

Eco-Friendly Bioconversion of Sewage Sludge: Strategies for Nutrient Recovery and Pollutant Mitigation

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ABSTRACT

Sewage sludge (SS), a byproduct of wastewater treatment, is rich in organic matter and nutrients but also harbors heavy metals, pathogens, and organic pollutants. Sustainable disposal and valorization of SS is critical to mitigate environmental and health risks. This review explores the potential of biological composting techniques including thermophilic composting; vermicomposting, co-composting, and black soldier fly larvae (BSFL) treatment as effective, low-cost alternatives to conventional methods such as incineration, pyrolysis, and wet oxidation. These biological approaches significantly reduce pathogenic load and heavy metal mobility, while enhancing nutrient recovery and producing high-quality compost. Microbial degradation during composting facilitates the breakdown of persistent organic pollutants such as PAHs and PCBs. Vermicomposting, in particular, promotes metal bioaccumulation and nutrient enrichment, making the final product suitable for agricultural use. Despite their promise, biological methods face challenges such as slower degradation rates and variability in pollutant removal efficiency. Future research should focus on optimizing composting conditions, microbial consortia, and bulking agents to improve the degradation of persistent pollutants like PPCPs and micro-plastics. Overall, biological composting represents a key strategy in circular waste management, turning SS from an environmental liability into a valuable resource for sustainable agriculture.

Keywords- sewage sludge, composting, vermicomposting, BSFL, nutrient recovery, microbial degradation, circular economy.

I. INTRODUCTION

The rising volume of sewage sludge (SS) generated by urban wastewater treatment plants presents a significant environmental challenge. SS is the semi-solid residue left after the treatment of municipal wastewater and typically contains 97–98% water along with a complex matrix of organic matter, nutrients (e.g., nitrogen and phosphorus), heavy metals (HMs), pathogens, and persistent organic pollutants (Ahmad et al., 2025; Kacprzak et al., 2017; Zhang et al., 2015). Despite its fertilizing potential due to high levels of organic carbon and essential nutrients, the safe and sustainable management of SS remains critical.

Global production of SS exceeds 300 million tons annually in developing countries alone, with rapid increases anticipated due to urbanization and industrial growth (Zhang et al., 2015). For example, China's SS output has reached 60 million tons and is projected to exceed 90 million tons in the near future (Guo et al., 2023). Traditionally, SS has been managed through landfilling, incineration, or direct land application. However, these approaches carry serious ecological and public health risks, including soil contamination, groundwater pollution, and bioaccumulation of toxins in food chains (Delibacak et al., 2020; Harrison et al., 2006). Moreover, energy-intensive technologies such as pyrolysis, incineration, and wet oxidation, though effective at reducing volume and degrading organic pollutants, are often economically unfeasible in developing regions (Liew et al., 2022). Thus, alternative low-cost and eco-friendly treatment methods are increasingly being prioritized.

Biological composting has emerged as a promising and sustainable option for SS management. Techniques such as thermophilic composting, vermicomposting, co-composting with agro-waste, and bioconversion using black soldier fly larvae (BSFL) offer multiple benefits. These include significant reduction in pathogenic load, stabilization of pollutants, enhancement of nutrient bioavailability, and degradation of organic contaminants (Adnan et al., 2022). These processes not only reduce sludge volume but also align with circular economy principles, transforming waste into value-added products such as organic fertilizers and soil conditioners.

This review critically assesses the role of biological and biotechnological strategies for SS treatment, focusing on pathogen elimination, heavy metal stabilization, nutrient recovery, and safe reuse in agriculture. In addition, it highlights existing research gaps and outlines future directions for optimizing composting methods, ensuring that SS management contributes positively to environmental sustainability and regenerative soil health.

II. PHYSICOCHEMICAL CHARACTERISTICS OF SS

Municipal wastewater treatment plants generate SS with extremely high moisture content, making dewatering a critical first step to reduce volume and facilitate handling. Dewatered sludge offers improved stability, elevated nutrient density, and better thermal properties (Liew et al., 2022; Ashraf et al., 2022). However, high concentrations of heavy metals (HMs) complicate its further processing and safe disposal. On a dry weight basis, SS typically contains 30–50% lignin and ash, ~40% proteins, 10–25% lipids, and ~14% carbohydrates (Liew et al., 2021). Its complex composition and environmental persistence make SS a major concern, especially in the context of rapid urbanization and population growth.

Composted SS contributes to improving soil structure, increasing organic matter content, and enhancing microbial activity (Adamcová et al., 2016; Veeresh et al., 2003; Mehran et al., 2025b). **Table 1** summarizes the key chemical and physical characteristics of SS relevant to its reuse in agriculture. However, successful land application still requires careful monitoring of contaminants such as Zn, Cu, Pb, and Cd (Zhang et al., 2009; Yasir et al., 2022).

Table 1:

Parameter	Unit	Value	References
pH		6.7	Ratanatamskul <i>et al.</i> , 2014
EC	dS/m	0.9	Nuagh <i>et al.</i> , 2020
Moisture content	%	73	Fei-Baffoe <i>et al.</i> , 2016
Organic Matter	%	63.51	Nuagh <i>et al.</i> , 2020
Total solids	%	27	Fei-Baffoe <i>et al.</i> , 2016
Total Carbon	%	36.84	Dumontet <i>et al.</i> , 1999
Total Nitrogen	%	3.9	Fei-Baffoe <i>et al.</i> , 2016
Total Phosphorus P ₂ O ₅	%	2.9	Manca <i>et al.</i> , 2020
Volatile solids	%	34	Jain <i>et al.</i> , 2019
C/N		22	Nuagh <i>et al.</i> , 2020
Ca	%	1.4	Manca <i>et al.</i> , 2020
Na	%	0.7	Dumontet <i>et al.</i> , 1999
Mg	%	1	Fei-Baffoe <i>et al.</i> , 2016
S	%	2	Manca <i>et al.</i> , 2020
Zn	mg/g	1.6	Gong, 2013

Two primary SS types are produced: primary sludge, which consists of sedimented solids from physical separation, and secondary (activated) sludge, rich in microbial biomass. Raw SS often harbors pathogenic bacteria such as *Salmonella*, *Enterococcus*, and *E. coli*, posing biohazard risks (Al-Gheethi et al., 2018). Due to the presence of both organic and inorganic contaminants, land application of untreated SS can lead to ecological damage, especially via entry into the food chain (Yasir et al., 2022). Traditional disposal methods landfilling, incineration, agriculture, and forestry are now limited or banned under evolving environmental regulations. Consequently, this review emphasizes the evaluation of sustainable and biotechnological strategies for SS treatment (Figure 1).



