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THE USE OF URBAN SEWAGE SLUDGE IN AGRICULTURE – A SOURCE OF ORGANIC MATTER AND NUTRIENTS OR A SANITARY AND ENVIRONMENTAL RISK?

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Abstract

Urban sewage sludge generated by municipal wastewater treatment plants represents a resource for agricultural use due to its high content of organic matter and plant nutrients, particularly nitrogen and phosphorous. When it is applied as an organic soil amendment, sewage sludge can restore soil fertility, improve soil structure, stimulate biological activity and reduce dependence on mineral fertilizers. However, sewage sludge may also contain hazardous substances, including heavy metals, organic contaminants, micro plastics and pharmaceutical residues. Moreover, it can act as a vector for pathogenic microorganisms, such as bacteria, viruses and helminth eggs, poising risk to soil, water resources and public health. Consequently, agricultural reuse of sewage sludge is regulated by strict legislative frameworks defining permissible pollutant concentrations and requiring stabilization and hygienization before application. Sludge application must be carefully managed through appropriate dosing, crop selection, avoidance of fresh-consumed crops and regular monitoring of sludge and soil to ensure environmental and human health protection.

Key words: *urban sewage sludge, sustainablee agriculture, organic matter, nutrients, environmental risk.*

INTRODUCTION

The increasing pressure on soil resources and the growing demand for mineral fertilizers have brought the use of sewage sludge ("urban sludge") back into focus as a resource for agriculture. Sludge originating from urban wastewater treatment plants contains significant amounts of stabilized organic matter, nitrogen, phosphorus, and trace elements, which makes it a potential organic amendment and fertilizer with a role in increasing humus content, improving soil structure, and stimulating biological activity. Recent meta-analyses show significant increases in soil organic matter, nitrogen and phosphorus content, and certain micronutrients (Zn, Cu) following sludge application at controlled rates (Paganini et al., 2024; Li et al., 2024).

At the same time, sewage sludge is a concentrate of pollutants resulting from the mixture of domestic and industrial wastewater: heavy metals (Cd, Pb, Hg, Ni, Cr), persistent organic compounds, microplastics, pharmaceutical residues, endocrine disruptors, PFAS ("forever chemicals"), and other emerging contaminants (Council Directive 86/278/EEC, 1986; Mara et al., 1989; Yakamercan et al., 2021; Frišták et al., 2024; Balkrishna et al., 2025; Chenu, 2025). In addition, sludge may contain a significant microbiological load: pathogenic bacteria, enteric viruses, protozoa, helminth eggs and larvae, which can survive for long periods in the environment and be transmitted to humans and animals through direct contact, aerosols, or the consumption of contaminated plant products (FAO, 1995; Jiménez et al., 2010; Amoah et al., 2018).

In the European Union, Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture, establishes limit values for heavy metals in soil and sludge, as well as treatment requirements for pathogen reduction, in order to encourage the proper use of sludge and prevent harmful effects on soil, vegetation, animals, and human health (Council Directive 86/278/EEC, 1986; Baltic Water Hub, 2022).

Some Member States have introduced additional regulations (codes of good practice, local protocols) that define the frequency of sludge and soil analyses and impose restrictions on crops intended for direct human consumption (Scottish Executive, 2002; US EPA, 2019).

On the other hand, there are also critical or restrictive positions. Some countries have completely banned the use of sludge in agriculture, opting instead for incineration and phosphorus recovery from ash, citing the risks associated with emerging contaminants and uncertainties regarding long-term effects on soil and the food chain (FAO, 1995; De Brouwere et al., 2006; Chenu, 2025).

Other analyses draw attention to documented cases of odors, discomfort, and possible illness in areas where insufficiently treated sludge was applied (Reilly, 2001; Yakamercan et al., 2021).

Against this background, this paper aims to synthesize recent bibliographic data regarding:

- the composition of urban sludge in terms of organic matter and nutrients;
- the content of pollutants and emerging contaminants;
- the load of parasite eggs, viruses, and other pathogens;
- the effects on agricultural yields and on product quality;
- the requirements and frequency of control analyses;
- to propose an evaluation and monitoring methodology for the controlled use of sludge in agriculture.

