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Transforming sewage sludge into a safe circular economy agronomic inputs through (co-)composting: Nutrient value, soil-structure benefits, and contaminant control

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ABSTRACT

An urgent management issue and a strategic opportunity for nutrient and organic-carbon recovery are presented by the increasing production of sewage sludge on a global scale due to the expansion of wastewater treatment. An efficient and scalable method for stabilizing sludge, reducing smells and pathogens, and producing a mature product that may be used as a biofertilizer for agriculture and an amendment to soil structure is composting, particularly when combined with carbon-rich, porous co-substrates. In this review, we will look at the most up-to-date research on the biochemical and physicochemical changes that lead to humification and nitrogen stabilization, as well as the fundamentals of the processes involved and the roles played by common bulking agents in addressing low porosity, high moisture, and low C/N constraints. There is evidence that organic complexation reduces bioavailable heavy metals, thermophilic hygienization is consistently achieved by well-designed co-composting, and many residual organic contaminants are partly degraded. When applied at nutrient-balanced rates, mature sludge co-composts provide consistent yield advantages by supplying slow-release nitrogen and durable phosphorus, improving soil organic carbon, aggregation, porosity, and water-holding capacity, and enhancing microbial biomass and enzyme activities. The need for upstream source management and enhanced monitoring is underscored by the fact that composting does not eliminate new pollutants like PFAS and microplastics, which may remain in the end products. With the availability of co-substrates and well-established compost markets, co-composting has the potential to bridge the gap between urban and rural areas in terms of nutrients, while also competing with thermal and disposal options from a techno-economic and life-cycle perspective. This might lead to advantages for the circular economy. Sludge valorization has some theoretical backing in Morocco, however the country's legislation regarding risk-based applications and agricultural quality requirements are lacking. As a result, we can see the country's huge potential as well as its serious governance problems. Integral components of trustworthy agricultural reuse frameworks include control of feedstocks, optimization of processes, certification of products, and monitoring of soil over extended periods of time. This will guarantee progress down the road.

Keywords: sewage sludge, biosolids, co-composting, soil amendment, biofertilizer, heavy metals, circular economy, pathogen reduction.

INTRODUCTION

Sewage sludge (biosolids) production is on the rise as a result of tighter wastewater treatment rules, expanding sewer networks, and fast urbanization. Wastewater treatment capacity increases are driving the demand for safe and cost-effective sludge management. Sludge management is now seen as an essential part of circular economy and urban environmental governance strategies (Manea and Bumbac, 2024). Landfilling, unregulated dumping, and costly incineration are becoming less acceptable in many places due to land scarcity, greenhouse gas footprints, and growing legal pressure to valorize organic wastes (Manea and Bumbac, 2024).

When considering the use of scarce resources, sewage sludge is more than just a "waste". Organic matter and plant nutrients, particularly nitrogen and phosphorus, as well as beneficial micronutrients, are concentrated in it. Soil fertility and resilience to price spikes and geopolitical supply disruptions caused by mineral fertilizers may be enhanced when these components are stabilized. Reducing residue management's environmental impacts and recovering nutrients for sustainable agriculture are two worldwide concerns that may be addressed simultaneously by composting sludge (Manea and Bumbac, 2024).

The fact that composting can accomplish stability, deodorization, and hygienization all at once, is very low-tech, and can be scaled from municipal windrows to designed reactors makes it an appealing approach. Composting, when done properly in thermophilic environments, may lower pathogen loads to an acceptable level for agricultural use, and the resulting humified, mature product is more stable than either raw or simply dewatered sludge (Aguado et al., 2025). However, there are several traditional technical limits to sludge composting on its own. These include a very high moisture content, limited porosity, and a carbon-to-nitrogen ratio that is often low. As a result, sludge composting may inhibit aeration, impede biodegradation, and increase ammonia losses or odor emissions (Manea and Bumbac, 2024).

Because of this, co-composting has become the standard method in the current era. Collaborative composting improves the biochemical and physical properties of sludge by mixing it with carbon-rich bulking agents such as green waste, straw, sawdust, agro-industrial residues, food waste, biochar, etc. A tighter C/N ratio, better structure and air dispersion, a moisture buffer, and microbially friendly conditions are all outcomes of this technique. Faster stabilization, improved final nutrient balance, and decreased phytotoxicity are only a few of the advantages of co-composting versus sludge-only composts, as shown in several studies (Vráblová et al., 2024).

