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Assessment of Sewage Sludge Impact: Physicochemical Characterization, Heavy Metal Contamination and Sustainable Disposal Practices

Pooja Tamuk[a]* and Mumgeri Tamuk[b]

[a]Division of Soil Science and Agricultural Chemistry, ICAR-Indian Agricultural Research Institute, New Delhi, India

[b]Division of Agronomy, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India

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Introduction

Sewage sludge, also known as biosolids, represents one of the final products derived from wastewater treatment plants and is recognized as a highly promising waste material for efficient and environmentally friendly utilization. When appropriately employed, sewage sludge can have minimal to zero environmental impact. Globally, the secure disposal of sewage sludge remains a significant environmental concern, with varying perspectives on its utilization due to both positive and negative aspects associated with handling and treatment. The production of sewage sludge continues to rise annually, representing a renewable product that perpetually forms, particularly with the constant growth of the global population. This organic waste is rich in plant nutrients and organic matter, contributing to soil fertility and enhancing soil properties through its organic constituents. Utilizing sewage sludge as a fertilizer through land application proves to be a practical and cost-effective disposal alternative. The composition of sewage sludge includes organic compounds, macro and micronutrients, as well as trace elements, encompassing toxic metals, microorganisms, and microcontaminants. The organic components offer plant nutrients such as N, P, K, Ca, Mg, while contributing to soil conditioning and stabilization. Sewage sludge is characterized by elevated concentrations of nitrogen, phosphorus, calcium, and magnesium.

Characterization of sewage sludge

Sewage sludge is a treated and processed end product of wastewater treatment processes rich in plant nutrients and organic matter. It is applied as a fertilizer amendment to preserve soil productivity and enhance plant growth. Its composition varies depending on the wastewater content, encompassing organic and inorganic materials, plant nutrients, trace elements, organic chemicals, and some pathogens, and is influenced by the treatment processes employed. The uptake pattern of heavy metals in plants is challenging to generalize, as it depends on factors such as metal nature, sludge characteristics, soil properties, and crop type. The diverse properties of sludge arise from variations in pumping station types, surrounding area characteristics, and unauthorized sewage connections. Knowledge of soil parameters, including pH, cation exchange capacity (CEC), buffering capacity, organic matter, and clay content, is crucial at the application site. Soils with lower buffering capacity are more likely to adsorb metals and transfer contaminants to harvested crops (McBride, 2003). Sewage sludge significantly enhances crop production by providing essential plant nutrients such as N, P, K, Zn, Mn, Cu, Fe etc. and improves the soil physical and biological properties through organic matter content. The composition of sewage sludge, including total organic matter, total nitrogen, total phosphorus, and total organic carbon, ranged from 21.74% to 44.39%, 0.52% to 3.95%, 0.52% to 3.23%, and 3.63% to 12.55%, respectively (Azzouz et al., 2017). In India, an estimated 38,354 million liters of sewage sludge are generated daily (Kaur et al., 2012), with a nutrient potential exceeding 350,000 tonnes of N, 150,000 tonnes of P, and 200,000 tonnes of K annually (Juwarkar et al., 1991). Sewage sludge application in soil exhibits both direct and residual effects on yield and soil fertility over an extended period, particularly in a rice-wheat cropping system (Latare et al., 2014).

Effect of sewage sludge on soil properties and heavy metal accumulation

The application of sewage sludge enhances soil physical and biological properties owing to its organic matter content. Higher levels of sludge application led to an increase in soil pH and electrical conductivity (EC), attributed to elevated salt content. Conversely, residual sludge application results in a decrease in soil pH, linked to the production of organic acids during enhanced sludge decomposition under aerobic conditions in a rice-wheat cropping system (Latare et al., 2014). The mineralization of these organic acids generates protons through nitrification and the mineralization process of sulfur-rich compounds, contributing to soil pH reduction (Kirchmann et al., 1996).

Sewage sludge application, both directly and residually, elevates N, P, and K content in soils. Sludge modification enhances soil physical properties, including porosity, bulk density, stability, water-holding capacity, and permeability. Commonly used as fertilizer for maize, rice, and wheat cultivation, sewage biosolids contribute to improved soil fertility, structure, moisture retention, and permeability, thereby reducing production costs (Latare et al., 2014). However, prolonged use may result in soil heavy metal accumulation and the transfer of phytotoxic elements to the food chain, posing potential risks to human health. Scientific research on various sewage sludge amendment rates is essential to determine safe application levels that minimize health hazards associated with excessive use.

