REVIEW OF SEWAGE SLUDGE COMPOSTING TECHNOLOGIES

SZENNYVÍZISZAP KOMPOSZTÁLÁSI TECHNOLÓGIÁK LEHETŐSÉGEINEK ÁTTEKINTÉSE

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Abstract

The recycling of wastewater residues plays a crucial role in the circular economy, a key focus of the EU's 2030 Green Deal. A byproduct of wastewater treatment, sewage sludge, can serve as a sustainable resource for plant nutrition through the application of various composting technologies. Composting helps mitigate pollution by converting organic waste, such as sewage sludge, into compost with the aid of microorganisms. The resulting compost enhances soil quality and health. Several composting approaches—windrow composting, aerated static windrow composting, vermicomposting, and in-vessel composting—each have unique advantages and disadvantages in terms of environmental impact, efficiency, and sustainability. This paper provides an overview of composting methodologies and explores advanced composting technologies for optimizing sewage sludge composting. Aerobic composting is the most widely used method due to its efficiency and ability to eliminate pathogens; however, concerns remain regarding greenhouse gas emissions and nutrient losses. To address these challenges, co-composting, vermicomposting, and two-phase composting have been developed to enhance compost quality and shorten processing times. Despite these advancements, land restrictions, complex technologies, and high costs remain significant limitations. This study emphasizes the importance of microbial dynamics, pathogen elimination, and compost maturation during key composting stages, from the mesophilic to the thermophilic phase, in order to produce stable, nutrient-rich compost. While composting technologies align with sustainability goals, further research is needed to improve efficiency, reduce emissions, and assess potential economic impacts. This review highlights the critical role of composting in achieving waste management and environmental sustainability objectives.
Keywords *composting, waste management, recycling waste*
JEL code: *Q01*

Összefoglalás

A szennyvíziszapok újrahasznosítása kulcsfontosságú szerepet játszik a körforgásos gazdaságban, az EU 2030-as Zöld Megállapodásának egyik fő fókuszterülete. A szennyvíztisztítás mellékterméke, a szennyvíziszap, fenntartható növényi tápanyagforrásként szolgálhat különféle komposztálási technológiák alkalmazásával. A komposztálás segít csökkenteni a szennyezést azáltal, hogy a szerves hulladékot, például a szennyvíziszapot, mikroorganizmusok segítségével komposzttá alakítja. A komposzt javítja a talaj minőségét és egészségét. A számos komposztálási megközelítés, mint a prizmakomposztálás, a levegőztetett

prizmakomposztálás, a gilisztahumusz készítés és a tartályban történő komposztálás mindegyikének egyedi előnyei és hátrányai vannak a környezeti hatás, a hatékonyság és a fenntarthatóság szempontjából. Ez a tanulmány áttekintést nyújt a komposztálási módszerekről, és bemutatja a szennyvíziszap komposztálásának optimalizálására szolgáló fejlett komposztálási technológiákat. Az aerob komposztálás a legszélesebb körben alkalmazott módszer a hatékonysága és a kórokozók eltávolítására való képessége miatt; azonban továbbra is aggályok merülnek fel az üvegházhatású gázok kibocsátása és a tápanyagveszteség miatt. E kihívások kezelése érdekében kifejlesztették az együttes komposztálást, a gilisztahumusz készítést és a kétfázisú komposztálást a komposzt minőségének javítása és a feldolgozási idő lerövidítése érdekében. Ezen fejlesztések ellenére a területi korlátozások, a komplex technológiák és a magas költségek továbbra is jelentős korlátokat jelentenek. Ez a tanulmány hangsúlyozza a mikrobiális dinamika, a kórokozók eltávolításának és a komposzt érésének fontosságát a komposztálás kulcsfontosságú szakaszaiban, a mezofil fázistól a termofil fázisig, a stabil, tápanyagban gazdag komposzt előállítása érdekében. Bár a komposztálási technológiák összhangban vannak a fenntarthatósági célokkal, további kutatásokra van szükség a hatékonyság javítása, a kibocsátások csökkentése és a lehetséges gazdasági hatások felmérése érdekében. Ez az összefoglaló felhívja a figyelmet a komposztálásnak a hulladékgazdálkodási és környezeti fenntarthatósági célok elérésében való fontos szerepére.
Kulcsszavak: *komposztálás, hulladékkezelés, hulladék újrahasznosítás*

Introduction

The European Union Green Deal 2030 represents a key component of the EU's strategy to achieve a climate-neutral economy by reducing greenhouse gas emissions by at least 55% through the implementation of circular economy principles. Based on the concept of the 3Rs (reduce, reuse, and recycle), this approach aims to minimize waste generation and promote material recovery within production and consumption cycles by recycling wastewater residues, such as sewage sludge, into useful products (Dragomir & Dumitru, 2024).