In addition to its potential in nutrient recycling, co-composted sludge shows a lot of promise as a soil structure supplement. When applied to degraded or low-organic-carbon soils, such as those found in semi-arid and dry climates, humified organic matter improves aggregate stability, bulk density, porosity, and water-holding capacity. According to Manea and Bumbac (2024), sludge co-compost has the potential to improve nutrient-use efficiency and drought resilience via physical upgrades.

This potential, however, depends on risk management. Sewage sludge may include bacteria, potentially dangerous metals (such as cadmium, lead, and chromium), and an ever-growing list of organic micropollutants from houses, hospitals, and companies. Even while composting reduces pathogens and, in many instances, metal bioavailability via humification and sorption processes, it doesn't always eliminate all contaminants (Sugurbekova et al., 2023). It is now well known that biosolids include novel pollutants such microplastics and PFAS, and regulations regarding these substances are evolving at a fast pace. Policy debates in Europe and beyond have lately revolved on these contaminants. A new age of "safe circularity" is heralded by the updated EU Urban Wastewater Treatment Directive, which will take effect in 2025 and clearly increases the expectations for sludge valorization while simultaneously pressing for the monitoring of contaminants such as PFAS and microplastics (Balkrishna et al., 2024). While these emerging concerns are becoming more understood, professional and regulatory organizations have noticed that current sludge-to-land frameworks aren't keeping up with the scientific community (Sugurbekova et al., 2023).

There is an extra sense of urgency and particular in the Moroccan context since the country is increasing its wastewater treatment capacity, which means there will be more sludge volumes. However, there are still barriers to national management strategies due to gaps in technology, the market, and regulations. Regardless of the obvious agronomic promise, the absence of a fully functional, comprehensive, agriculture-specific regulatory and quality framework for sewage sludge products in Morocco is preventing widespread deployment and lowering farmer trust, according to published evaluations (Ghacha et al., 2020). Assuming quality control and risk-based regulation move in tandem, sludge co-composting becomes a viable option for cities and a tool for the national soil-fertility and circular economy initiatives. The threefold reasoning for this review is thus:

- To analyze and summarize the existing research on composting and co-composting processes for sewage sludge, with a focus on how operating conditions and co-substrates affect the stages of stability, hygiene, and maturity (Manea and Bumbac, 2024).
- To assess the efficiency of sludge co-compost as a biofertilizer and soil-structure amendment in terms of agronomic performance, crop responses, and enhancements to the physical and biological health of the soil (Manea and Bumbac, 2024).

The third objective is to examine the risks and governance surrounding both traditional (metals, diseases) and new (PFAS, microplastics, pharmaceuticals) pollutants, and to talk about how current global trends might guide a risk-based framework for safe agricultural valorization in Morocco (Benlemlih et al., 2024).

The overarching goal of this analysis is to set the record straight on when and how sewage sludge co-composting accomplishes "safe circularity" by transforming a potentially harmful byproduct into a trustworthy agronomic input that promotes soil repair, nutrient stability, and environmentally responsible wastewater treatment.

Sewage sludge as a feedstock: Characteristics and constraints

According to several studies, sewage sludge, also called biosolids after stabilization, is a semi-solid byproduct of municipal wastewater treatment that primarily includes settled organic solids, microbial biomass from biological reactors, and adsorbed inorganic particles (Chang et al., 2022; Elgarahy et al., 2024; Kominko et al., 2024). The origin inside the treatment line and any pre-treatments used before dewatering substantially influence its composition and composting behavior (Chen et al., 2025). Primary sludge, which is physically settled, is often coarser and contains more organic elements that degrade quickly. Many studies found that activated sludge is usually wetter, finer, and nitrogen-rich than other types of sludge (Chang et al., 2022; Yu et al., 2023). Chemical conditioning, liming, and anaerobic digestion may drastically change sludge's biodegradability, pH buffering capacity, nitrogen speciation, and cleanliness. Since sewage sludge is not a homogenous substrate but rather a collection of components, its composting capacity must be assessed individually (Chang et al., 2022; Elgarahy et al., 2024; Kominko et al., 2024).

The physicochemical and biological properties of composted sludge are paradoxical, given its agronomic importance, and the fact that it is technically difficult to compost on its own. Anaerobic zones are favoured in the absence of structural correction due to its high bulk density, low free-air space, and strong tendency to compress, which is a result of its high water content and very small particle sizes (Chang et al., 2022; Yu et al., 2023). Additionally, sludge often has a low carbon-to-nitrogen ratio due to its nitrogen content and carbon limitation. When there is an imbalance in the composting process, it may lead to odor emissions, inadequate microbial metabolism, and excessive ammonia volatilization (Manea and Bumbac, 2024; Noor et al. 2024). Sludge has the ability to concentrate a lot of organic matter, nitrogen, phosphorus, and micronutrients, which makes it a promising slow-release biofertilizer and a base for humified soil amendments (Balkrishna et al., 2024; Mesbah et al., 2025; Lucia et al., 2025). According to Almási et al., (2025), compost that isn't completely developed or contains too much sludge might cause phytotoxicity and osmotic stress because to its moderate to high salinity and electrical conductivity levels.

