ЗАБЕЗПЕЧЕННЯ СТАЛОГО РОЗВИТКУ СІЛЬСЬКОГО ГОСПОДАРСТВА НА ОСНОВІ ВИКОРИСТАННЯ ОСАДУ СТІЧНИХ ВОД

Актуальність. Події останніх років (пандемія Covid-19, бойові дії в Україні) призвели до значного зростання світових цін на продукти харчування. Таким чином, індекс цін ФАО у лютому 2022 року досяг історичного максимуму в 140,7 процентного пункту. Одним із суттєвих факторів у цій ситуації є значне підвищення цін на добрива для сільського господарства, що призводить до їх дефіциту. Це актуалізує пошук вирішення проблеми використання альтернативних ресурсів (в тому числі осадів стічних вод) як біологічного ресурсу для сталого сільського господарства і забезпечення реалізації цілей сталого розвитку, зокрема цілей 2, 6, 11, 12, 15.

Мета та завдання. Метою статті є аналіз різних аспектів використання осадів стічних вод у сільськогосподарському виробництві як один з перспективних шляхів реалізації цілей сталого розвитку.

Результати. Вміст органічної речовини в мулі може покращити фізичні, хімічні та біологічні властивості ґрунту, забезпечуючи кращу обробку ґрунту та здатність утримувати воду, особливо коли використовується знедовіданий мул стічних вод. Біотверді речовини зменшують стік і збільшують утримання поверхневої води. Органічний азот в мулі набагато рідше спричиняє забруднення підземних вод, ніж хімічні азотні добрива. Використання осаду стічних вод на сільськогосподарських угіддях є найкращим способом переробки поживних речовин, які вони містять. Тому осад стічних вод можна вважати важливим біологічним ресурсом для сталого сільського господарства.

У статті порівнюється фізико-хімічні характеристики осадів стічних вод різного походження. Виявлено, що концентрація біогарму, азоту і фосфору була однаковою. Тим не менш, існують деякі специфічні для об’єкта фактори, які роблять кожен осад стічних вод унікальним, і їх необхідно враховувати для прогнозування результатів очищення осаду стічних вод. У статті порівнюється фізико-хімічні характеристики осадів стічних вод різного походження. Виявлено, що концентрація біогарму, азоту і фосфору була однаковою. Тим не менш, існують деякі специфічні для об’єкта фактори, які роблять кожен осад стічних вод унікальним, і їх необхідно враховувати для прогнозування результатів очищення осаду стічних вод.
ENSURING SUSTAINABLE DEVELOPMENT OF AGRICULTURE BASED ON THE USE OF SEWAGE SLUDGE

Topicality. The events of recent years (the Covid-19 pandemic, hostilities in Ukraine) have led to a significant increase in world food prices. Thus, the FAO price index in February 2022 reached a historic high of 140.7 percentage points. One of the significant factors in this situation is a significant increase in prices for fertilizers for agriculture, which leads to their shortage. This actualizes the search for a solution to the problem of using sewage sludge as a biological resource for sustainable agriculture and ensuring the implementation of sustainable development goals, including goals 2, 6, 11, 12, 15.

Aim and tasks. The purpose of the article is to analyze various aspects of the use of sewage sludge in agricultural production as one of the promising ways to achieve sustainable development goals.

Research results. The content of organic matter in the sludge can improve the physical, chemical, and biological properties of the soil by ensuring better soil cultivation and water retention capacity, especially when dehydrated sewage sludge is used. Biosolids reduce runoff and increase surface water retention. Organic nitrogen in sludge is much less likely to cause groundwater pollution than chemical nitrogen fertilizers. The use of sewage sludge on agricultural land is the best way to recycle the nutrients it contains. Sewage sludge can therefore be considered an important biological resource for sustainable agriculture and ensuring the implementation of sustainable development goals, including goals 2, 6, 11, 12, 15.

To achieve the goal, an analysis was made of the effect of sewage sludge on the physico-chemical and microbial properties of the soil; its impact on plants and their productivity; the problems of...
using soil sludge in agriculture, taking into account its contamination with various substances (heavy metals, microplastics and pharmaceuticals), have been studied.

**Conclusions.** Sewage sludge is a promising fertilizer for sustainable agriculture, taking into account the need for an effective technology for its purification from hazardous substances.