MATERIALS AND METHODS

The methodology is conceptual in nature and integrates recommendations from directives, international guidelines, and experimental studies (Council Directive 86/278/EEC, 1986; Scottish Executive, 2002; Navarro et al., 2010). A combined design is proposed, including sludge characterization studies, soil monitoring, and a factorial field experiment.

Sludge characterization. For each wastewater treatment plant, a quarterly sampling program of dewatered/stabilized sludge is carried out. The minimum recommended analyses include: dry matter, organic matter (organic C), total N, total P, total K, pH, and electrical conductivity; heavy metals (Cd, Cu, Ni, Pb, Zn, Hg, Cr) according to Directive 86/278/EEC; selected emerging contaminants (for example, representative pharmaceuticals, PFAS, microplastics, where analytical capacity exists) (Council Directive 86/278/EEC, 1986; Mara et al., 1989; US EPA, 2019; Frišták et al., 2024; Chenu, 2025). For the microbiological component, bacterial indicators (*E. coli*, *Salmonella* spp.), viable helminth eggs, and, where justified, enteric viruses (adenovirus, norovirus) are determined (FAO, 1995; Jiménez et al., 2010; Gholipour et al., 2022).

Soil characterization and experimental design. Before application, agrochemical and pedological mapping of the experimental field is performed: texture, pH, organic C, total N, available P, available K, cation exchange capacity, and background heavy metals (FAO, 1995). A randomized experiment is proposed with at least four treatments: control (no sludge), recommended mineral fertilizers, moderate sludge dose (equivalent to 50-60% of the recommended N dose), and high sludge dose (equivalent to 100% of the N dose), with four replications (FAO, 1995; Navarro et al., 2010; Singh et al., 2010; Kildare County Council, 2023; Marin et al., 2023).

Monitoring. Each year, the following are monitored: (i) soil fertility parameters (organic C, N, P, K, micronutrients); (ii) accumulation of heavy metals and possible emerging contaminants in soil; (iii) microbiological soil load (bacterial indicators, helminth eggs); and (iv) crop yields and heavy metal content in edible plant organs (grains, leaves, roots) (FAO, 1995; Navarro et al., 2010; Singh et al., 2010; Zhai et al., 2018; Trinomics, 2020; Kildare County Council, 2023). The frequency of analyses is adjusted according to the results, in line with the regulatory framework and good practice guidelines (Council Directive 86/278/EEC, 1986; Scottish Executive, 2002; Navarro et al., 2010; US EPA, 2019).

RESULTS AND DISCUSSIONS

Characteristics of urban sludge as an alternative source of fertilization in agriculture

Organic matter and nutrient content. Urban sludge originating from municipal wastewater treatment plants is rich in stabilized organic matter and nutrients, especially nitrogen and phosphorus, and to a lesser extent potassium and micronutrients (Fe, Mn, Zn, Cu) (FAO, 1995; Kildare County Council, 2023; Marin et al., 2023; Paganini et al., 2024). The meta-analysis conducted by Paganini et al. (2024) shows that sludge application at adapted rates significantly

increases soil organic matter content, improves structure and porosity, and stimulates microbial activity, with favorable effects on medium-term fertility (Paganini et al., 2024).

Field studies indicate positive crop responses (maize, wheat, barley, legumes) to sludge application, as a result of the supply of mineralizable N and P (FAO, 1995; Navarro et al., 2010; Singh et al., 2010; Zhai et al., 2018; Kildare County Council, 2023; Marin et al., 2023). In an experiment conducted in Belgium, De Brouwere et al. showed that wheat and barley yields increased up to threefold in sludge-fertilized treatments compared with the control, at rates that did not exceed the heavy metal thresholds in soil (De Brouwere et al., 2006). In Turkey, sludge application in a wheat-cabbage-tomato rotation system led to significant yield increases for all species, associated with improved nutritional status and some physical soil properties (Trinomics, 2020).

Experiments with composted sludge show that, in addition to nutrient supply, composting contributes to the partial reduction of pathogens and to the stabilization of organic matter, resulting in yield increases of over 100% compared with the control under certain conditions (Li et al., 2024). At the same time, an increase in microbial carbon and enzymatic activity is observed, indicating an intensification of nutrient cycling (Mara et al., 1989; Kildare County Council, 2023; Li et al., 2024).