Figure 1: Overview of novel biological and biotechnological treatment strategies for SS, including anaerobic digestion, composting, bioremediation, and pyrolysis, with potential resource recovery outcomes.

III. CONVENTIONAL SS DISPOSAL METHODS

Conventional methods such as land application, incineration, pyrolysis, wet oxidation, bioremediation, and alkaline stabilization remain essential for SS management due to their established infrastructure and effectiveness in volume reduction and pathogen control (Bertanza et al., 2017; Cieřlik et al., 2019; Lu et al., 2021). Despite their widespread application, concerns about environmental contamination, energy consumption, and long-term sustainability persist (Li et al., 2018; Yang et al., 2022). In recent years, significant efforts have focused on optimizing these technologies to support circular economy principles by integrating resource recovery and emission control (Awasthi et al., 2022; Bian et al., 2020).

3.1 Land application

Land application is widely regarded as a low-cost and ecologically beneficial option, especially in agricultural settings (Lu et al., 2021; Malekian et al., 2020). The nutrient-rich composition of treated SS

enhances soil organic carbon, nitrogen, phosphorus, and micronutrients, thereby improving soil fertility and reducing synthetic fertilizer dependence (Zhao et al., 2021; Song et al., 2022; Murtaza et al., 2022; MEHRAN et al., 2023). In addition to supplying nutrients, SS improves soil physical properties, including porosity, water retention, and aggregation, which enhance root development and microbial diversity (Liang et al., 2018; Gao et al., 2020).

However, repeated application of SS can lead to the accumulation of heavy metals like Cd, Pb, Zn, and Cu, which pose environmental and health risks if transferred into crops and groundwater (Malekian et al., 2020; Li et al., 2023). Studies have shown increased bioavailability of metals in soils receiving long-term SS inputs, especially without proper stabilization or regulation (Lu et al., 2021; Zhao et al., 2021). To ensure safe land application, regulatory standards mandate prior treatment and regular monitoring of sludge quality and application frequency (Song et al., 2022; Zhang et al., 2020).

3.2 Pyrolysis and gasification

Pyrolysis thermochemically decomposes SS in oxygen-limited environments to produce biochar, syngas, and bio-oil, offering a viable route for waste-to-energy conversion (Bian et al., 2020; Gai et al., 2023; Rahim et al., 2025). Biochar derived from SS has promising applications in soil amendment and carbon sequestration due to its high carbon content and porous structure (Liu et al., 2021; Yu et al., 2022; Ikram et al., 2024b). Syngas and bio-oil can be combusted to generate renewable energy, contributing to circular and low-emission sludge management systems (Wang et al., 2019; Gai et al., 2023).

Nonetheless, the retention of toxic heavy metals in biochar is a serious concern, necessitating post-treatment or restricted use to prevent soil contamination (Liu et al., 2021; Bian et al., 2020). Additionally, pyrolysis emissions such as volatile organic compounds (VOCs) and PAHs require advanced gas cleaning technologies (Gai et al., 2023; Yu et al., 2022). Gasification, a related process operating under partial oxidation, is better suited for energy recovery but has higher operational costs and technical requirements (Cieřlik et al., 2019; Gai et al., 2023).

3.3 Incineration

Incineration is a high-temperature treatment process widely used for its efficiency in reducing sludge volume and eliminating pathogens (Cieřlik et al., 2019; Yang et al., 2022). The energy recovered during incineration can be utilized for internal heating or electricity generation, enhancing the energy balance of wastewater treatment plants (Zhang et al., 2023; Gao et al., 2020; Naz et al., 2024). In regions like Japan, where land for disposal is scarce, over 55% of SS is incinerated (Yang et al., 2022).

However, incineration produces ash enriched with heavy metals and may emit air pollutants such as

dioxins, furans, and NO_x, necessitating strict regulatory compliance and emission control systems (Cieřlik et al., 2019; Zhang et al., 2023). Current research focuses on reusing incineration ash in construction materials like bricks and cement to reduce landfill disposal (Wang et al., 2019; Yang et al., 2022). Despite its effectiveness, incineration is cost-intensive and better suited for sludge with high calorific value and low moisture content (Zhang et al., 2023).

3.4 Wet oxidation (WO)

Wet oxidation is a hydrothermal process conducted at high temperatures (150–320°C) and pressures (20–150 bar), oxidizing organic matter in SS using air or pure oxygen (Bertanza et al., 2017; Menoni & Bertanza, 2019). This process reduces sludge volume and organic load without generating harmful gaseous emissions, distinguishing it from incineration (Johansson et al., 2018; Wang et al., 2020). Intermediate products like volatile acids can be further degraded or reused in biological nutrient removal systems (Houillon & Joliet, 2005).

Although WO is environmentally favorable, it requires high energy input and complex reactor designs, making it more feasible for centralized treatment plants (Menoni & Bertanza, 2019; Bertanza et al., 2017). Stable ammonia formed during the process cannot be removed without catalytic post-treatment, while acid production reduces pH and may necessitate neutralization (Wang et al., 2020). Still, WO shows potential as a pre-treatment step or for treating highly recalcitrant sludges (Johansson et al., 2018; Houillon & Joliet, 2005).

3.5 Bioleaching

Bioleaching uses microbial metabolism to solubilize heavy metals in sludge through acid generation and redox reactions, making it an environmentally sound alternative to chemical leaching (Li et al., 2018; Zhang et al., 2020). Organisms like *Acidithiobacillus ferrooxidans* oxidize Fe²⁺ and sulfur compounds to produce acid, which helps extract metals such as Zn, Cu, Ni, and Cr from the sludge matrix (Meulepas et al., 2015; Liu et al., 2019).