The presence of pollutants complicates wastewater wastes already. Sludge may be formed by a variety of sources, including household plumbing, urban runoff, and especially industrial discharges (Grobelak et al., 2024; Kominko et al., 2024). Sludge can include metals that are potentially dangerous, such as cadmium, lead, chromium, nickel, copper, zinc, or mercury. Pesticide residues, surfactants, polycyclic aromatic hydrocarbons, and pharmaceuticals are among the organic micropollutants that composting decomposes (Grobelak et al., 2024; Nahar et al., 2024). Microplastics and Per- and polyfluoroalkyl substances (PFAS) have recently been the subject of research (Hassan et al., 2023; Arvaniti et al., 2024; Bünemann et al., 2024; Leino et al., 2025). Anxietiest of all, these pollutants could end up in treated soil. Because untreated sludge contains chemical concerns, helminth eggs, viruses, and hazardous bacteria (Grobelak et al., 2024), hygienization is a crucial aim for agricultural valorization. The fact that these risks change depending on factors like industrial contributions, seasonality, sludge age, treatment configuration, polymer/chemical use, storage conditions, and hospital effluents explains why sludge characteristics can vary significantly in space and time, even among plants with the same capacity (Chang et al., 2022; Kominko et al., 2024).

Taken together, these properties explain why sludge-only composting is rarely optimal: excess moisture and fine texture suppress aeration, low C/N destabilizes nitrogen pathways and increases odor, and contaminant/pathogen uncertainty requires especially robust thermophilic control and monitoring (Yu et al., 2023; Manea et al., 2024). Co-composting therefore becomes a structural necessity rather than a simple option. By blending sludge with carbon-rich and porous co-substrates, the initial mixture can be engineered to reach suitable C/N, moisture, and free-air space, while also diluting or immobilizing contaminants and enabling stable thermophilic hygienization (Tsabedze et al., 2025; Vráblová et al., 2024; Noor et al., 2024). In this sense, sewage sludge provides the fertility and organic-matter core, whereas co-substrates provide the physical architecture and carbon energy required to drive composting efficiently and safely (Manea and Bumbac, 2024).

Choice of bulking agents and co-substrates

Co-composting sewage sludge is widely regarded as a technical necessity rather than a marginal refinement, because sludge alone is structurally and chemically poorly suited to aerobic composting. Dewatered biosolids typically exhibit high moisture content, fine particle size and high bulk density, which together generate low free-air space, rapid compaction and a strong tendency toward localized anaerobic conditions if no structural amendment is added (Manea and Bumbac, 2024; Almási et al., 2025). At the same time, sewage sludge is usually rich in nitrogen but relatively poor in readily available carbon, producing low C/N ratios that favor ammonia volatilization, odor emissions and inefficient microbial metabolism during the initial stages of composting (Mesbah et al., 2025; Lucia et al., 2025). These constraints explain why co-composting—blending sludge with carbon-rich, porous bulking agents—is repeatedly identified as a prerequisite for achieving stable thermophilic conditions, effective hygienization and a mature, agronomically acceptable end-product (Rani et al., 2024; Elgarahy et al., 2024; Kominko et al., 2024).

During this stage of design, the bulking agent and co-substrates selection procedure is front and center. It has been extensively shown that co-substrates may perform several functions (Grobelak et al., 2024; Noor et al., 2024; Almási et al., 2025). Co-substrates have several uses: they may increase structural porosity and free-air space, soak up excess moisture, mitigate pH and salinity trends, and even serve as sorption sites for immobilizing contaminants or retaining nutrients. The primary bulking agents often used in buildings to facilitate airflow and pile geometry are lignocellulosic materials such as green waste, pruning residues, straw, or wood-based fractions (Sugurbekova et al., 2023, Rani et al., 2024). However, process behavior and product quality may be adjusted using lower volumes of other organic wastes or additions.