Pollutants and emerging contaminants content. The main cause for concern regarding sludge use in agriculture is the accumulation of inorganic pollutants and persistent organic compounds. The heavy metal content of sludge varies depending on the city's industrial structure and the efficiency of industrial pretreatment. Studies from different countries show typical concentrations for Zn, Cu, Cr, Pb, Ni, Mo, As, Cd, Se, and Hg, in descending order of frequency and average levels: Zn > Cu > Cr > Pb > Ni > … > Hg (Council Directive 86/278/EEC, 1986; FAO, 1995; Yakamercan et al., 2021).

Directive 86/278/EEC sets limits for heavy metals in sludge and soil, but recent assessments suggest that these limits, established in the 1980s, may be insufficient for the long-term protection of European soils (Council Directive 86/278/EEC, 1986; Baltic Water Hub, 2022). Proposals to tighten the limits for Cd, Pb, Hg, and other metals are based on repeated sludge application scenarios and on the risk of bioaccumulation in the food chain (Council Directive 86/278/EEC, 1986; US EPA, 2019).

In recent decades, attention has also turned to emerging contaminants: pharmaceutical residues, endocrine disruptors, PFAS, microplastics and nanoplastics, brominated flame retardants, etc., identified in sludge at significant levels (Mara et al., 1989; Frišták et al., 2024; Balkrishna et al., 2025; Chenu, 2025). Recent investigations regarding sludge application on large agricultural areas have highlighted significant accumulations of microplastics in soil and the presence of PFAS and other persistent organic compounds in the sludge matrix, while regulations still focus almost exclusively on heavy metals (Council Directive 86/278/EEC, 1986; US EPA, 2019; Frišták et al., 2024; Chenu, 2025).

At high doses or in the absence of rigorous source selection, sludge application may lead to exceeding heavy metal limits in soil or to significant accumulation in edible plant organs, especially for Cd, Zn, and Cu (De Brouwere et al., 2006; Singh et al., 2010; Trinomics, 2020). In a study on mung bean, higher sludge doses increased yield, but also resulted in greater metal accumulation in seeds, limiting their use for human consumption (Singh et al., 2010). Thus, the fertilizing effect must always be balanced against the risk of chemical contamination of the soil and crop.

Presence of parasite eggs, viruses, and other pathogens. Sewage sludge is recognized as a major reservoir of pathogens: enteric bacteria (*Salmonella* spp., *Shigella* spp., pathogenic *E. coli*), helminth eggs (*Ascaris, Trichuris, Taenia*), protozoa (*Giardia, Entamoeba*), and enteric viruses (adenovirus, norovirus, rotavirus, hepatitis A), which may survive for long periods in sludge and even after soil application (FAO, 1995; Jiménez et al., 2010; Amoah, I.D. et al., 2018). A number of studies have reported high concentrations of viable helminth eggs in dewatered sludge from Africa and other regions, associated with high infection risks for farmers applying sludge and for consumers of vegetables cultivated on insufficiently protected amended soils (Navarro et al., 2010; Amoah et al., 2018; Sabbahi et al., 2022; Lucia et al., 2025).

WHO guidelines for the safe use of wastewater, excreta, and sludge propose strict criteria regarding the concentration of helminth eggs in sludge intended for agriculture, considering helminths the main public health risk category in developing countries (Mara et al., 1989; WHO, 2006; Navarro et al., 2010). In general, a maximum level of 0.25-1 helminth egg/g dry matter is recommended, which is difficult to achieve in the absence of advanced sanitization technologies (thermophilic composting, high-temperature anaerobic digestion, thermal drying, or sludge irradiation) (WHO, 2006; Navarro et al., 2010; Sabbahi et al., 2022).

Another group of biological contaminants is represented by enteric viruses. A recent systematic review shows that adenoviruses and noroviruses are the most frequently identified in urban sludge, and these viruses may persist in sludge even after certain treatment stages and may be transferred to soil, groundwater, or crops (Gholipour et al., 2022). The COVID-19 pandemic drew attention to the presence of SARS-CoV-2 genetic material in sludge, which led to additional recommendations regarding treatment and withholding periods, although the risk of transmission through properly disinfected sludge appears low (ANSES, 2020).