**Keywords:** sustainable agriculture, sewage sludge as resource, plant productivity, priorities of economic use of sewage sludge.

**Problem statement and its connection with important scientific and practical tasks.** Sewage sludge (SS) is a heterogeneous mixture that is formed as a by-product at a wastewater treatment plant (WWTP). It can be defined as a complex suspension of solid organic and inorganic substances and colloids that have separated from the wastewater during the treatment process (Gray, 2005). One of the main scientific and applied problems is to develop organization and economic approaches to the use of wastewater (sewage sludge) in economic activities, namely in agriculture. It is needed a solution to the problem of using sewage sludge as biological resource for sustainable agriculture and ensuring the implementation of sustainable development goals, including goals 2, 6, 11, 12, 15.

**Analysis of recent publications on the problem.** Sludge is rich in nutrients such as nitrogen and phosphorus and contains valuable organic substances, but it tends to concentrate heavy metals, hardly biodegradable trace organic compounds, pathogenic organisms, bacteria such as enterococci, streptococci and others, and viruses present in wastewater (Ribeirinho, 2015).

The global production of sewage sludge is estimated at 45 million tons of dry matter per year (Zhang et al., 2017, Buta et al., 2021). Sewage sludge production in EU countries increased by 1.5 million t of DM in the last 10 years, from 11.5 million t in 2010 to 13 million t in 2020 (Buta et al., 2021), therefore its management is a problem of great concern (Bianchini et al., 2016).

**Allocation of previously unsolved parts of the general problem.** In sludge management it is necessary to follow the waste management hierarchy, where its disposal at the landfill should be a last resort. Possibilities of sludge recovery from municipal wastewater treatment are compost production, application directly to agricultural and forest land, production of growing substrates, and further lower in the waste management hierarchy, energy recovery (Trošanová et al., 2018).

Various methods had been applied to manage SS, including thermal processing, composting, agricultural use and landfilling. The percentage of used methods in selected countries is presented in Figure 1.

![Figure 1](image_url)

**Fig.1.** Disposal of sewage sludge from urban wastewater treatment by method of disposal

Concluded according to Eurostat data and (Collivignarelli, Abba, A. et al, 2019)
For practical and legal reasons, SS is increasingly reused rather than landfilled. This approach is consistent with zero waste strategy and aims to minimise generated waste and promote the development of the bioeconomy which provides intelligent waste management (Buta et al, 2021).

**Formulation of research objectives (problem statement).** The purpose of the article is to analyze various aspects of the use of sewage sludge in agricultural production as one of the promising ways to achieve sustainable development goals.

**An outline of the main results and their justification.** Different countries have chosen different strategies for the use of urban sewage sludge. Fig. 1 shows disposal of sewage sludge from municipal wastewater treatment plants in the states of the European Union. In many of the member states prevails the application directly to the agricultural and forest land, combined with composting. Ireland is leading with over 90% of SS being used in agriculture.

After analysing the data from Eurostat between the years 2014 and 2018, use of SS in agriculture combined with composting had been the main route for sludge disposal in EU with 44.58%, followed by incineration (32.70%) and other methods of disposal (9.16%). Landfill disposal was at the level of 7.81%.

Over the nine-year period, attitudes towards the use of sewage sludge in agriculture have changed in various European countries.

### Table 1 - The composition of SS of different WWTPs

<table>
<thead>
<tr>
<th>Inhabitants thousands</th>
<th>Latvia</th>
<th>Poland</th>
<th>Czech Republic</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>&lt;10</td>
<td>10-100</td>
<td>100-1000</td>
</tr>
<tr>
<td>Dry matter, %</td>
<td>14.4</td>
<td>15.8</td>
<td>22.1</td>
</tr>
<tr>
<td>pH</td>
<td>6.3</td>
<td>6.7</td>
<td>6.8</td>
</tr>
<tr>
<td>N, g kg⁻¹</td>
<td>0.84 (58)</td>
<td>1.16 (73)</td>
<td>40.2</td>
</tr>
<tr>
<td>P, g kg⁻¹</td>
<td>25</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>K, g kg⁻¹</td>
<td>9.6</td>
<td>9.9</td>
<td>n.d.</td>
</tr>
<tr>
<td>Ca, g kg⁻¹</td>
<td>37.8</td>
<td>28.8</td>
<td>n.d.</td>
</tr>
<tr>
<td>Mg, g kg⁻¹</td>
<td>0.41</td>
<td>1.11</td>
<td>n.d.</td>
</tr>
<tr>
<td>C, %</td>
<td>36.88</td>
<td>39.8</td>
<td>n.d.</td>
</tr>
<tr>
<td>S, g kg⁻¹</td>
<td>8.4</td>
<td>11.1</td>
<td>n.d.</td>
</tr>
<tr>
<td>Zn, mg kg⁻¹</td>
<td>165.4</td>
<td>560.8</td>
<td>720</td>
</tr>
</tbody>
</table>