Sewage sludge (SS) is a byproduct generated during wastewater treatment, resulting from the separation of solids from liquids at wastewater treatment plants (WWTPs). Its management and disposal remain among the most critical economic and environmental challenges faced by treatment facilities, with sludge treatment and disposal accounting for up to 50% of WWTP operating costs (Spinosa et al., 2011). Moreover, SS contains a complex mixture of organic and inorganic matter, heavy metals, and pathogenic microorganisms**,** making its management both technically demanding and environmentally sensitive. The disposal of SS therefore demands a complex process that requires technical expertise due to its heterogeneous composition**,** which can pose significant environmental and public health risks if not properly treated and handled.

To address these challenges, the European Union (EU) has established a comprehensive legislative framework for the managing sewage sludge. The Sewage Sludge Directive (86/278/EEC) (Council of the European Communities, 1986) regulates the use of treated sludge in agriculture by setting limit values for heavy metals and other contaminants to prevent the contamination of soil and crops. In parallel, the Landfill Directive (1999/31/EC) (European Parliament & Council, 1999) restricts the disposal of organic waste, including sewage sludge, in landfills to minimize the contamination of surface water, groundwater, soil, and air, as well as greenhouse gas emissions, particularly methane. These directives are further reinforced by the Waste Framework Directive (2008/98/EC) (European Parliament & Council, 2008), which establishes the waste hierarchy, prioritizing prevention, reuse, and recycling over disposal and promoting sludge valorisation in accordance with circular economy principles.

The EU Taxonomy Regulation (2020/852) (European Parliament & Council, 2020) and the Circular Economy Action Plan (European Commission, 2020) further strengthen these goals by recognizing nutrient recovery, particularly phosphorus, from sewage sludge as an important sustainable process. These policies are consistent with the EU Soil Strategy for 2030 (European Commission, 2021b) and the Zero Pollution Action Plan (European Commission, 2021), both of which emphasize reducing pollution from waste streams and enhancing soil health using safe, recycled organic amendments. By prioritizing resource recovery over disposal, these legislative instruments support sustainable sewage sludge management (SSM) and advance the transition toward a closed-loop circular economy (Turlej & Banaś, 2018).

Composting is one of the various sludge valorisation techniques offering a sustainable and cost-effective biological process that converts organic waste materials including sewage sludge into stable, humus-like products. Composting involves the aerobic degradation of organic matter by microorganisms such as bacteria, fungi, and actinomycetes under controlled temperature and moisture conditions (Senesi et al., 2007). This process not only reduces sludge volume but also sanitizes the material by eliminating pathogens and toxic compounds, thereby producing an organic amendment suitable for soil application (Walling & Vaneeckhaute, 2020).

Several factors influence the effectiveness of composting, including the carbon-to-nitrogen (C: N) ratio, aeration rate, moisture content, and the addition of bulking agents such as straw, sawdust, or recycled compost. These agents improve the structural porosity of the compost pile, enhance oxygen transfer, and optimize microbial activity (Muscarella et al., 2023). The composting process typically consists of preprocessing (mixing of bulking agents), active decomposition, curing and stabilization, and post-processing stages such as screening and grinding to produce a homogeneous product. The resulting compost can be used for soil conditioning, land reclamation, and erosion control, provided that its contaminant concentrations comply with EU regulatory limits (Council of the European Communities, 1986).

The final compost products can be utilized for soil conditioning and the revegetation of eroded or disturbed land in compliance with legal standards, as well as for other land applications, provided that the heavy metal and organic pollutant concentrations remain below the threshold levels established under the EU Fertilising Products Regulation (2019/1009) (European Parliament & Council, 2019). However, despite its environmental and economic benefits, composting can be land- and time-intensive, depending on the technology and operational scale employed. Therefore, optimizing process efficiency and ensuring microbial stability are essential for producing high-quality, mature compost suitable for safe environmental application (Kosobucki et al., 2000; Meena et al., 2021).

Composting phases

The sludge undergoes three distinct phases during composting, which have been determined by variations in temperature and the succession of microorganisms (Haug, 2018) as shown in Fig.1. The first phase is mesophilic, in which a continuous temperature rise that begins to kill some microorganisms occurs, along with rapid consumption of readily assimilated substrates like monosaccharides and amino acids. This leads to an exponential growth of mesophilic and some thermophilic microorganisms (Muscarella et al., 2023).