However, nutrient loss is a significant drawback; studies report up to 76% phosphorus and 38% nitrogen depletion during bioleaching (Wong et al., 2020; Li et al., 2018). pH optimization is crucial, as excessively low pH accelerates nutrient solubilization alongside metals (Zhang et al., 2020). Future approaches include integrating bioleaching with recovery systems to reclaim valuable nutrients while removing metals (Meulepas et al., 2015; Liu et al., 2019).

3.6 Alkaline stabilization

Alkaline stabilization, typically using quicklime (CaO), raises sludge pH above 12, thereby inactivating pathogens and reducing odor (Wang et al., 2019; Awasthi et al., 2022). The elevated pH alters metal solubility, converting toxic metals into less mobile forms and improving sludge safety for land application (Awasthi et al., 2022; Liang et al., 2018). Additionally,

the heat generated through lime hydration helps in further disinfection and volume reduction (Wang et al., 2019; Zhao et al., 2021).

Despite its advantages, overuse of lime may increase total solids and alter soil pH unfavorably upon land application (Liang et al., 2018; Lu et al., 2021). Excess lime requirements also elevate costs and may necessitate blending with other organic amendments to balance pH and nutrients (Awasthi et al., 2022). When combined with composting or vermistabilization, alkaline treatment can enhance both sludge quality and agronomic value (Wang et al., 2019; Zhao et al., 2021).

IV. NOVEL BIOLOGICAL COMPOSTING APPROACHES

Biological composting is a sustainable, low-cost method that uses microbial or organism-based activity to convert SS into stable, pathogen-free, and nutrient-rich organic fertilizers. This process has gained considerable attention as a promising alternative to conventional chemical and thermal treatments, which often suffer from drawbacks such as nitrogen loss, high operational costs, or harmful byproducts (Lam et al., 2019; Liew et al., 2022). Composting offers dual benefits: waste stabilization and nutrient recycling. It enhances the carbon-to-nitrogen (C:N) ratio, stabilizes heavy metals, and destroys pathogens such as *Escherichia coli*, *Salmonella*, and *Enterococcus* spp. (Zigmontiene & Sereviciene, 2023; Guo et al., 2020). Additionally, composting supports soil restoration and promotes sustainable agricultural practices by reducing environmental pollution and the overuse of chemical fertilizers (Ayilara et al., 2020; Lin et al., 2022).

Several biological composting types have been developed and optimized for sewage sludge management, including thermophilic composting, vermicomposting, co-composting, and black soldier fly larvae (BSFL) composting. These methods vary in microbial or biological mechanisms, environmental conditions, decomposition rates, and nutrient retention. For instance, thermophilic composting leverages high temperatures to kill pathogens, while vermicomposting uses earthworms for rapid organic degradation (Giagnoni et al., 2020; Liew et al., 2022). Co-composting balances nutrients and structure by mixing SS with other organic residues like food or garden waste, and BSFL composting produces protein-rich insect biomass and frass biofertilizer. All these approaches share key outcomes: reduction of heavy metals, nitrogen conservation, stabilization of organic matter, and improved fertilizer quality (Mawede, 2023).

4.1 Thermophilic composting

Thermophilic composting is a microbial-driven process that operates at elevated temperatures, typically between 50°C and 70°C, promoting rapid decomposition and effective pathogen removal (Sunar et al., 2014; Zhu et al., 2021). The addition of bulking agents like maize

straw enhances oxygen flow, porosity, and the C:N ratio, which are critical for microbial activity and compost quality (Zhu et al., 2021; Ikram et al., 2025). This process is characterized by high CO₂ emissions and minimal ammonia volatilization, reducing nitrogen loss and producing stable compost (Li et al., 2013). Thermophilic composting also lowers greenhouse gas emissions and provides a hygienically safe, nutrient-rich organic fertilizer (Lim et al., 2016). It has been shown to reduce contaminants, such as polycyclic aromatic hydrocarbons (PAHs), by over 60%, making it an ideal method for hazardous waste stabilization (Guo et al., 2020).

Moreover, this method is known for reducing greenhouse gas emissions, particularly methane and ammonia, as it maintains an aerobic environment (Lim et al., 2016; Li et al., 2013). Thermophilic composting is considered a hygienic and sustainable technique, especially suitable for municipal wastewater sludge, because it produces a safe, nutrient-rich end product. Its ability to sanitize the compost by eliminating pathogens such as *E. coli*, *Salmonella*, and *Enterococcus* species makes it suitable for agricultural land application (Ayilara et al., 2020). With proper management of temperature, moisture, and aeration, this approach ensures efficient stabilization of organic matter and significant recovery of nitrogen and carbon in compost.

4.2 Vermicomposting

Vermicomposting is a bio-oxidative stabilization technique that uses earthworms—most commonly *Eisenia fetida* in synergy with microorganisms to degrade sewage sludge into stable, nutrient-rich vermicast. Earthworms ingest and fragment the organic material, while gut-associated microbes further digest it, resulting in finely humified castings that are rich in nitrogen, phosphorus, calcium, magnesium, and beneficial enzymes (Sharma et al., 2021; Kumar et al., 2023). Vermicompost contains growth-promoting substances like amino acids, plant hormones, and vitamins, making it an ideal biofertilizer for sustainable agriculture. The vermin-stabilization process significantly reduces the bioavailability of heavy metals and suppresses pathogens in SS (Alidadi et al., 2016; Zigmontiene & Sereviciene, 2023).

Vermicomposting has been shown to be faster than traditional composting up to three times more efficient due to the earthworms' continuous burrowing and microbial interaction that improves oxygen diffusion and microbial biomass (Liew et al., 2022). This method is associated with lower nitrogen loss; for instance, 12.52 g/kg of nitrogen was retained in vermicomposting compared to 10.35 g/kg in conventional composting (Zigmontiene & Sereviciene, 2023). Additionally, its adaptability in different climates and co-substrate use (e.g., green waste, manure) makes it viable for wide-scale use. Countries like New Zealand have successfully implemented vermicomposting systems for SS treatment and soil rehabilitation.

4.3 Co-composting

Co-composting is the integrated composting of sewage sludge with other organic materials such as food waste, yard trimmings, straw, or sawdust to balance the C:N ratio, optimize compost structure, and improve microbial efficiency. SS is often deficient in carbon but rich in nitrogen, whereas the added bulking agents are carbon-rich, thus promoting microbial metabolism and preventing nitrogen losses through ammonia volatilization (Bien et al., 2011; Mawede, 2023). This technique results in better compost texture, increased aeration, and reduced compaction, ultimately enhancing microbial decomposition. Studies report that co-composting significantly reduces the concentration of heavy metals (Cd, Cr, Ni, Pb) and improves germination index, indicating reduced phytotoxicity (Grgas et al., 2023).