Sludge co-composting has been investigated in recent years for its potential to improve nitrogen conservation, speed up stabilization, and decrease the bioavailability of contaminants. (Table 1). These strategies, which involve additives and multi-waste co-composting, aim to align sludge co-composting with larger circular economy and climate goals (Frišták et al., 2024; Noor et al., 2024; Aguado et al., 2025). Several studies have agreed that when selecting co-substrates for compost, it's important to consider potential additional contaminants like microplastics or emerging organic pollutants. This will ensure that the final compost is safe for agricultural use and supports process performance (Hassan et al., 2023; Bünemann et al., 2024; Chen et al., 2025; Leino et al., 2025).

Composting/co-composting process fundamentals

Composting and co-composting of sewage sludge are aerobic, microbially driven stabilization processes in which organic matter is biologically oxidized to CO_2, water and heat, while a more humified, soil-like material is formed (Manea and Bumbac, 2024). Independently of the specific technology, the process follows a

Table 1. Common co-substrates for sewage sludge co-composting and their main functions

Co-substrate / bulking agent	Typical proportion with sludge	Typical guidance (starting point)	Key notes (main role, benefits / constraints)
Green waste / pruning residues	Sludge : green waste ≈ 1:1 to 1:3 (v/v)	Use as main structural bulking agent for urban plants; adjust ratio to reach ~50–60% moisture and good free-air space.	Provides structure, porosity, C/N correction and moisture absorption; widely available but quality varies with season and fraction (woody vs leafy) (Almási et al., 2025; Rani et al., 2024; Tsabedze et al., 2025).
Woodchips / bark	Sludge : woodchips ≈ 1:2–1:3 (v/v)	Prefer in windrows/static piles with very wet, dense sludge; combine with some finer organics for better contact.	Very strong structural bulking, excellent aeration and temperature control; high C/N may slow degradation and immobilize N if overdosed (Manea and Bumbac, 2024; Noor et al., 2024).
Sawdust / wood shavings	Sludge : sawdust ≈ 1:0.6–1:1 (dry basis)	Use when sludge is very wet and N-rich; mix with coarser bulking (woodchips/green waste) to avoid overpacking.	Increases C/N and absorbs water; helps reduce odors and NH_3, but fine particles can reduce porosity if used alone (Manea and Bumbac, 2024).
Cereal straw / maize stalks	Sludge : straw ≈ 1:0.6–1:1 (dry basis)	Always chop straw; useful in agro-based platforms; monitor temperature to avoid excessive cooling at high straw ratios.	Adds coarse structure and carbon; supports thermophilic phase but too much straw can slow humification and lower bulk density excessively (Rani et al., 2024; Noor et al., 2024).
Food waste / OFMSW	Usually ≤ 30–40% of total mix (v/v) and always with a structural BA	Combine with green waste/woodchips; avoid high proportions with already wet sludge; monitor compaction and odor.	Supplies labile carbon and moisture, boosts microbial activity and heat; often wet, acidic and contaminated with impurities (plastics) (Noor et al., 2024; Aguado et al., 2025).
Animal manures (poultry, cattle, etc.)	Often ≤ sludge share; always with high-C bulking	Use to enrich nutrients and microbiota, but only in recipes with strong structural bulking and sufficient carbon.	Increases N, P and biological activity; manure + sludge both N-rich → risk of salinity, NH_3 losses and extra pathogen load (Sugurbekova et al., 2023; Mesbah et al., 2025; Balkrishna et al., 2024).
Olive pomace / olive mill residues	Roughly 15–40% of total mix (DM basis)	Particularly suitable in Mediterranean/Moroccan platforms; keep proportion moderate and ensure good mixing and curing.	Provides fibrous carbon, structure and K; valorizes local agro-waste but phenolics and salinity can cause phytotoxicity at high doses (Ghacha et al., 2020; Lucia et al., 2025).
Biochar (wood / green-waste)	About 2–10% of mixture (w/w)	Use as additive, not main bulking agent; target higher rates when NH_3 and contaminant immobilization are priorities.	Increases porosity and sorption; can reduce NH_3 losses and metal/organic mobility; high doses may overdry and slow the process (Frišták et al., 2024; Grobelak et al., 2024; Noor et al., 2024).
Peat / mature compost (conditioner/inoculum)	Typically 5–15% of mixture (v/v or w/w)	Use in start-up or in small plants to stabilize process and inoculate; not intended as main bulking agent.	Buffers moisture, provides inoculum and improves physical properties; peat has sustainability issues and mature compost supply may be limited (Almási et al., 2025).

characteristic sequence of phases: an initial mesophilic stage where readily degradable compounds are rapidly metabolized, a thermophilic phase in which temperatures typically exceed 45–55 °C and decomposition rates and pathogen inactivation are maximal, and a subsequent curing/maturation phase during which temperature declines, humification progresses and phytotoxic intermediates are removed (Almási et al., 2025). Successful sludge co-composting requires that the feedstock mixture be formulated within suitable "windows" of moisture, C/N ratio, and air-filled porosity so that microbial activity can sustain this thermal progression without collapsing into anaerobic conditions (Manea and Bumbac, 2024; Noor et al., 2024; Tsabedze et al., 2025).