During the primary composting (PC) stage, temperatures rise to approximately 55–65°C within 24–72 hours after the pile is formed and remain at this level for several weeks, marking the "thermophilic" phase. For successful composting during this phase, oxygen must be replenished through passive or forced aeration or by turning the compost pile (Bhave & Kulkarni, 2019). A well-ventilated compost pile maintains an oxygen content of at least 5%, ideally closer to 10%, during active composting. Thermophilic microorganisms such as bacteria, fungi, and actinomycetes dominate this phase, although some mesophilic organisms may also survive (Gajalakshmi & Abbasi, 2008). When temperatures approach 70°C, the compost undergoes sanitization, eliminating pathogens harmful to humans and plants, deactivating weed seeds, and breaking down organic compounds toxic to plants (Gajalakshmi & Abbasi, 2008). Common pathogens eradicated during this phase include *Escherichia coli, Staphylococcus aureus, Bacillus subtilis,* and *Clostridium botulinum* (Jones & Martin, 2003). As microbial activity intensifies, oxygen consumption increases. Without sufficient oxygen replenishment, the pile can shift to anaerobic decomposition, slowing the composting process and generating unpleasant odours. Eventually, as microorganisms deplete nutrient resources, the process decelerates, and temperatures decline. At this stage, mesophilic microorganisms recolonize the pile, marking the transition to the maturation phase, during which the temperature gradually decreases to around 38°C (Gajalakshmi & Abbasi, 2008).

During the secondary composting (SC) stage, temperatures range from 30 to 50°C, with mesophilic microorganisms becoming more prevalent. Nitrogen levels decrease slightly, and greenhouse gas emissions rise but remain minimal. The PC stage experiences multiple thermophilic phases with temperatures above 55°C, and an additional 2–4 thermophilic phases occur during the SC stage. The introduction of bamboo vinegar in the SC stage boosts thermophilic temperatures to 55–70°C, helping maintain nitrogen levels and enhancing the breakdown of organic materials through microbial activity. This process further sanitizes the compost, improving its safety as a bio-fertilizer. The quality and effectiveness of the final compost depend on factors such as bulking agents, proper aeration, and particle size reduction (Zhang & Sun, 2014). The compost can be placed without turning when the rate of oxygen consumption gradually slows down. Organic elements continue to break down and transform into biologically stable humic compounds during the maturation process, which results in the mature or finished compost. One important yet frequently disregarded stage of composting is maturation. If the pile has had too little air or too much or too little moisture, a lengthy maturation period is required (Cooperband, 2000).

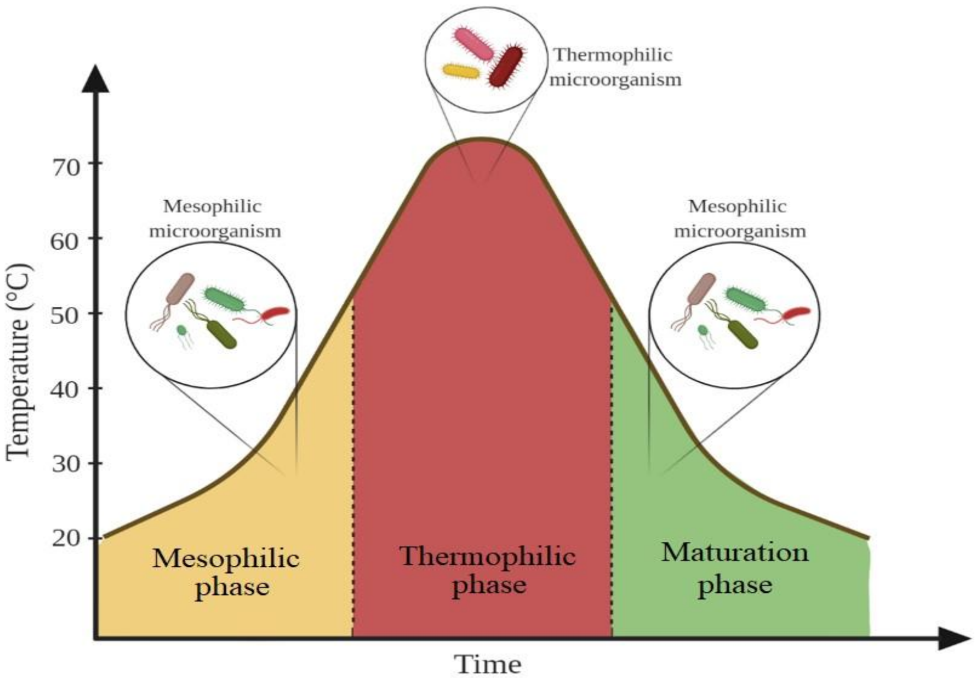

Figure 1: Composting Phases.
Source: Muscarella et al. (2023)

Aerobic Composting

Aerobic composting occurs in the presence of oxygen, where aerobic microorganisms decompose organic materials to produce humus, a stable organic product, along with carbon dioxide (CO_2), ammonia, water, and heat, with minimal phytotoxicity. The heat generated during the process accelerates the degradation of complex carbohydrates, proteins, and lipids, thereby shortening the processing time, while the high temperatures destroy most pathogens and weed seeds (Flynn & Hagevoort, 2013). Although aerobic composting can lead to greater nutrient losses compared to anaerobic composting, it remains more effective and advantageous for agricultural productivity. This method is the most widely used approach for large-scale sewage sludge composting globally.