Furthermore, co-composting enhances microbial diversity and activity, which accelerates compost maturity and improves organic matter stabilization (Giagnoni et al., 2020; Balaganesh et al., 2020). The microbial consortia involved in co-composting degrade organic pollutants and fix nutrients such as nitrogen and phosphorus, making the compost more suitable for soil application. It has been demonstrated that composting SS with green and food waste not only minimizes environmental pollution but also leads to the production of bioavailable and pathogen-free organic fertilizers (Guo et al., 2020). Thus, co-composting is a valuable strategy in sustainable sludge management and nutrient recycling.

4.4 Black Soldier Fly Larvae (BSFL) composting

BSFL composting is a rapidly emerging bioconversion method that uses the larvae of *Hermetia illucens* (black soldier fly) to digest organic waste, including sewage sludge. These larvae have an extraordinary appetite and decompose organic matter efficiently, transforming it into protein- and lipid-rich biomass suitable for animal feed and a residual frass that serves as an excellent organic fertilizer (Zheng et al., 2022; Lalander et al., 2019). The process is fast, taking only 10–15 days and significantly reduces the waste volume. BSFL composting is odor-free and suppresses the breeding of houseflies (*Musca domestica*), making it particularly suitable for urban organic waste treatment

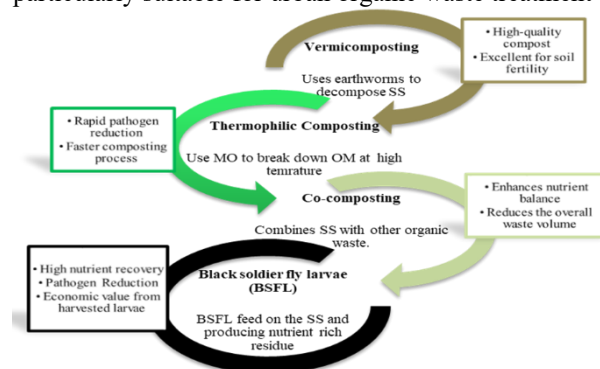


Figure 2 (Liew et al., 2022; Ikram et al., 2024a).

In addition to waste reduction, BSFL composting supports the circular bioeconomy by converting waste into high-value products like insect meal and organic soil amendments. This method requires low water and land use and emits fewer greenhouse gases compared to thermochemical processes (Zheng et al., 2022; Naz et al., 2025).

BSFL frass is rich in nitrogen and phosphorus, making it comparable to commercial fertilizers in terms of nutrient content (Lalander et al., 2019). Research also shows that co-digestion of SS with kitchen waste further enhances BSFL growth and bioconversion efficiency. As a scalable and climate-resilient solution, BSFL composting is gaining traction as a next-generation sustainable waste management technique. Sewage sludge composting via the biological method with different bulking agents including green manure, animal manure, rice straw microbes, etc is given in **Table 2**.

Table 2:

Biological approaches	Detail	Research duration	Outcome	References
Thermophilic Composting	Sewage sludge, MSW, grass, sawdust	30 days	Heavy metal (Cr, Cd, Ni, Pb, Hg) concentration significantly decreased with pathogen destruction	Bien et al., 2011
Vermicomposting	Use sewage sludge with peat and tree leaves for composting Californian worms and compost (cow manure, straw, and organic residue) used for vermicomposting	91 days	10.35 g/kg nitrogen stored during conventional composting while 12.52 g/kg preserved during vermicomposting	Zigmontiene and Sereviciene, 2023
Co-composting	Sewage sludge with green waste and food waste	3 month	89% germination obtained, better carbon and nitrogen recovery	Grgas et al., 2023

Conventional Composting	Sewage sludge with rice straw	September 2019 (S1) June 2020 (S2)	In season 2 Organic (2.32-2.50%), nitrogen with phosphorus (3.02-4.44%), potassium (0.531-0.953%), calcium (4.28-8.19%), and traces elements significantly enhanced after the composting process	Rodriguez-Carretero et al., 2023
Co-composting	Sewage sludge, forest green waste, compost mature	50 days	PAHs reduction 62.4-75.2%	Guo et al., 2020

V. IMPACT ON HEAVY METALS AND PATHOGENS IN SS VIA BIOLOGICAL TREATMENTS

Biological treatments such as composting, vermicomposting, bioleaching, and biosurfactant application are widely acknowledged for their dual efficacy in stabilizing heavy metals (HMs) and inactivating pathogens in SS. These techniques not only reduce the volume and toxicity of waste but also enhance the quality of the final product for agricultural use.

Composting processes significantly influence HM bioavailability by altering metal speciation and promoting the formation of stable humic complexes. Thermophilic composting reduces the total and volatile solids by 28–50%, concurrently generating high temperatures that facilitate pathogen destruction (Chi et al., 2010; Neklyudov et al., 2021; Bustamante et al., 2020). The presence of organic matter, nitrogen (N), phosphorus (P), potassium (K), and humic substances in the composted product further aids in HM immobilization, making the compost safe for land application (He et al., 2020; Singh & Kalamdhad, 2018). Metals like Cu and Zn tend to bind with humified organic components during composting, limiting their environmental mobility (He et al., 1995; Zheljazkov & Warman, 2004). However, the fine particulate matter in sludge, often enriched with HMs such as Pb, Cr, and Ni,

requires preprocessing or bioconversion to enhance removal efficiency (Sharma et al., 1997). Vermicomposting, involving epigeic earthworms like *Eisenia fetida*, further stabilizes metals by bioaccumulation in worm tissues. Studies show that vermicomposting can achieve removal efficiencies of up to 97.5% for Pb, 88.4% for Cu, and 81% for Cr within 105 days (Azizi et al., 2013; Domínguez-Crespo et al.,

2019). The earthworms also reduce organic matter and enhance nutrient content, while their gut microbiota contributes to the mineralization and detoxification processes (Suthar et al., 2014). Yet, the extended duration required and the potential for re-release of accumulated metals necessitate careful removal of the biomass after treatment (Azizi et al., 2013).

