t/ha.

From the obtained calculated data (table 2), it follows that when SSA is introduced into the soil of the Leningrad Region at the rate of 28.53 t/ha per year, the content of heavy metals in the arable horizon will not exceed the normative permissible values (where 28.53 t/ha is the annual dose of Zn in soil).

In order to assess the effect of SSA as a useful component of the waste-based soil mixture on the plants growth, Klever meadow (Trifolium pratense) of the Fabáceae family was selected as a plant capable of accumulation of heavy metals (based on literature data). Also Trifolium pratense is a siderate, i.e. additionally contributes to the enrichment of the soil with nitrogenous compounds and strengthening.

| Me | Regulatory allowable value | Soil | SSA | \( D_p \) | \( D_a \) | B+A |
|----|---------------------------|------|-----|---------|--------|-----|
| Mn | 1500                      | 30   | 965 | 3,510,000 | 363.73 | 52.29 |
| Pb | 32                        | 3    | 200 | 678.00   | 33.90  | 7.62 |
| Cu | 132                       | 3    | 492 | 307.800  | 62.56  | 14.37 |
| Zn | 220                       | 10.5 | 1,740 | 496,500  | 28.53  | 50.69 |

**Figure 1.** Composition of soil mixture model samples

Based on the established allowable doses of waste into the soil, the composition of model samples was calculated (Fig. 1). *Trifolium pratense* seeds were sown in a 80x90x90 mm tank with a mass of initial soil in each sample of 100 g. The seed seeding rate of Trifolium pratense (as a lawn grass) is 10 g/m²; 25 seeds were planted on each model sample. Regular watering was done three times a week (volume 50 ml) to maintain humidity.
The first seedlings are marked on the third day. The germination in the control sample reached 88%. In the remaining samples (except for the sample with a dose of ash "20 g"), the germination rate exceeded the control one. The best dynamics of germination was observed in samples "5 g" and "10 g", while it should be noted that the sample "10 g" reached 100% germination on the fifth day, and the sample "5 g" on the sixth day. Other model samples did not reach 100% germination until the end of the experiment (fig. 2).

In the course of the experiment, soil acidity control was also performed in accordance with the method [20]. While the initial pH value of the salt extract of the control sample (soil of the Leningrad region) was 5.03 pH. When SSA was introduced into the soil, the pH of the salt extract increased to 2 pH compared with the control; at the same time, the growth of pH depends on the dose of the introduced SSA.

![Germination dynamics](image)

**Figure 2.** Dynamics of germination of *Trifolium pratense*

**4. Discussion and conclusion**

SSA-based soil mixture can be used as fertilizer for planting trees along the roads, for recultivation of disturbed lands, slopes of roads, landfills for municipal solid waste. All of these ways are extremely relevant in the metropolis. In the long term the use of product has a significant resource saving effect by recycling waste and reducing the amount of original soil required for reclamation processes, as well as the economic benefit, because the cost of waste-based soil mixture is significantly lower than the market value of soil.

The data obtained in the course of the experiment demonstrate the positive effect that SSA from the Vodokanal of St. Petersburg has on the *Trifolium pratense* growth in the soil of the Leningrad Region.

The economic effect from the implementation of the results of theoretical and scientific-practical developments at the facilities of the Vodokanal of St. Petersburg and in large metropolitan areas is determined taking into account the following aspects.

The SSA-based soil mixture is proposed as a development result. The product is most promising for use as a fertilizer of the second group - for the recultivation of disturbed land, road slopes, and solid municipal waste landfills. This makes the product suitable for use by housing and communal services, as well as by private enterprises, which need a useful component for the land reclamation.

The use of the product has a significant resource-saving effect due to the disposal of waste and reducing the amount of initial soil required for remediation, as well as the economic effect, since the cost of soil mixture is much lower than the market value of the initial soil.

As an example, the authors consider the data of the Address Program of repair of roads for 2018 at the expense of the budget of St. Petersburg for 2018-2020 (for the target item "The cost of repairing
roads”). It follows from the document that during this period it is planned to carry out road construction works that require landscaping improvement on a total area of 237.75 hectares. Taking into account the fact that the average annual allowable amount of SSA applied to the landscaped area will be 28.53 t/ha, the total amount of waste required for the improvement of the specified area will be 6,783 tons. At the same time, about 20 m³ of SSA per day or about 4964 tons/year is generated only at The South-West wastewater treatment plant.

The removal of heavy metals from SSA and the search for ways of its beneficial use have been announced as one of the priority scientific topics for the maintenance of the Committee on Energy and Engineering of St. Petersburg. Further research is supposed to be directed to the development of a methodological approach to the choice of a rational composition of the SSA-based organic-mineral mixture as well as assessment of the effectiveness of its use in the conduct of recultivation in the field with filing application for the invention.

Sewage sludge management is an integral part of the work of any modern wastewater treatment plants. It is important to recover the nutrients contained in the sludge, to use it as a material or energy source and to dispose of it effectively.

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