Sludge is rich in organic matter, nitrogen, phosphorus and other macro and microelements, which makes it a useful raw material to be used in agriculture. Physico-chemical characteristics of SS of different origin were compared. The concentration of carbon, nitrogen, and phosphorus were similar. Nevertheless, there are some site-specific factors that make each SS unique and must be taken into account to predict the outcome of SS treatment. Determination of these factors remains challenging. (González et al., 2019)
The composition of SS varies considerably both between WWTPs and within the same plant mainly due to applied technology, quantity and the origin of raw wastewater. Untreated sewage sludge usually contains 2-8% of dry matter (DM) (Buta et al., 2021).

At small WWTPs, up to approximately 10,000 inhabitants, only one type of sludge is produced directly in the water line and is called aerobically stabilized sludge. At larger WWTPs, with more than 10,000 inhabitants, it is divided into primary and secondary sludge (Kecskesova et al., 2020). The primary sludge contains settling substances contained in the wastewater (from primary settling tanks), usually it has a granular structure. Secondary sludge, also called excess sludge, consists of a mixture of microorganisms and settleable substances from the biological stage of the WWTP. Primary and secondary sludge are referred to as so-called raw. The raw sludge is still microbially active, it can contain pathogenic microorganisms, with total content of organic substances in the dry matter at about 70%. However, dewatered sludge is considered harmless, as the organic substances decompose during stabilization. In the past, sludge stabilization has been carried out mainly aerobically on sludge fields, currently the most widespread sludge stabilization process in the EU is methaneisation, where the final product is biogas and stabilized sludge, using 40% of the organic matter present in the raw sludge (Gray, 2005).

The average concentrations are 31.75 g of N (3.2%), 17.37 g of P (1.75%) and 4.62 g of K (0.5%) per kg of treated dry SS. (Aleisa et al., 2021)

Dry sewage sludge contains on average 50 - 70% organic matter and 30 - 50% mineral components. The nitrogen content in the sludge dry matter is in the range of 1.6 - 6% and the phosphorus content in the range of 1 - 4%. From the point of view of plant nutrition, the potassium content of the sludge is usually low and, in comparison with the nitrogen and phosphorus content, the potassium content can be considered insufficient. The content of other macro- and micronutrients, as well as risk elements, differs significantly according to individual wastewater treatment plants (Mercl et al., 2018).

Dehydrated SS contains 20-45% of DM and its suitability for agriculture is determined mainly by high content of organic matter, and biogenic elements (C, N, P), which increases soil fertility and is essential for plant growth and development as well as for soil microbiota.

Microbiological decomposition of sludge changes the amount of mineral elements available to plants in the soil (Dubova et al., 2020)

Different methods can be used for the processing of activated sludge, but, the biological processing aims to provide degradation not only reduce pathogenic organisms, mitigating effects on human health and environment, but biodegrade toxic organic compounds (petroleum derivatives, pharmaceutical compounds, and other xenobiotics (Vucāns et al., 2006; Biswas and Turner, 2012).

However, sludge may also contain significant amounts of hazardous and often very persistent substances, such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, halogenated hydrocarbons, polychlorinated dibenzo-p-dioxins and dibenzofurans, pesticides, personal care products, hormonal substances, drugs and their metabolites, microplastics or nanoparticles. In addition, various types of pathogenic organisms, such as bacteria, viruses or protozoa, may be present in the sludge (Mercl et al., 2018).