Table 3: Heavy metals stabilization in SS through biological treatments

Treatments	Time	Zn mg/kg	Ni mg/kg	Cd mg/kg	Cu mg/kg	Cr mg/kg	Pb mg/kg	Reference
Bioleaching	8 days	99	84	-	74	65	58	Wong et al., 2004
Biosurfactants	5 days	44	-	38	24	-	32	Yang et al., 2016
Vermicomposting	105 days	-	-	37	88	81	97	Azizi et al., 2013
Biosurfactants	24 hr	-	-	-	59	-	-	Maier et al., 2001
Bioleaching	12 days	88	-	-	79	-	50	Wen et al., 2013
Composting Wood waste, paper waste, food waste, green waste, and SS		768	21	3.10	312	46	224	Zheljazkov and Warman, 2004
Composting Fruit waste, green waste, vegetable waste, and SS		178	21	1	55	37	77	Sharma et al., 1997
Composting Food waste and SS		38	5	0.70	36	<1	24	He et al., 1995

Bioleaching, primarily driven by *Acidithiobacillus ferrooxidans* and *A. thiooxidans*, solubilizes metals via sulfur oxidation, lowering pH and promoting metal mobility (Fang & Zhou, 2007; Pathak et al., 2020). Application of these microbes in SS has shown high solubilization efficiencies, including 92.2% for Cu and 96.5% for Zn (Wen et al., 2013; Saleem et al., 2021). Similarly, biosurfactants like glycolipids, produced by *Burkholderia* sp., have been used for efficient metal recovery, with up to 59.5% Cu removed in 24 hours (Maier et al., 2001; Yang et al., 2016). These treatments also possess mild antimicrobial properties that can contribute to the reduction of microbial loads in SS.

Concurrently, biological treatments play a vital role in pathogen reduction. Thermophilic composting, in particular, achieves temperatures of 55–65°C, which are lethal to most pathogens, including bacteria, viruses, fungi, and helminths (Gurtler et al., 2018; Kabak et al., 2022). Composting for 30 days has been shown to eliminate 99% of *Salmonella*, 96% of fecal coliforms, and 81% of helminth eggs (Cabañas-Vargas et al., 2013). The inactivation mechanisms include heat generation, microbial competition, antimicrobial metabolites (e.g., phenols, lignin), and enzymatic degradation of

pathogenic cell walls (Pandey et al., 2016; Dutta et al., 2023; Boulahouat et al., 2023).

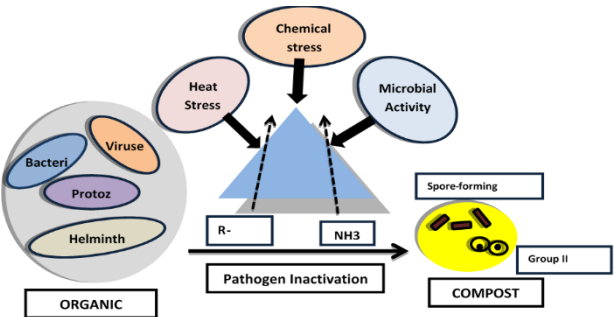


Figure 3: Demonstrate that composting is a stabilization technique that can kill pathogens by producing heat biologically and biodegrade organic components for forming final compost that can be added to the soil (Kabak et al., 2022). ermicomposting also contributes to pathogen suppression through the activity of digestive enzymes and the gut flora of earthworms, which break down pathogenic organisms (Suthar et al., 2014). While not as effective as thermophilic composting in temperature-based pathogen kill-off, vermicomposting provides a secondary barrier to pathogen persistence. Additionally, the bioleaching process, due to its highly

acidic environment and oxidative stress, may reduce pathogen viability, though this effect is less well-documented and warrants further study (Saleem et al., 2021; Ikram et al., 2024c).

Table 4: Impact of sewage sludge composting on population of pathogens

Microbial Pathogens	Average Population before composting	Average Population after composting	Percentage eliminated
Salmonella MPN/g sludge	2.4×10^8	3.0×10^3	99%
Faecal Coli MPN/g sludge	2.4×10^6	9.3×10^4	96%
Helminth Eggs / g sludge	146	27	81%

Despite the presence of resilient microorganisms such as *Escherichia coli*, *Salmonella*, *Cryptosporidium*, and various enteric viruses (Bibby & Peccia, 2013; Schlindwein et al., 2010; Medeiros & Daniel, 2018), comprehensive biological treatment strategies significantly mitigate these risks. For instance, a study by Huang et al. (2018) identified over 240 potentially pathogenic bacterial species in activated sludge, yet many are eliminated or suppressed through biological composting and microbial interactions. Antimicrobial compounds naturally occurring in compost, such as humic acids and lignin, further aid in suppressing fungi like *Trichophyton* sp. and phytopathogens such as *Mucor circinelloides* (Fr  c et al., 2017; Manual, 2023; Minhas et al., 2024).

Thus, integrating biological treatments not only stabilizes hazardous metals in SS but also effectively reduces the microbial and parasitic load, rendering the treated sludge safer for environmental use and agricultural application.

5.1 Fate of Organic Pollutants During Microbial-Driven Sewage Sludge Composting

Composting of SS is a biologically mediated process that relies on diverse microbial communities to degrade organic matter, promote humification, and transform persistent organic pollutants (L   et al., 2021; Wang et al., 2022; Abena et al., 2019). The high nutrient content and microbial diversity in SS facilitate enhanced biodegradation and mineralization of various recalcitrant organic compounds (Alves et al., 2019; L   et al., 2021). Optimized composting conditions can improve microbial abundance and enzymatic activity, thereby accelerating the breakdown of contaminants such as polycyclic aromatic hydrocarbons (PAHs) and phthalic acid esters (PAEs) (Gonz  lez-Abradelo et al., 2019; Guo et al., 2020).

Dominant microbial genera including *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Sphingomonas*, and *Thermus* have been repeatedly identified in SS

composting and are known for their capacity to degrade hydrophobic pollutants such as PAHs (L   et al., 2021; Al-Saeed et al., 2023). Thermophilic species like *Bacillus* and *Thermus* actively contribute to the thermogenic phase of composting, which reaches temperatures between 50–80  C, accelerating the degradation of organic substrates and inhibiting pathogenic microbes (Bhattacharya & Pletschke, 2014; Nemet et al., 2021).