Influence of fertilization with urban sludge on agricultural production. Numerous field studies confirm that sewage sludge, when applied at moderate doses and according to good practices, can consistently increase agricultural yields (FAO, 1995; Navarro et al., 2010; Singh et al., 2010; Trinomics, 2020; Marin et al., 2023; Kildare County Council, 2023). Sludge application increased maize, wheat, and barley yields, correlated with higher N concentrations in reference leaves and improved phosphorus nutrition (Zhai et al., 2018; Kildare County Council, 2023). In vegetable rotation systems, sludge promoted high cabbage and tomato yields while improving soil physical quality (lower bulk density, greater structural stability) (Trinomics, 2020).

At the same time, studies underline the existence of an optimal threshold: at excessively high doses, yield gains tend to plateau or even decrease, while the risk of salinization, phytotoxicity, and heavy metal accumulation in plants increases (De Brouwere et al., 2006; Singh et al., 2010; Trinomics, 2020). For example, in the case of mung bean, the authors recommend doses below 9 kg m^{-2}, at which a good compromise is achieved between fertilizer valorization and limiting metal accumulation in seeds (Singh et al., 2010).

Interesting results also come from the use of composted or thermochemically treated sludge, which maintains fertilizing benefits while reducing pathogen load and increasing organic matter stability. Long-term experiments with composted sludge indicate yield increases of over 100% compared with the unfertilized control (Mara et al., 1989; IAEA, 2002; Li et al., 2024). The use of sludge transformed into biochar or other stabilized forms represents an emerging direction with the potential to better separate benefits from risks (Mara et al., 1989; Institute for European Environmental Policy, 2014; Frišták et al., 2024; Balkrishna et al., 2025).

Frequency of analyses and monitoring requirements. The European framework and national guidelines emphasize the role of continuous monitoring of sludge and of the soils on which it is applied. Directive 86/278/EEC provides that the frequency of analyses is determined according to the results of the initial analysis, changes in the nature of the treated wastewater, and other relevant factors, with the recommendation that a complete sludge analysis be carried out at least once every 6–12 months (Council Directive 86/278/EEC, 1986; Institute for European Environmental Policy, 2014; US EPA, 2019). National codes of practice go further, recommending sludge analyses for regulated parameters (heavy metals, basic parameters) at least every 6 months, and soil analyses every 2 years, with heavy metals determined every 5 years or more frequently in the case of high application rates (Scottish Executive, 2002; Kildare County Council, 2023).

International organizations (WHO, FAO) recommend that, in situations where sludge is applied to crops consumed fresh (leafy vegetables, root crops), microbiological monitoring should be more frequent (for example, annually or even before each application campaign) and combined with minimum withholding periods between application and harvest (FAO, 1995; Navarro et al., 2010). In addition, where analytical

infrastructure allows, the gradual introduction of indicators for emerging contaminants is encouraged, at least at screening level (for example, PFAS, selected pharmaceutical residues, microplastics) (Mara et al., 1989; Frišták et al., 2024; Chenu, 2025).

Based on these recommendations and the specialized literature, the following minimal monitoring framework can be proposed for the agricultural use of urban sludge:

Sludge: 2–4 analyses/year for basic parameters (moisture, organic matter, N, P, K), at least 1–2 analyses/year for regulated heavy metals; microbiological analyses (bacterial indicators, helminth eggs) at least annually or prior to application on crops consumed fresh.

Soil: agrochemical analyses (pH, organic C, N, P, K) every 2 years; heavy metals every 3–5 years or more frequently in the case of repeated applications; microbiological monitoring at critical points or in pilot projects.

Risk reduction methods and good practices. To maximize benefits and reduce the risks associated with urban sludge, the literature describes a wide range of technologies and good practices. From a technological point of view, stabilization and sanitization processes are recommended: mesophilic/thermophilic anaerobic digestion, thermophilic composting, thermal drying, and, in certain contexts, sludge irradiation (IAEA, 2002; Navarro et al., 2010; Institute for European Environmental Policy, 2014; Sabbahi et al., 2022; Balkrishna et al., 2025). Irradiation, for example, can ensure substantial pathogen reduction, allowing sludge use on sensitive crops, although costs and infrastructure requirements limit large-scale application (IAEA, 2002; Sabbahi et al., 2022).