Various aerobic composting methods influence key operational parameters such as aeration, greenhouse gas (GHG) emissions, odour control, temperature, and maturation time. The main GHGs emitted during aerobic composting of sewage sludge include CO_2, CH_4, and N_2O (M. Wang et al., 2017). Among these, N_2O is the dominant direct GHG emitted from well-aerated compost piles, accounting for an average of 62% of total emissions, primarily originating from manure or farmyard waste. Manure-based composting tends to produce higher N_2O emissions, while farmyard waste results in lower emissions. Since aerobic composting relies on adequate aeration to suppress CH_4 emissions, effective management must focus on optimizing feedstock composition and aeration to minimize N_2O production (Nordahl et al., 2023). According to global climate models, the continued rise in GHG emissions is projected to increase average global temperatures by approximately 1.5°C in the near future. Despite significant mitigation efforts, current measures remain insufficient to limit warming below 2°C or 1.5°C across all regions and sectors (Calvin et al., 2023).

A wide range of composting technologies is currently available, with the choice depending on operational costs, land availability, composting duration, and the type of feedstock. Recent advancements have improved composting performance through modified systems such as co-composting, vermicomposting, and windrow composting (Zhou et al., 2018). In most modern aerobic composting facilities, the process is conducted in enclosed reactors or tunnels under forced aeration and negative pressure, which ensures an adequate oxygen supply and efficient heat removal (Michel et al., 2022). The mature compost is then subjected to a curing phase, allowing further stabilization and the formation of a safe, stable product suitable for soil application without adverse environmental effects (Wichuk & McCartney, 2013).

The conventional composting process typically follows a two-phase approach, integrating multiple methods to enhance process efficiency, compost quality, and environmental performance (Kulikowska & Gusiatin, 2015). Common two-phase systems include aerated static pile (ASP) composting, vermicomposting, and windrow or in-vessel composting. Additional mechanical-biological treatment (MBT) techniques and anaerobic digestion (AD) prior to composting are also employed to improve biodegradability (Lim et al., 2017). A complete composting cycle can take approximately seven months, including around 201 days of maturation in windrows after an initial 10-day decomposition and sanitation phase. However, such extended processing times pose challenges for regions with limited land availability or high waste generation rates (Amuah et al., 2022).

Despite technical progress, limited research has been done on the economic and ecological implications of two-phase composting processes using in-vessel, ASP, or windrow systems (Lim et al., 2017). The capital costs of sewage sludge composting facilities range between USD 164,000 and 350,000, with annual operating costs from USD 100,000 to 300,000, depending on technology type and sludge moisture content. Moisture content is a critical factor influencing both capital and operating expenses, as dewatering requirements substantially affect costs. Windrow composting is generally the least expensive option to construct and operate but is constrained by land requirements and bulking agent costs. In contrast, ASP systems are more suitable for small- to medium-scale municipal wastewater treatment plants, particularly in China, where equipment costs dominate total expenditures, while land acquisition and surfacing remain the primary costs for windrow systems (Wei et al., 2001).

In addition, when making decisions, it is vital to consider environmental and economic assessments along with market demand for final products. The optimal approach should prioritize reducing pollution and enhancing environmental quality, beyond purely economic and energy considerations (Turlej & Banaś, 2018).

Windrow Composting (WC)

Windrow composting is a biological treatment process in which the organic components of biosolids biologically decompose under controlled aerobic conditions. It is the most common used composting method (Hubbe et al., 2010), particularly in the United States (USEPA, 2015). The process involves forming long, narrow piles of sludge and organic materials called "windrows," which are roughly twice as wide as they are high. The length of these windrows varies depending on available space and material volume, often extending up to 23 meters or more. Windrows are usually constructed over perforated pipes to facilitate passive aeration and are periodically turned to promote oxygen distribution and homogeneous decomposition (Dentel & Qi, 2014a). This method is highly adaptable, accommodating both small- and large-scale operations depending on land availability and processing capacity.