The composting process progresses through four distinct phases. Initially, the mesophilic phase (10–42  C) persists for 24–72 hours and is marked by a rapid rise in microbial activity and temperature (Wainaina et al., 2020). This is followed by the thermophilic phase (45–70  C), which can last from days to weeks, during which thermophiles dominate and complex organic molecules are actively decomposed (Nemet et al., 2021). The subsequent cooling or maturation phase sees the return of mesophilic organisms and stabilization of organic matter over 1–2 months (Bhattacharya & Pletschke, 2014). Finally, the curing or maturation stage, occurring over 1–4 months at temperatures between 50–23  C, completes the transformation of compost into a stable humus-like product (Wainaina et al., 2020).

Composting substrates are commonly amended with bulking agents and additives to optimize porosity, aeration, moisture retention, and nutrient balance (Nemet et al., 2021). While bulking agents like sawdust or straw improve the physical structure, additives enhance microbial metabolism and reduce leachate, greenhouse gas emissions, and odors (Wainaina et al., 2020). Compost microorganisms require essential macronutrients (carbon, nitrogen, phosphorus) and micronutrients (trace metals), which must be bioavailable for effective degradation (Bhattacharya & Pletschke, 2014).

The bioavailability and degradability of organic substrates significantly affect composting dynamics. Easily degradable compounds like sugars decompose rapidly, whereas complex polymers such as lignin and cellulose are more recalcitrant (Wang et al., 2023; Zhou et al., 2022; Barthod et al., 2018). Microbial enzymatic capabilities vary; hence, the decomposition of a compound often depends on both substrate accessibility and the metabolic pathways present in the microbial consortia (Wang et al., 2015). An optimal carbon-to-nitrogen (C/N) ratio between 25 and 30 is critical for initiating rapid microbial degradation (Zhou et al., 2022; Barthod et al., 2018).

PAHs are among the most extensively studied organic contaminants in SS composting due to their persistence and carcinogenic potential. Various studies have demonstrated PAH removal efficiencies of over 85%, though values may range between 50% and 80% depending on composting conditions, bulking agent type, and microbial activity (Guo et al., 2020; Fu et al., 2013; Rorat et al., 2017). However, in some cases, total PAH concentrations increased during compost maturation due to mass loss and insufficient

mineralization of high molecular weight PAHs (Lazzari et al., 2000).

Microbial degradation remains the principal mechanism for PAH dissipation in compost, supported by co-metabolism with cellulose-degrading genera such as *Bacillus*, *Hydrogenobacter*, *Geobacillus*, and *Nonomuraea* (Liu et al., 2019; Beffa et al., 1996; Ma et al., 2020; Li et al., 2023). Removal efficiencies differ based on bulking agents: waste from markets (85.8%) and bark/peat (92.5%) have demonstrated higher PAH removal compared to rice straw (45.5%) due to improved microbial accessibility and enzymatic degradation (Rorat et al., 2017; Poluszynska et al., 2017).

In addition to PAHs, SS composting also targets phthalic acid esters (PAEs), which are commonly used plasticizers. Their removal efficiency varies from 32.2% to 91–99% depending on microbial community composition, oxygen availability, and bulking agents such as pig manure or sawdust (Fu et al., 2013; Cai et al., 2007). Intermittent aeration and nutrient-rich substrates promote rapid mineralization via pathways such as β -oxidation, de-esterification, and transesterification (Fu et al., 2013; Zhao et al., 2018; Ullah et al., 2023).

Persistent organic pollutants (POPs) such as polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) are more resistant to biodegradation. Composting may concentrate these compounds due to mass loss rather than degradation (Munoz et al., 2018; Diez, 2010). Limited microbial transformation of OCDD has been observed, highlighting the need for advanced composting strategies with enhanced aeration and microbial inoculation to

mitigate their persistence (Munoz et al., 2018; Yang et al., 2013).

PCBs, although banned, remain detectable in SS with declining concentrations attributed to long-term environmental attenuation and partial microbial breakdown during composting (Zennegg et al., 2013; Ramirez et al., 2008). Some studies reported average PCB concentrations below 1 $\mu\text{g/kg}$ post-composting, with higher efficiency when using substrates like pine wood chips (Gibson et al., 2008; Jiang et al., 2021).

High aeration regimes and the presence of key microbial genera like *Bacillus*, *Pseudomonas*, *Sphingomonas*, and *Alicyclophylus* have been linked with enhanced removal of other endocrine-disrupting chemicals such as nonylphenol (Zheng et al., 2018). Nevertheless, despite the growing evidence connecting microbial community dynamics to pollutant degradation, the exact relationship between microbial structure and functional biodegradation of complex pollutants remains partially understood (Yang et al., 2017; Guo et al., 2020). Fate and composting mechanism of sewage sludge with different raw material demonstrate in Fig.4

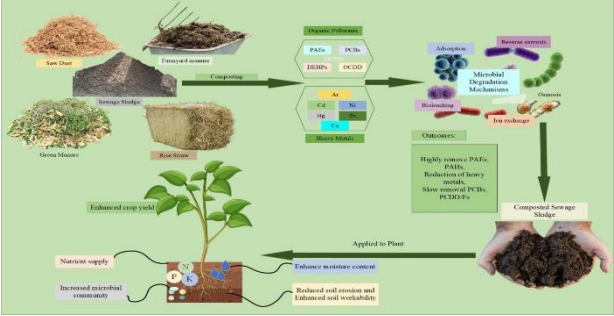


Figure 4: Fate of heavy metals and organic pollutants during composting

Table 4: Organic pollutant concentrations and their removal after SS composting with different bulking agents