Storage and treatment methods influence quality and properties of SS. In municipal WWTPs, the phylum Proteobacteria (21–65 %) predominates, of which β-proteobacteria is the most abundant class, largely responsible for organic and nutrient removal. The municipal waste and sediment samples from the food industry are dewatering (with flocculant) and/or liming to improve the sludge hygiene properties. Processing with lime decreased the number of bacteria in municipal sediments and caused an increase in sediment samples from food industry compared to the non-limed ones. The treatment of SS in a mesophilic regime did not providing secure materials. (Blaszczyk and Krzyzko-Lupicka, 2013; Nascimento et al., 2018).

**Application in agriculture. SS effects on soil physico-chemical properties.** The content of organic matter in the sludge can improve the physical, chemical, and biological properties of the soil by ensuring better soil cultivation and water retention capacity, especially when dehydrated sewage sludge is used. Biosolids reduce runoff and increase surface water retention. Organic nitrogen in sludge is much less likely to cause groundwater pollution than chemical nitrogen fertilizers. The use of sewage sludge on agricultural land is the best way to recycle the nutrients it contains. Sewage sludge can therefore be considered an important biological resource for sustainable agriculture. It produces favourable crop reactions when used as an organic fertilizer (Fließbach et al. 1994; Collivignarelli et al., 2019). The main problems related with the reuse of sewage sludge or removed from it biosolid is the presence of heavy metals, organic contaminants, and/or pathogens, but no agreement about the adverse effects caused by application of sludge. According to
Manzetti and van der Spoel (2015), the following aspects can be reported: (a) raising of the levels of persistent toxins in soil, vegetation, and wild life, (b) potentially slow and long-term biodiversity reduction through the fertilizing nutrient pollution operating on the vegetation, (c) greenhouse gas emissions (e.g., CH₄ and N₂O), and (d) the release of odorous compounds.

When using sewage sludge for soil fertilization, there is a certain contradiction between the wishes of sludge producers and users, on the one hand, and environmental protection requirements, on the other. Sludge producers and sludge users are usually interested in incorporating the highest possible doses and thus introducing large amounts of plant nutrients into the soil. At the same time with plant nutrients, a certain amount of harmful substances to the environment and human health enter the soil. If these substances exceed a certain concentration, they can become dangerous to the environment - soil, water, and plants. Excessive concentrations of plant nutrients, mainly nitrogen and phosphorus, can also harm the environment, especially inland waters. Therefore, the incorporation of sludge and its compost in soil is regulated by setting emission limit values for dry matter, heavy metals and plant nutrients, as well as the permissible doses of sludge for incorporation (Picariello et al., 2021).

The annual emission limit values for dry matter, heavy metals, total nitrogen, and total phosphorus are the maximum mass of these substances that can be applied per hectare of sludge or compost on average per year. Emission limit values for sludge dry matter vary considerably between EU Member States, ranging from 1 to 10 t ha⁻¹ per year. According to Cuevas et al. (2003), a high rate of SS composites applied once (60 t ha⁻¹ compost in seedbed) is not recommendable since high nitrate concentration is not taken up by maize and increases the leaching risk.

Many studies reported an increase of organic with SS application to agricultural soils. High organic matter (OM) content of SS improves the physicochemical and biological characteristics of agricultural soils. It reduces bulk density and in turn increases the soil - air recirculation, increases the water holding capacity, improves soil porosity and structure, soil moisture and increases soil humus. Organic matter enhances soil nutrient storage, soil biota and diversity. Reduces exposure to erosion. High OM content facilitate the formation of stable organic complexes with HM, thus reducing metal availability (Eid et al., 2020).

SS is recognized to increase soil acidity, perhaps as a result of the formulation of organic and inorganic acids throughout the decomposition process of SS components under aerobic conditions. Soil salinity was positively correlated with the increased application rate of SS. Amendment of loamy clay soil with SS at dose 60 t ha⁻¹ increased soil carbon content from 0.16% to 1.45% (Eid et al., 2018).

The SS application has a positive effect on carbon mineralisation in various soil types, climatic regions, cropping systems and land uses. It plentifully releases mineral elements and improves the physical, chemical, and biological parameters of the soil, which benefits from an increased gas exchange, better water infiltration and retention (Boudjabi & Chenchouni, 2021).