From an agronomic point of view, the following are recommended:

-application of sludge outside the harvest season, to allow further pathogen reduction in soil through the action of time, UV radiation, and microbial competition;

-prohibition of direct application on crops consumed fresh (leafy vegetables, aromatic plants) and establishment of appropriate withholding periods (for example, a minimum of 30–36 days between application and harvest for certain vegetables) (Amoah et al., 2018; Lucia et al., 2025);

-adjustment of doses to the actual nutrient requirements and to the heavy metal and other pollutant content of sludge and soil, avoiding exceedance of regulated limits and long-term accumulation;

-alternation of organic matter sources (manure, plant compost) with sludge, in order to reduce the risk of one-directional accumulation of certain elements.

From the perspective of public policy management, recent evaluations of the Sewage Sludge Directive underline the need to update limits and gradually introduce new parameters (PFAS, microplastics, pharmaceutical residues), as well as to move from models based predominantly on heavy metals toward an integrated risk approach (Navarro et al., 2010; Trinomics, 2020; Frišták et al., 2024; Chenu, 2025). At the same time, the importance of source control is emphasized (preventing uncontrolled industrial discharges into sewer networks), as a more efficient solution than simply restricting sludge application in agriculture.

The balance between resource and risk. The analysis of bibliographic data shows that urban sludge has real potential to contribute to the circular economy of nutrients, especially through the supply of N and P and by increasing soil organic matter content (FAO, 1995; Navarro et al., 2010; Institute for European Environmental Policy, 2014; Kildare County Council, 2023; Li et al., 2024; Paganini et al., 2024). At the same time, its agricultural use involves a series of risks related to inorganic pollutants (heavy metals), emerging contaminants, and pathogens, whose management requires adequate treatment technologies, an updated regulatory framework, and a rigorous monitoring system (Council Directive 86/278/EEC, 1986; FAO, 1995; Jiménez et al., 2010; Navarro et al., 2010; US EPA, 2019; Yakamercan et al., 2021; Frišták et al., 2024).

If these conditions are met, sludge can be valorized as an organic amendment and source of nutrients, reducing dependence on mineral fertilizers and contributing to carbon sequestration in soil. In their absence, however, there is a risk of transforming sludge from a "resource" into a pollution vector and sanitary hazard, with possible long-term consequences

for agricultural soils, water, and public health (FAO, 1995; Reilly, 2001;Yakamercan et al., 2021; Frišták et al., 2024).

CONCLUSIONS

The use of urban sludge in agriculture represents an attractive technical option in the context of the transition toward a circular economy and rising costs of mineral fertilizers. The scientific literature shows that, under conditions of rigorous control of sludge and soil quality, it can lead to increased agricultural yields, improved soil fertility, and reduced pressure on phosphate and mineral nitrogen resources (FAO, 1995; Navarro et al., 2010; Institute for European Environmental Policy, 2014; Zhai et al., 2018; Kildare County Council, 2023; Paganini et al., 2024).

On the other hand, the presence of heavy metals, persistent and emerging organic contaminants, microplastics, PFAS, and a wide range of pathogens (bacteria, viruses, parasites) means that this practice is not without risks. Some studies and critical reports highlight cases of soil and agricultural product contamination, as well as dissatisfaction among rural communities exposed to the application of insufficiently treated sludge (FAO, 1995; Reilly, 2001; Yakamercan et al., 2021; Frišták et al., 2024).

The balance between benefits and risks depends on:

-the technological level of wastewater treatment plants (effective stabilization and sanitization);

-the strict application of the regulatory framework and, where needed, the updating of limits and the introduction of new parameters;

-the responsible design of application rates and crop rotations;

-the implementation of a coherent monitoring program for sludge, soil, and yields.

The proposed methodology - which combines detailed characterization of sludge and soil, a controlled field experiment, and multiannual monitoring of yields and contaminants provides a practical framework for evaluating risks and benefits under specific local conditions.

In the long term, the integration of advanced recovery technologies (composting, anaerobic digestion, biochar, phosphorus recovery) may help transform sludge from a potentially problematic waste into an agricultural resource managed responsibly.

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