Organic pollutant	Bulking agent (%)	Common Bacteria used for composting	Composting time (d)	Initial conc. (mg/kg g)	Final conc. (mg/kg)	Removal efficiency (%)	Ref.
ΣPAHs	Green forest waste	<i>Hydrogenobacter</i> sp., <i>Bacillus</i> sp.	50	5.6-9.8	1.8-2.9	62-75	Guo et al., 2020; Beffa et al., 1996; Ma et al., 2020
ΣPAHs	Food and industry wastes	<i>Hydrogenobacter</i> sp., <i>Bacillus</i> sp.	365	82 $\pm$ 25 ng/g	83 $\pm$ 33 ng/g	57 $\pm$ 31	Ozaki et al., 2017; Beffa et al., 1996; Ma et al., 2020
ΣPAHs	sawdust	<i>Geobacillus toebii</i> , <i>Bacillus</i> sp. <i>Firmicutes</i>	30	10.1-25.3	1.3-5.2	84.7	Poluszynska et al., 2017; Sung, 2002; Jiang et al., 2021; Ma et al., 2020
ΣPAHs	Green wastes (55%)	<i>Hydrogenobacter</i> spp. <i>Bacillus</i> sp.	35	2.9	1.16	61.6	Rorat et al., 2017; Beffa et al., 1996; Ma et al., 2020
ΣPAEs	Pig manure	<i>Nonomuraea</i> sp., <i>Virgibacillus</i> sp., <i>Rummeliibacillus pycnus</i> , <i>Bacillus</i>	60	25.5	5.6-6.5	74.7-78	Fu et al., 2013; Qiao et al., 2019; Li et al., 2020; Ma et al., 2020

		sp.					
Σ PAEs	Rice straw	<i>Bacillus thermophilus</i> , <i>Firmicutes</i> , <i>Chloroflexi</i> , <i>Proteobacteria</i> , <i>Bacillus</i> sp.	60	25.5	13.9-17.3	32.2-45.5	Fu <i>et al.</i> , 2013; Yang <i>et al.</i> , 2013; Papale <i>et al.</i> , 2021; Jiang <i>et al.</i> , 2021; Ma <i>et al.</i> , 2020
DEHP	Pig manure	<i>Nonomuraea</i> sp., <i>Virgibacillus</i> sp., <i>Rummeliibacillus pycnus</i> , <i>Bacillus</i> sp.	60	22.5	2.8-5.2	76.9-87.4	Fu <i>et al.</i> , 2013; Qiao <i>et al.</i> , 2019; Li <i>et al.</i> , 2020; Ma <i>et al.</i> , 2020
DEHP	Rice straw	<i>Bacillus thermophilus</i> , <i>Firmicutes</i> , <i>Chloroflexi</i> , <i>Proteobacteria</i> , <i>Bacillus</i> sp.	60	22.5	12.7-16.1	28.4-43.6	Fu <i>et al.</i> , 2013; Yang <i>et al.</i> , 2013; Jiang <i>et al.</i> , 2021; Papale <i>et al.</i> , 2021; Ma <i>et al.</i> , 2020
Σ PAHs	Waste from market	<i>Firmicutes</i> , <i>Proteobacteria</i> , <i>Bacillus</i> sp.	35	3.96	0.6	85.8	Rorat <i>et al.</i> , 2017; Jiang <i>et al.</i> , 2021; Ma <i>et al.</i> , 2020
Σ PAHs	Bark and peat	<i>Bacillus stearothermophilus</i> , <i>Thermus thermophilus</i> HB8, <i>Bacillus</i> sp.	124	8	0.6	92.5	Kapanen <i>et al.</i> , 2013; Beffa <i>et al.</i> , 1996; Abdullallah <i>et al.</i> , 2023
DEHP	Green waste	<i>Hydrogenobacter</i> sp., <i>Bacillus</i> sp.	28	6.4 $\pm$ 1	8.1 $\pm$ 0.2		Patureau <i>et al.</i> , 2012; Beffa <i>et al.</i> , 1996; Ma <i>et al.</i> , 2020
DEHP	manure	<i>Nonomuraea</i> sp., <i>Virgibacillus</i> sp., <i>Bacillus</i> sp.	62	55.1	1.64	97	Pakou <i>et al.</i> , 2009; Qiao <i>et al.</i> , 2019; Ma <i>et al.</i> , 2020
DEHP	sawdust	<i>Geobacillus toebii</i> , <i>Bacillus</i> sp., <i>Firmicutes</i>	18	200-300	<100	85-88	Cheng <i>et al.</i> , 2008; Sung, 2002; Du <i>et al.</i> , 2019; Jiang <i>et al.</i> , 2021; Ma <i>et al.</i> , 2020
PCDD/Fs	Sawdust and straw	<i>Bacillus thermophilus</i> , <i>Firmicutes</i> , <i>Bacillus</i> sp.	40	1-13.2 (ng/g)	1.38-39.7 (ng/g)		Munoz <i>et al.</i> , 2018; Yang <i>et al.</i> , 2013; Jiang <i>et al.</i> , 2021; Ma <i>et al.</i> , 2020
PCDD/Fs	Green waste	<i>Hydrogenobacter</i> sp., <i>Bacillus</i> sp.	28	6-11.1 (ng/kg)	12.2-5 (ng/kg)		Patureau <i>et al.</i> , 2012; Beffa <i>et al.</i> , 1996; Ma <i>et al.</i> , 2020
OCDD	Sawdust and straw	<i>Bacillus thermophilus</i> , <i>Firmicutes</i> , <i>Bacillus</i> sp.	40	0.5-11.2 (ng/g)	1.0-34.9 (ng/kg)		Munoz <i>et al.</i> , 2018; Yang <i>et al.</i> , 2013; Jiang <i>et al.</i> , 2021; Ma <i>et al.</i> , 2020
PCBs	Pine wood chips	<i>Bacillus pallidus</i> , <i>B.stearothermophilus</i> , <i>B.thermodenitrificans</i> , <i>Firmicutes</i>	75	34 μ g/kg	15 μ g/kg	44	Ramirez <i>et al.</i> , 2008; Blanc <i>et al.</i> , 1997; Jiang <i>et al.</i> , 2021
PCBs	Straws	<i>Bacillus thermophilus</i> ,	143	137 μ g/kg	124 μ g/kg	11.7	Gibson <i>et al.</i> , 2008; Yang <i>et al.</i> , 2013; Ma <i>et al.</i>

		<i>Firmicutes, Bacillus sp.</i>					<i>al.</i> , 2020
PCBs	Municipal waste	<i>Bacillus pallidus</i> , <i>B.stearothermophilus</i> , <i>B.thermodenitrificans</i>	182	0.4 (µg/g)	<1.0 µg/kg	16-Jul	Siebielska and Sidelko, 2015; Blanc <i>et al.</i> , 1997

Table 4: summarizes the concentrations and removal efficiencies of selected organic pollutants—including PAHs, PAEs, DEHP, PCDD/Fs, and PCBs—after SS composting with different bulking agents and microbial consortia. The removal rates for total PAHs (ΣPAHs) varied widely depending on the bulking agent and composting duration.