**SS effects on soil microbial properties.** Despite the presence of potential contaminants, the use of sludge improved the N mineralization potential of the soil. When sewage sludge is applied to soil, it causes changes in the structure and functioning of the agroecosystem. The most sensitive component is the soil microbiota, which can undergo both stimulatory and inhibitory changes in the activity and structure. The use of sludge has been shown to increase the activity of soil enzymes (aryl sulphatase, acid phosphatase and alkaline phosphatase). But application of sludge at a high rate (200 t ha⁻¹) was found to significantly reduce the functional diversity of the soil microbial community (Usman et al., 2012), but sewage sludge rich in heavy metals causes decrease of microbial biomass greater in sandy soil than in clayey soils (Khan and Scullion, 2000). Mbagwu and A. Piccolo (1990) reported that degradation of the organic matter in sludge significantly increases the availability of nutrients e.g. nitrogen and phosphorus. Application of sewage sludge at a rate of 200 t ha⁻¹ increased the total nitrogen of soil aggregates by 57% and available phosphorus by 64.2%. Mineral nutrients are released more slowly during the degradation of organic matter than in the case of used inorganic fertilizers and, therefore, the compounds are available for a longer period (Khan and Scullion, 2000).

The heavy metals present in sewage sludge causes not only a direct toxic effect but also may indirectly affect soil enzymatic activities (Kandeler et al. 2000). Amending soils with sewage sludge can increase soil microbial activity, soil respiration, and soil enzymatic activities. But effect also depends on the duration of use of the sludge and the concentration of metals, when high microbiological activity were longer and heavy metal availability was higher, reduced soil enzyme activities were reported (Fließbach et al. 1994).

Applied biosolids doses increased the C_met/C_total and N_met/N_total ratios in the soil. This is related to an increased amount and quality of organic matter added to the soil via sewage sludge (Fernandes et al., 2005).
But application of sludge with high heavy metal amounts, according to Fließbach et al (1994) and Chander and Brookes (1993), C$_{\text{geo}}$/C$_{\text{total}}$ ratio decreases to 32 and 50% accordingly.

Many factors may modulate microbial community structure within sewage sludge, which may change from autotrophic to heterotrophic bacteria depending on effluent source. *Proteobacteria* phylum (21–65%) was predominant in municipal sewage sludge, mostly belonging to *β-proteobacteria* that represents a class of microorganisms related to organic matter degradation and nutrient cycling. Other less dominant taxa were *Bacteroidetes*, *Acidobacteria*, and *Chloroflexi* (Nielsen et al., 2010). Biological treatment condition may be another important modulating factor. *Proteobacteria* was most abundant in aerobic whereas *Bacteroidetes* was most abundant in anaerobic bioreactors (Hu et al., 2012).

SS has great microbial diversity, which may vary depending on the origin of sewage, its treatment, and industrial activity. SS microbial activity, transformation by-products, and residues may impact soil quality if SS is used as fertilizer (Nascimento et al., 2018).

**SS effects on plants. On seed germination.** Experiments demonstrate that the hygienically treated (by liming) sewage sludge has inhibitory effect on the growth of white mustard (*Sinapis alba* L.) seeds already at a ratio of 10%. This is why the sludge is not suitable for direct application on agricultural soils. The addition of compost resulted in the suppressed phytotoxicity of sludge in all tested ratios and hence in the reduced inhibitory effect. (Sindelar et al., 2021). Our experiments showed that the use of sewage sludge affects the germination and development of seedlings. Concentrations exceeding 7 g kg$^{-1}$ inhibit the germination of cucumber seeds and necrotising primary roots.

Air dried SS mixed with agricultural soil at rates of 0 (control), 10, 20, 30, 40, and 50 g kg$^{-1}$ decreased Broad bean (*Vicia faba* L.) seed germination from 70.0% (control), to 63.3, 56.7, 50.0, 50.0 and 46.7% respectively (Eid et al., 2018).

**SS effects on plant productivity.** Effect of SS differs depending on the SS application method, i.e. at the soil surface “mulching” or mixed homogeneously with soil. The application of SS on the surface limits water evaporation by forming a physical barrier which allows soil moisture to be retained longer. Due to that the biological and chemical processes of organic matter transformation intensified (Boudjabi & Chenchouni, 2021).

The best yield of wheat (*Triticum durum* Desf.) was obtained when SS (dried) is applied at the soil surface (Boudjabi & Chenchouni, 2021).