Windrow composting often requires front-end loaders, excavators, or windrow turners for the repeated lifting and turning of materials (USEPA, 2015). Using a loaders can be labour and time consuming, whereas specialized windrow-turning machines can significantly enhances operational efficiency, with some systems capable of processing several thousand cubic meters per hour (Rynk & Richard, 2001). Maintaining the appropriate moisture content, generally between 50–60%, is essential to sustain microbial activity while preventing anaerobic conditions (Nelson et al., 2006; USEPA, 2015).

The active composting process lasts up to eight weeks (Misra et al., 2003). Optimal pile dimensions typically 1-3 meters high and 4-5 meters wide—combined with periodic aeration using windrow turners ensure adequate aeration, heat generation, and microbial efficiency (USEPA, 2015). The biological decomposition of organic matter generates significant heat, with internal temperatures reaching 55–70°C, sufficient to achieve pathogen reduction and efficient organic matter stabilization (Ambade et al., 2013; Lopes et al., 2019).

However, the aerobic degradation of sewage sludge also releases gaseous by-products. The prolonged decomposition period, along with frequent turning, results in the emission of ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs), contributing to odors and air pollution. The intensity and composition of these emissions depend on the feedstock characteristics and environmental conditions (Epstein, 2011).

Despite these drawbacks, windrow composting (WC) remains highly effective for processing large volumes of sludge at relatively low operational costs. Nevertheless, due to its odor and emission potential, it is more appropriate for rural areas or small municipalities with low population density (Dentel & Qi, 2014; Turovskiy & Mathai, 2006). To mitigate odor emissions and improve aeration**,** bulking agents such as wood chips or straw are commonly added to the compost mixture (Epstein, 2011).

Aerated static windrow

Aerated static windrow (ASW) composting is a controlled aerobic technology used for composting in which the composting piles are not mechanically turned instead air is supplied through blowers connected to the perforated pipes running under the pile (Gonawala & Jardosh, 2018). The aeration system delivers oxygen, removes carbon dioxide, water vapor, and other gaseous by-products, and helps to regulate internal temperature. Temperature and oxygen levels are monitored using embedded sensors, allowing operators to maintain optimal composting conditions (Ahmed et al., 2007). According to Krogmann et al. (2010), windrows equipped with forced-air ventilation are less likely to develop anaerobic conditions, thereby minimizing odorous emissions.

In ASW systems, large volumes of homogeneous organic waste are stacked over a porous base layer to facilitate uniform air distribution (Diaz et al., 2007a). The composting process generally lasts three to five weeks and is widely applied for the treatment of municipal sewage sludge (Misra et al., 2003). However, the Food and Agriculture Organization (FAO, 2024) notes that ASW composting is less effective in producing high-quality compost when used with food processing residues or animal dung. The windrow dimensions are constrained by equipment type, waste density, and the risk of compaction, with pile heights typically ranging from 2–4 m and lengths from 40–80 m (Diaz et al., 2007b). The static nature of the system can cause compaction and uneven decomposition, leading to odour formation, leachate production, and extended composting times. ASW composting may therefore be unsuitable for arid climates, where moisture retention is critical, or for cold regions, where passive aeration is often inadequate (Gajalakshmi & Abbasi, 2008).

Apart from these benefits, ASW composting faces several technical and operational challenges that can reduce efficiency. The blower capacity and placement of perforated pipes strongly influence oxygen distribution throughout the pile. Insufficient aeration may cause the central zones of large piles to become anaerobic, leading to incomplete decomposition and poor compost quality (Kanachi et al., 2023; Jiang-ming, 2017). Anaerobic pockets also promote the formation of odorous gases such as ammonia, formic acid, and acetic acid. While forced aeration can significantly reduce these emissions, uneven airflow or blocked pipes can negate these benefits and increase energy consumption and operational costs (Rosenfeld & Grey, 2004). Furthermore, power interruptions, particularly in remote or arid areas, can cause uncontrolled temperature rises, which may inactivate beneficial microorganisms and halt the composting process (Michel et al., 2022).

According to Wang et al. (2025), ASW systems rely on consistent mechanical aeration to maintain oxygen levels. Because the piles are not turned, any aeration failure may result in compaction, especially in wet or dense waste streams, thereby promoting anaerobic zones. Moisture management is therefore critical: excessive moisture increases compaction and anaerobic activity, while insufficient moisture slows microbial metabolism (De Oliveira et al., 2024). Although forced aeration assists in maintaining adequate moisture and temperature, it must be precisely controlled to prevent overdrying or insufficient oxygen transfer (Blazy et al., 2014).

Properly managed ASW systems offer several benefits, including efficient temperature control, reduced odour emissions, enhanced decomposition rates, and improved compost quality (Michel et al., 2022). The elevated temperatures achieved during composting reduce microbial populations, particularly thermophilic and mesophilic bacteria and fungi, depending on organic matter content and temperature regime (González et al., 2016).