Setback in the use of sewage sludge

Sewage water comprises a diverse range of wastes, spanning from domestic to industrial, and may consequently harbor various toxic chemicals (Wolejko et al., 2014; Ikenaka et al., 2010). Often sewage is discharged directly into rivers, canals, and agricultural fields without treatment, potentially leading to the addition of toxic metals and their uncontrolled absorption in different parts of plants during growth, as well as accumulation in the soil, posing various health hazards (Rizzardini and Goi, 2014; Shamuyarira and Gumbo, 2014). The elevated levels of heavy metals in sewage sludge pose significant issues when applied to fields used for agriculture. The occurrence of problems depends on factors such as soil pH, soil organic matter content, cation exchange capacity, the movement of heavy metals in the soil profile, and changes in the forms of heavy metals. It is advisable to use sewage sludge in low doses to reduce the bioavailability of toxic heavy metals. The concentration of heavy metals in sewage sludge is influenced by factors such as sewage origin, sewage treatment processes, and sludge treatment processes. Therefore, continuous monitoring and proper treatment of sewage biosolids applied to agricultural land are essential to avoid environmental risks. Wang et al., (2008) studies have observed Cd concentrations above permissible levels in agricultural soil and *Z. japonica* tissue at specific sludge loading rates (30 t ha^{-1}). Municipal sewage sludge has been found to contain high levels of Pb (102.83 to 171.87 mg kg^{-1}) and Ag (6.13 to 21.93 mg kg^{-1}) (Shamuyarira and Gumbo, 2014). Domestic sewage sludge is a significant source of heavy metals, contributing a substantial percentage to loads of Cd, Zn, Cu, and Ni in domestic wastewater, and more than 20% of these elements in combined wastewater from domestic and industrial premises (Rizzardini and Goi, 2014). Sewage sludge amendment (SSA) rates above 4.5 kg m^{-2} pose a contamination risk, as concentrations of Ni and Cd in grains exceed Indian safe limits for human consumption, with Pb concentrations above safe limits at SSA rates exceeding 6 kg m^{-2} (Singh and Agrawal, 2010).

Solution to Setbacks in the use of sewage sludge

The thermal conversion of municipal sewage sludge affects the content of heavy metals and the phytotoxicity of biochars, leading to a decrease in the mobility of the analyzed trace elements compared to the original unprocessed sewage sludge. Bioavailable forms of trace elements, such as Cd, Cu, Pb, and Zn, were reduced from 1.97, 338, 60, and 1680 mg kg^{-1} to 0.3, 1.7, 1.65, and 1.85 mg kg^{-1}, respectively, as reported by Gondek and Hersztek (2017). Intensive composting of kitchen and garden waste resulted in the immobilization of Cr and Ni and decreased the total as concentration in household waste (Hanc et al., 2012). The impact of treated and untreated domestic wastewater on seed germination, seedling growth, and amylase and lipase activities varies. Untreated wastewater, being highly contaminated, had an inhibitory effect on seed germination and seedling growth in *Avena sativa* L., while treated wastewater showed no inhibitory effect on seedling growth parameters (Fendri et al., 2012). In the case of untreated effluent, there was a reduction in lipase and amylase activities (Fendri et al., 2012). The choice of a sampling method is crucial for reducing uncertainty in degradation rates of organic micro-pollutants during full-scale sewage sludge composting, helping to assess whether composting has the potential to remove organic pollutants in sewage sludge (Sadef et al., 2016).

Conclusion

In India, the increasing production of industrial and municipal wastes poses a significant disposal challenge due to rapid urbanization, industrialization, and a growing population. Municipalities worldwide are seeking safe and feasible disposal methods. Given the high costs of installing and maintaining sewage treatment plants, untreated sewage is often discharged directly into rivers, canals, and agricultural fields. Land application of sewage sludge is a preferred option due to its economic and environmental advantages over incineration and landfilling. This method allows for the recycling of organic matter, N, P, and other plant nutrients, along with wastewater used for supplemental irrigation. Besides being a cost-effective plant nutrient source, using sewage sludge in agriculture reduces reliance on chemical fertilizers. However, the potential health risks of heavy metal contamination in the soil necessitate regular monitoring to protect local inhabitants. It is strongly recommended to implement a monitoring program for heavy metals in common vegetable plants to minimize the risk of bioaccumulation in humans.

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