5.2 SS compost as a fertilizer: Benefits & Risks

SS compost, produced through the microbial stabilization of organic residues from wastewater treatment, has emerged as a valuable organic fertilizer for agricultural systems. Rich in essential plant nutrients (Fatima et al., 2024) such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), and micronutrients, SS compost contributes significantly to crop productivity and soil fertility (Kratz et al., 2020; Sayara et al., 2020). It enhances soil organic matter, improves soil structure, water-holding capacity, and boosts microbial activity, making it a promising alternative to synthetic fertilizers (Kominko et al., 2017; Wang et al., 2019).

Primary and secondary SS formed during sedimentation and microbial degradation respectively can be composted and applied to agricultural soils to support the growth of cereals, vegetables, and fruit trees (Roychoudhury & Das, 2022). Compared to traditional chemical fertilizers, composted SS offers a slow-release mechanism of nutrients, reducing leaching and promoting long-term nutrient availability (Elsalam et al., 2021). The application of SS compost has been shown to improve biomass and yield in crops like maize (*Zea mays*), hemp (*Cannabis sativa*), wheat (*Triticum aestivum*), and alfalfa (*Medicago sativa*), among others (Leontopoulos & Arabatzis, 2021; Seleiman et al., 2020).

In addition to nutrient enrichment, SS compost introduces proteinaceous compounds, polysaccharides, and aliphatic and aromatic acids into the soil, which increase the soil organic carbon (SOC) and dissolved organic matter (DOM), thereby influencing the mobility and bioavailability of trace elements (Azeem et al., 2023; Abdul Khaliq et al., 2017; Chen et al., 2024; Mehran et al., 2025a). Its use has also been linked to soil remediation and the prevention of land degradation, particularly when applied in degraded or nutrient-depleted soils (Alvarenga et al., 2015). Commercial products such as “Kala compost” are increasingly adopted due to their effective role in improving soil health and supporting sustainable crop yields (Abdul Khaliq et al., 2017).

Despite the agronomic benefits, SS compost poses certain environmental and health risks if not properly treated. One primary concern is the potential accumulation of heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu) in the soil, which may be taken up by plants and transferred through the food chain (Gupta & Sinha, 2020; Usman et al., 2012; Haider et al., 2024; Ashraf et al., 2025). Composted sludge can also contain trace levels of organic contaminants, including pharmaceuticals, personal care products, and persistent organic pollutants (POPs), which may persist in the soil and affect ecological health (Chen et al., 2021; Lü et al., 2021).

Furthermore, incomplete composting or inadequate sanitization processes can result in the survival or regrowth of pathogens, posing potential biological hazards (Sidhu & Toze, 2019). Therefore, regulatory compliance, pathogen monitoring, and heavy metal thresholds are critical when applying SS compost to agricultural fields. Although composting reduces many of these risks, the use of SS-based fertilizers must be managed cautiously to prevent long-term soil contamination and ensure food safety (Mudhoo & Mohee, 2010; Cardenas-Talero et al., 2022).

VI. FUTURE PERSPECTIVES & RECOMMENDATIONS

The sustainable management of SS remains a pressing environmental and agricultural challenge. While conventional methods such as incineration, pyrolysis, wet oxidation, and land application continue to play significant roles, biological approaches particularly composting, vermicomposting, and bioleaching have demonstrated substantial potential for eco-friendly and resource-efficient sludge treatment. However, these methods face limitations including slower degradation rates, incomplete removal of persistent organic pollutants (e.g., PAHs, PCBs, PCDD/Fs, PPCPs), and challenges in heavy metal stabilization and pathogen kill-off under inconsistent operational conditions.

Future research should focus on optimizing biological treatment technologies to enhance their efficiency, scalability, and contaminant removal capacity. Integrating microbial consortia, thermophilic and vermicomposting stages, and functional amendments (such as zeolite, biochar, and perlite) can significantly improve compost quality, reduce heavy metal mobility, and enhance organic pollutant

degradation. Moreover, tailoring treatment protocols to site-specific sludge characteristics and environmental conditions will be critical. Emerging concerns such as micro-plastics and antibiotic resistance genes (ARGs) in sludge also require urgent attention, particularly in the context of land application. Development of low-cost, rapid assessment tools for compost maturity, stability, and residual toxicity is essential to ensure environmental safety and compliance with regulatory standards.

To promote large-scale adoption, policies must encourage sustainable SS reuse in agriculture through incentives, training, and public awareness. Establishing strict regulatory frameworks for permissible contaminant levels in compost, monitoring compost application rates, and long-term impact assessment on soil and crop systems are equally important. Collaboration across disciplines microbiology, soil science, waste engineering, and public health—is vital to develop holistic solutions that balance waste reduction, resource recovery, and environmental protection.

VII. CONCLUSION

SS, once viewed solely as a waste byproduct, is increasingly recognized as a valuable resource when treated through sustainable and biologically driven approaches. Among these, composting and related biological treatments offer a cost-effective, environmentally sound, and agriculturally beneficial strategy to stabilize sludge, reduce pathogens, and immobilize or degrade toxic pollutants. These treatments support soil fertility, promote beneficial microbial activity, and reduce reliance on chemical fertilizers, contributing to circular economy models and sustainable agriculture. Despite these advantages, several limitations persist including slow processing times, incomplete degradation of certain organic contaminants, and risks of heavy metal accumulation in soils. Therefore, advancing biological treatment methods through technological innovation, process integration, and policy support is essential. Continued research should aim to improve treatment kinetics, expand pollutant degradation capabilities, and ensure safe reuse in agriculture without compromising soil or human health. Ultimately, a multidisciplinary, systems-based approach will be required to fully realize the potential of sewage sludge as a sustainable resource for environmental restoration, agricultural productivity, and climate resilience.

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