In-Vessel Composting

In-vessel composting (IVC) is a controlled aerobic process that occurs within an enclosed container or reactor system (Gonawala & Jardosh, 2018). This technology is increasingly adopted for biosolid stabilization and organic waste management due to its ability to contain and treat odorous and gaseous emissions, enhance process control, and improve public acceptance. An IVC facility typically comprises several interconnected components, including a feed preparation unit (sludge cake and soil amendments), a reactor system, aeration and odour control units, external curing and storage areas, and facilities for compost marketing and distribution. Before loading into the vessel, biosolids and bulking agents are thoroughly mixed to ensure uniformity in texture, porosity, and moisture content.

The IVC process generally consists of two primary phases: the high-rate (active) phase and the curing phase. The high-rate phase takes place in enclosed bioreactors and is characterized by intense microbial activity, rapid biodegradation, high oxygen demand, elevated temperatures, and a greater potential for odour production. The curing phase, on the other hand, involves slower microbial processes, gradual temperature decline, and stabilization of organic matter. Although the curing phase often occurs externally in open piles, it may also take place within the reactor or in a hybrid arrangement combining both approaches (Dentel & Qi, 2014a).

Several reactor configurations are employed in IVC systems, including periodic bioreactors (actively aerated vessels without mechanical agitation), plug-flow reactors (horizontal or vertical), and agitated-bed reactors. The core operational parameters influencing compost quality are aeration rate, temperature, and moisture content, as well as the mixing ratio between sludge and amendments. Proper mixing and recycling of materials in suitable proportions enhance porosity, moisture balance, and energy distribution, which collectively support efficient aeration and microbial activity (Stelmachowski et al., 2003).

Aeration and continuous monitoring of key parameters facilitate rapid organic matter decomposition, effective odour control, and the treatment of a wide range of waste materials. For these reasons, IVC systems are widely implemented in municipal and commercial composting facilities (Dentel & Qi, 2014a). However, Ahmed et al. (2007) highlighted that IVC facilities require significant capital investment, high operating costs, and skilled management personnel, which can limit their applicability in low-resource settings.

Common IVC designs include bin composting (non-aerated systems such as wooden or storage bins), silo composting (vertical silos with top feeding and bottom discharge), and rectangular agitated beds (long, narrow channels equipped with automated turners) (Amuah et al., 2022). Compared to anaerobic digestion, IVC is considered more environmentally sustainable due to its aerated and enclosed operation, which reduces methane and odour emissions. Furthermore, it requires less land area, making it suitable for urban and space-constrained environments.

Nevertheless, IVC systems are energy-intensive due to continuous aeration and environmental monitoring, and they can generate nitrous oxide (N_2O), a potent greenhouse gas, thereby limiting their overall climate friendliness (Mu et al., 2017). In addition, IVC facilities incur high operating costs and labour demands, and unlike anaerobic digestion, they do not produce biogas as a revenue source (Slorach et al., 2019). Consequently, while IVC offers superior compost quality and emission control, it is best suited for applications prioritizing environmental performance and product quality over energy recovery or economic efficiency (Lu et al., 2020).

The principal benefits of IVC include compact design, shorter composting duration, and precise control of temperature, moisture, and airflow. Leachate and odour generation are minimal, and decomposition occurs rapidly (USEPA, 2017). However, the system's technical complexity, labour intensity, and sensitivity to low temperatures make it less suitable for cold climates. Moreover, the produced compost must undergo proper cooling and stabilization before use to ensure safe application (FAO, 2021).

Vermicomposting

Vermicomposting (VC), also known as vermistabilization, is a biological degradation and stabilization process in which earthworms and microorganisms jointly decompose organic waste under aerobic conditions (USEPA, 2017). Earthworms ingest, grind, and digest organic material in their gut with the assistance of microbial symbionts, altering the substrate's physical, chemical, and biological properties. The resulting excreta, known as vermicast, is a stable, humified, and microbiologically active organic product that contains essential plant nutrients such as phosphorus (P) and potassium (K) in forms that are readily bioavailable (Huang et al., 2013; Liew et al., 2022).

The nutrient transformation process is enhanced by endosymbiotic microbes within the worm's gut that secrete extracellular enzymes capable of degrading cellulose, lignin, and phenolic compounds. Through their burrowing and feeding activity, earthworms aerate, fragment, and homogenize the organic substrate, thereby stimulating microbial activity and accelerating the mineralization of carbon and nitrogen. The rate of decomposition is closely correlated with earthworm density and microbial community activity. The resulting vermicompost consists of earthworm casts mixed with partially decomposed material, progressively developing optimal biological and physicochemical properties that enhance plant growth and disease suppression, depending on environmental conditions (Insam et al., 2010).