In vegetation pot experiments with broad beans (*Vicia faba* L.), where air dried SS was blended with agricultural soil at rates of 0 (control), 10, 20, 30, 40, and 50 g kg$^{-1}$ (equal to 0, 30, 60, 90, 120, and 150 t ha$^{-1}$), all the growth and morphometric parameters of broad bean showed a positive response under SS soil compared to non-amended soil. The most effective for biomass yield of broad bean was application of 120 t ha$^{-1}$ SS (Eid et al., 2018).

Compared to plants grown in control soil, all of the SS amendment doses enhanced the growth of barley plants. The increases in dry weights were more pronounced than the increases in shoot and root lengths indicating an active metabolism in the SS-amended soils that enhanced the plant power to accumulate more biomass. The leaf area, number of leaves, and tillers per plant also significantly increased in plants grown in SS-supplemented soils. The recommended amendment dose for best growth of barley plants would be 40 g SS per kg of soil (Eid et al., 2020).

Rehman et al. (2018) results showed that SS can be used as fertilizers either as sole application or after pyrolysis. Both sole application of SS and their respective biochars provided enough P for the plants to achieve biomass higher than conventional P-fertilizer. Properties of sewage sludge-derived biochar depend on the properties of sewage sludge and also the temperature of pyrolysis (Zielińska et al., 2015).

Amendment with SS is useful for enhancing crop production, as well as the accumulation of nutrients and OM in soil, but regular observation of HM accumulations in soil and plant tissues must be taken in the course of its continuous use. (Eid et al., 2018)

Pot experiments were carried out with substratum made from SS anaerobic digestate (SSAD) and its biochar, perlite and quartz sand (w/w 9:6:60:25). The results showed that the seedling survival rate and individual biomass of ryegrass in substrate were 100% and 100.02 mg, which were 14.4% and 231.4% higher than those in only SSAD, but were 1.3% and 19.6% higher than those in soil. (Zhang et al., 2021). Pot experiments with maize plants grown with SS, SS and additional mineral fertilizers and mineral fertilizers as control showed that SS alone and in combination with potassium fertilizers does not provide maize plants with mineral nutrients in appropriate amounts. However the combination of SS with mineral fertilizers significantly improves plant growth and promotes their development. The use of SS increases the
microbiological activity of the soil. This can have a beneficial long-term effect on the mineral nutrition of plants. (Dubova, et al, 2020)

Experiments done at Latvia University of Life Sciences and Technologies showed that different species of plants react differently to the incorporation of a sewage sludge preparation into the soil. The preparation is used for the cultivation of snapdragon, but it is not recommended for the cultivation of amaranths and sweet tobacco (Nicotiana alata). That could be explained by: • Sensitivity of different plants to the compounds in the sewage sludge preparations. • Demands of different plants for mineral elements in the early stages of ontogenesis. The nutrients in the SS do not appear to be released quickly enough for the plants to use them in their metabolism. As a result, plants show signs of a lack of mineral elements. It is possible that the organic fertilizer has not undergone a sufficient process of maturing the compost and retains plant growth inhibitors. The effect of the preparation depends on the substrate used in the cultivation of the plant. Plant growth was faster in peat and had a greater inhibitory effect. This can be explained by the most intense microbiological processes in the soil, which can degrade the growth inhibitory compounds of incomplete composting. • Slower decomposition of SSP, as a result of which plants feel more deficient in nutrients.

**Challenges of soil sludge application in agriculture.** Sludge is formed as a by-product of wastewater treatment, concentrating and discharging from these waters the substances that caused their pollution. Their type and concentration depends on the composition of the wastewater supplied to the WWTP. The composition of the sludge and the concentration of pollutants in it predetermine the possibilities of its use (Kozáková and Sumegová, 2020).

Sewage sludge has been and still is used as a fertilizer in many areas around the world. Recently, however, its direct use for agricultural land applications has changed. The reason is fundamental changes in the composition of the sludge, when changes in the lifestyle of the population led to an increase in the content pollutants in the sewage sludge (Manzetti and van der Spoel, 2015).

The main problems related with the reuse of sewage sludge or removed from it biosolid is the presence of heavy metals, organic contaminants, and/or pathogens, but no agreement about the adverse effects caused by application of sludge. According to Manzetti and van der Spoel (2015), the following aspects can be reported: (a) raising of the levels of persistent toxins in soil, vegetation, and wild life, (b) potentially slow and long-term biodiversity reduction through the fertilizing nutrient pollution operating on the vegetation, (c) greenhouse gas emissions (e.g., CH\(_4\) and N\(_2\)O), and (d) the release of odorous compounds.