The efficiency of VC largely depends on the diversity and activity of microbial populations. Recent research indicates that lignocellulose degradation is governed more by microbial co-occurrence networks than by overall community diversity (Meng et al., 2022). Certain microbial strains, such as fungi and actinomycetes, play pivotal roles in breaking down lignocellulosic agricultural residues (Varma et al., 2017). Furthermore, earthworm biomass can serve as a high-protein feed source for livestock such as poultry.

VC improves soil structure, aeration, and water-holding capacity, while also enhancing soil microbial activity and fertility. It is especially suitable for small- and medium-scale operations, offering a low-cost and environmentally sustainable approach for managing organic waste. According to Barthod et al. (2018), earthworms and microorganisms together facilitate nutrient recycling, soil process regulation, and maintaining soil fertility. Vermicomposting has been successfully applied to various waste streams, including agricultural, food, textile, and winemaking residues (Gupta & Garg, 2008). Despite its advantages, however, VC requires a longer processing time compared to anaerobic digestion and does not yield biogas as an energy by-product.

Experimental studies typically report processing durations of 30–60 days (Huang et al., 2013; Liew et al., 2022) under optimal temperature ranges of 25–37 °C, depending on the earthworm species employed (Barthod et al., 2018). Selecting an appropriate species is crucial, as worms require a controlled environment with adequate drainage, ventilation, and protection from direct sunlight and rainfall. The red wiggler (*Eisenia fetida*) is one of the most widely used species due to its rapid reproduction rate and efficiency in decomposing organic matter to produce biohumus, a nutrient-rich compost (Garg et al., 2005). Nonetheless, VC has limitations, including the need to maintain worm viability, potential pathogen survival, leachate generation, and the emission of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4). Worms must also be separated from the final compost before its agricultural application (USEPA, 2015).

Vermicomposting of sewage sludge (SS) has been implemented at industrial scale, often through co-composting with carbon-rich substrates to improve feedstock properties. For instance, sludge co-processed with pulp mill solids or cow manure enhances organic matter degradation but may increase acidification and heavy metal concentrations, though typically within regulatory limits (Gupta & Garg, 2008). While data on calcium and magnesium content remain limited, VC generally increases nitrogen and phosphate concentrations. However, high sludge concentrations can inhibit worm reproduction and biological activity.

In Tasman, New Zealand, a large-scale commercial VC facility processed 2,000 tons of pulp mill solids and 900 tons of municipal sewage sludge annually as of 2008 (Quintern, 2014), producing vermicast that complied with New Zealand biosolid standards (Quintern & Morley, 2017). Further research by Yuvaraj et al. (2020) demonstrated that co-vermicomposting textile sludge with cow manure improved NPK content while reducing heavy metal concentrations. Similarly, the addition of organic bulking agents such as rice hulls and wheat straw enhanced organic matter and nitrogen content while reducing coliform bacteria and metal levels (Ghahdarijani et al., 2022).

Integrating vermicomposting with room drying has been shown to improve substrate stabilization but can lead to nitrogen loss (Huang et al., 2022). Overall, VC increases most nutrient concentrations, contributes to substrate acidification, and reduces basal respiration (Georgi et al., 2022). However, the success of VC depends strongly on maintaining low heavy metal concentrations in the raw sewage sludge to avoid adverse effects on worm survival and microbial dynamics.

A summary of some frequently used composting techniques, such as aerated static pile, turning windrow, passive windrow, and in-vessel channel, is shown in Table 1 below. Comparing elements such as general attributes, labour demands, land area, bulking material, active duration, curing period, and size (height, breadth, length) is done in the table. Every composting technique has pros and cons related to labour, technology, amount of area needed, time length, and adaptability.

Table 1. **Advantage/disadvantages of commonly used Composting Technologies**

Factors	**Passive windrow**	**Turned windrow**	**Aerated static pile**	**In-vessel channel**
General	**Low technology**	*Active systems are required on farms*	**Efficient in farm and municipal use**	*Requires systems for commercial use on a large scale*
Labour	**Low labour required**	*Labour intensive*	System design and planning are important. Monitoring needed	**Consistent level of management/product flow to be cost-efficient**
Land	*Large land area required*	*Large area*	Less required	**Minimal land required**
Bulking material	Less flexible Must be porous	**Flexible**	Less flexible Must be porous	**Flexible**
Active period	6 to 24 Months	21 to 40 days	21 to 40 days	21 to 35 days
Curing period	Not applicable	> 30 days	> 30 days	> 30 days
Height	1 to 4 m	1 to 2.8 m	3 to 4.5 m	Dependent on bay design
Width	3 to 7 m	3 to 6 m	Varies	Varies
Length	Varies	Varies	Varies	Varies
Aeration	Natural convection only	Mechanical turning and natural convection	Forced positive/ negative airflow through the pile	Extensive mechanical turning and aeration
Odour	*Odour from the windrow occurs*	**Turning can create odour during the initial weeks**	**Odour may occur but can be controlled through pile insulations and filters**	*Equipment failure/system design constraints can cause odour*

Source: Amuah et al. (2022)

Bold characters refer to advantages; *Italic characters refer to disadvantages*

To obtain high-quality compost and early maturation, several of the composting parameters must be regulated during the composting process. Porosity, temperature, oxygen concentration, moisture content, pH, electrical conductivity, C/N ratio, and cation exchange capacity are some of these characteristics (Raza & Ahmad, 2016). Table 2 reports each of these factors at its ideal value.

Table 2. Optimal parameters during the composting process

Parameters	Optimal value
pH	6-8
Moisture	55-65%
O_2	5-7%
Bulk Density	150-950 kg m^{-3}
C/N ratio	30-40

Source: (Muscarella et al., 2023)

Risks of sewage sludge composting technologies (SST)

The sewage water could contain different organic and inorganic pollutants appearing in sewage sludge compost, and some of them, like pharmaceutical residues, are out of the recent pollutions with environmental limit of regulations, but they are in the focus of research today (Mosharaf et al., 2024)

Microorganism plays a key role in eliminating medicinal residues from sludge and compost because certain microbes possess enzymes capable of breaking down specific pharmaceutical substances (Wiśniowska, 2019) while some can metabolize them as carbon or energy source. Although there have been significant advancements in sewage treatment technology in recent years, particularly in advanced oxidation processes (AOPs) that target the breakdown of complex organic compounds (Yang et al., 2022), but still, conventional biological treatment processes are unable to remove the pharmaceutical residuals solely from sewage. Hence, combining AOPs with the already existing activated sludge method is an important step forward (Bezsenyi et al., 2021). Several studies reported that integrating AOPs with activated sludge systems poses practical challenges, such as high energy or operational cost, catalyst management and potential residual toxicity in treated effluents (Lofrano et al., 2017). The efficiency of this combined approach can be optimised using environmental factors like pH and redox potential to balance both chemical oxidation and microbial degradation process (Jin & Kirk, 2018).

Therefore, conventional activated sludge treatment technologies that have been treated are highly effective in eliminating naproxen, ibuprofen, and ketoprofen (Tóth et al., 2023). In comparison to the control plant, the diclofenac-specific bacterial mix demonstrated a mild but favourable removal efficiency of pharmaceuticals and personal care products that is controlled by the hydraulic retention time (Matamoros et al., 2009). Pure culture indicates that the microbial community is necessary for the biodegradation of non-steroidal anti-inflammatory drugs (NSAIDs), according to Almeida et al. (2013). Moreover, all the degradation processes depend on many factors such as temperature, oxygen level and the microbial diversity of the community (Roberts et al., 2016). Despite the efficiency of the microbes in reducing medicinal residues in sludge and compost, careful monitoring is essential in ensuring environmental safety and less risk to human ecosystemic health.

Conclusion

The European Union Green Deal 2030 emphasizes environmentally friendly practices, including the circular economy policy, to achieve its sustainability goals. One key aspect is the integration of sustainable waste management techniques, such as composting.

Composting technology involves converting residues, such as sewage sludge from wastewater treatment plants, into compost to address environmental issues. These include pollution, excessive solid waste deposition in landfills, and heavy metal accumulation, while also enhancing soil health through amendments.

Composting technologies can be classified as aerobic or anaerobic, depending on the available technology. However, most composting is carried out using aerobic methods, which include windrow composting, aerated static pile composting, in-vessel composting, and vermicomposting. Each of these technologies presents distinct benefits and drawbacks, which must be considered when selecting the most suitable composting method for implementation.

Compost is a soil fertility-enhancing product that provides essential nutrients to agricultural soils, helps reduce greenhouse gas emissions, supports habitat reclamation, and aids in the remediation of contaminated soils. Proper curing during composting optimizes waste volume efficiency and minimizes pathogenic microorganisms present in sewage sludge.

To fully maximize the benefits of composting while mitigating drawbacks such as odors, emissions, and prolonged maturation periods, selecting appropriate bulking agents and improving aeration techniques are essential. Advancements in these areas are crucial for producing high-quality, mature compost.

Additionally, incorporating sustainable waste management practices strengthens composting's role within the Green Deal, positioning it as a key solution for an economically viable and environmentally sustainable future. By embracing composting as a core component of circular economy strategies, the Green Deal 2030 aims to create a future that is both ecologically responsible and resource efficient.

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