**Heavy metals and their content in soil and plants.** Long-term accumulation of toxic elements in soil and their uptake by plants is currently the biggest concern in terms of direct SS land application. Utilization in agriculture is, however, only regulated by the limits of heavy metals specified in Council Directive 86/278/EEC (CEC, 1986), which sets the limits of heavy metal concentrations in both the sludge and SS treated soil (Table 2).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hg</th>
<th>Ni</th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>in soil</td>
<td>1 – 1.5</td>
<td>30 - 75</td>
<td>50 - 140</td>
<td>50 - 300</td>
<td>150 - 300</td>
<td>1 - 3</td>
</tr>
<tr>
<td>in sludge</td>
<td>16 - 25</td>
<td>300 - 400</td>
<td>1000 - 1750</td>
<td>750 - 1200</td>
<td>2500 - 4000</td>
<td>20 - 40</td>
</tr>
</tbody>
</table>

The bioavailability of heavy metals in the soil is closely related to the value of the soil exchange reaction (soil pH measured in KCl or CaCl\(_2\) form), as well as to the sorption properties of the soil, which change with the addition of sewage sludge. According to various studies, the availability of heavy metals in soils decreases in the order (Zn + Cd) > (Ni + Cu) > (Pb + Cr). However, in connection with physico-chemical processes, the accumulation of heavy metals may occur over time, so it is necessary to monitor their concentration for a long time after the application of sludge (Samešová, 2012).
Ďuricová and Samešová (2014) compared the heavy metal distribution after different types of sludge stabilization. In all cases higher values of metal concentrations were recorded in the anaerobically stabilized sludge than in the aerobic sludge and, conversely, the supernatant, resp. the sludge water obtained from the anaerobically stabilized sludge contained higher metal concentrations compared to the supernatant obtained from the anaerobic sludge stabilization. The addition of flocculant had the greatest effect on the concentration of copper (Cu) in the sludge, which was released from the sludge. On the other hand, iron (Fe) was bound after the addition of the floculant to the sludge.

During 18 years, the amount of heavy metals in Jelgava sewage sludge has significantly decreased (Table 3). Similar regularities have been observed in other treatment plants and this shows that heavy metals are no longer the most important limiting factor for the use of sewage sludge.

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cd</th>
<th>Cr</th>
<th>Cu</th>
<th>Hg</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>1.2</td>
<td>2602</td>
<td>151</td>
<td>2.9</td>
<td>28</td>
<td>465</td>
<td>1010</td>
</tr>
<tr>
<td>2019</td>
<td>&lt;0.17</td>
<td>82.8</td>
<td>102</td>
<td>1.39</td>
<td>44.2</td>
<td>29.2</td>
<td>492</td>
</tr>
<tr>
<td>Permissible amount*</td>
<td>10</td>
<td>600</td>
<td>800</td>
<td>10</td>
<td>200</td>
<td>500</td>
<td>2500</td>
</tr>
</tbody>
</table>

* according to Latvian legislation (MK . Nr.365.20.08.2002)

When sludge is incorporated into the soil, the heavy metals in it bind to organic matter and clay particles, which usually accumulate in the soil. In the deeper layers, the content of heavy metals is significantly lower, except in the case of soils formed on chemically rich rocks. The reduction of heavy metals in the soil occurs through their transfer to plants (removal by yield), leaching into the deeper layers, movement through surface runoff, and evaporation (e.g. mercury).

The uptake of heavy metals by plants depends on their 'mobility', which is affected by soil reaction, organic matter content, particle size distribution, temperature and humidity. Acidification of the soil significantly increases the 'mobility' of heavy metals and increases their uptake by plants. Soil acidification has a lower effect on the uptake of lead, chromium and copper by plants.

The 'mobility' of heavy metals also depends on whether they are adsorbed on the soil or in the form of ions. Because heavy metals are bound to organic matter in activated sludge, they are less 'mobile' and less accessible to plants than metals in the form of ions.

The uptake of heavy metals by plants is hindered by the antagonism of several other elements in the soil. Its phosphorus and calcium inhibit the uptake of several heavy metals, such as zinc, cadmium, nickel, by nitrogen, mainly lead and zinc, and potassium, cadmium, copper and mercury. Therefore, the incorporation of activated sludge, which is usually high in nitrogen and phosphorus, also reduces the uptake of heavy metals in plants to some extent.

Dry matter, heavy metals, total nitrogen and total phosphorus may not be incorporated into the soil at the same time as sewage sludge or compost, up to a maximum of seven years. In Latvia, no more than 14 t ha\(^{-1}\) of dry matter may be incorporated at a time with sludge or compost. This corresponds to 55 t ha\(^{-1}\) of naturally moist sludge with a dry matter content of about 25%. (Gemste, et al., 2002)

The heavy metals present in sewage sludge causes not only a direct toxic effect but also may indirectly affect soil enzymatic activities (Kandeler et al. 2000). Amending soils with sewage sludge can increase soil microbial activity, soil respiration, and soil enzymatic activities. But effect also depends on the duration of use of the sludge and the concentration of metals, when high microbiological activity were longer and heavy metal availability was higher, reduced soil enzyme activities were reported (Fließbach et al. 1994).

**Other pollutants. Microplastics.** Ragoobur et al., (2021) reported on 5150-21,800 particles.kg\(^{-1}\) wet weight in sewage sludge of Mauritius. MPs in sewage sludge were mainly composed of cotton-PA fibres,
PE spheres and EVA foams. Cotton-PA fibres were found to be in abundance and were identified in both sewage sludge and effluents. The percentages of cotton-PA, PE and EVA foams were 88.85%, 2.77% and 1.66%, respectively. Due to the small sizes (0.5-0.25 mm), a majority of the MPs could not be removed. Pignattelli et al. (2020) highlighted the toxicity caused by small MPs (PP, PE and PVC) on the growth of garden cress (Lepidium sativum). The impacts of MPs particles on plants remain unknown and further works are required to explore the effects of MPs on a wider range of vegetables.

Sewage sludge is often stabilised by anaerobic digestion. MP particles can affect methane production Ragoobur et al., (2021).

Studies of Yang et al. (2021) showed that nine years of repeated sludge application led to the accumulation of microplastics in the soil. The abundance of microplastics was significantly higher in the municipal sludge (149.2 ± 52.5 particles kg⁻¹) than in the mixed (68.6 ± 21.5 particles kg⁻¹) or dried (73.1 ± 15.4 particles kg⁻¹) sludge and this was related to the microplastic abundance in the sludges. This field study confirms that sludges are drivers of soil microplastic pollution.

**Pharmaceuticals.** Domestic sewage sludge is a major source of antibiotic resistance genes, so it is important to ensure its biodegradation during sludge treatment. The amount and type of antibiotics in wastewater affect the composition of bacteria. Sewage containing penicillins was dominated by phyla *Proteobacteria* and *Firmicutes* and bacteria from the classes *Clostridia* and *Bacilli*. The presence of tetracyclines, penicillins, sulfonamides in the sludge correlated with the amount of *e*-proteobacteria but negatively with β- and γ-proteobacteria and *Firmicutes*. *Sulfuritalea, Armatisomonas, Prosthecobacter, Hyphomicrobium, Azonexus, Longilinea, Paracoccus, Novosphingobium* and *Rhodobacter* were identified as potential tetracycline-resistant bacteria (Błaszczyk, K. and Krzyśko-Łupick, 2013).

**Conclusions and perspectives of further research.** Concerning the organic contaminants, a large number of scientific studies investigated the possible environmental threats that could be posed by organic contaminants in SS when applied to farmland; however, there was no evidence for soil–crop transfer, with the studies finding no or negligible risk to human health when consuming crop plants grown in SS-amended soils. This conclusion is ascribed to the compartmentation of organic contaminants in soil and the persistence of only tiny negligible concentrations of certain possibly hazard compounds in bio-solids, for example, dioxins. Thus, accepting the recycling of SS to agricultural lands is not limited by organic contaminants that could be found in SS. (Eid et al., 2020).

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**REFERENCES**


35. Ribeirinho V.: Heavy metals and soil organic matter after eight years of the last application sewage sludge (in Portuguese), Campinas, SP, 2015.