In practice, these fundamentals are implemented through different process configurations. Open windrow systems remain widely used for sludge co-composting because of their relatively low capital cost and operational simplicity, with aeration provided by periodic mechanical turning to redistribute heat and moisture, restore oxygen, and break up compaction (Manea and Bumbac, 2024). Aerated static piles use forced aeration through perforated pipes or floors to maintain oxygen levels without frequent turning, which can be advantageous for very wet, dense sludge mixtures (Rani et al., 2024; Almási et al., 2025). More engineered in-vessel or reactor systems provide tighter control over air supply, temperature and residence time, often shortening the active thermophilic period and reducing land footprint at the expense of higher energy use and investment (Yu et al., 2023). Across these systems, the design objective is similar: maintain sufficient oxygen and structural integrity in the pile so that aerobic microorganisms can dominate, heat is generated uniformly, and stabilisation proceeds efficiently.

For sewage sludge in particular, thermophilic hygienization and adequate curing are non-negotiable components of process fundamentals. Because untreated sludge can carry a wide range of pathogens and emerging contaminants, operating conditions must be chosen to maintain thermophilic temperatures throughout the mass for a sufficient duration, and to allow a subsequent maturation phase in which nitrification, humus formation and the dissipation of phytotoxicity can occur (Almási et al., 2025; Tsabedze et al., 2025; Grobelak et al., 2024). Composting can produce higher levels of NH_3, N_2O, and other air pollutants if the aeration or mixture structure is not adequate; however, with proper bulking agents and aeration strategies, composting can be well-designed to limit these losses and improve overall life-cycle performance (Nordahl et al., 2023; Yu et al., 2023; Aguado et al., 2025). Mixture formulation, aeration regime, reactor type, and curing time are all part of the design and operational choices that affect stabilization efficiency, hygienic safety, product quality, and environmental footprint when composting or co-composting sludge.

Biochemical transformations during (co-)composting

Sewage sludge and its co-substrates go through a series of biochemical changes when they are (co-)composted (Manea and Bumbac, 2024). Microbe populations shift in response to environmental cues such temperature, substrate availability, and oxygen saturation. Under both thermophilic and mesophilic environments, simple carbohydrates, proteins, and lipids are rapidly oxidized in the first weeks by microbes, resulting in a reduction of total organic matter and volatile solids (Manea and Bumbac, 2024; Almási et al., 2025). As the supply of easily biodegradable carbon decreases, microbial communities begin to concentrate on components that are more difficult to breakdown, such as the lignocellulosic carbon present in bulking agents like straw or green trash (Rani et al., 2024; Noor et al., 2024). Humification, according to certain research (Lucia et al., 2025; Mesbah et al., 2025; Tsabedze et al., 2025), is based on this gradual change in substrate utilization. Humification entails changing partly degraded residues into more complex and aromatic humic-like compounds. Afterwards, the compost's stability and soil-improving qualities are enhanced.

Nitrogen dynamics is very important for agricultural quality and managing processes. When the pH increases and the organic nitrogen in the sludge is mineralized to ammonium, a large amount of ammonia might be released into the air if the active phase mixes and aeration are not properly regulated (Manea and Bumbac, 2024; Noor et al., 2024). As the system cools and oxygen remains available, nitrifying microorganisms convert NH_4^+ to NO_3^-, stabilizing nitrogen in less volatile forms and contributing to the slow-release behavior observed when mature sludge composts are applied to soil (Mesbah et al., 2025; Almási et al., 2025). In parallel, phosphorus and micronutrients become increasingly associated with organic and mineral matrices, improving their retention and reducing leaching risks (Lucia et al., 2025; Mesbah et al., 2025). For contaminants, co-composting generally does not eliminate heavy metals but tends to shift them from more labile to more stable fractions through complexation with humic substances and sorption onto newly formed organo-mineral phases, thereby reducing their bioavailability and ecological risk (Grobelak et al., 2024; Bünemann et al., 2024; Frišták et al., 2024). Many organic micropollutants, including some pharmaceuticals, can be partially degraded under thermophilic and curing conditions, especially in well-structured, well-aerated mixtures (Vráblová et al., 2024; Nahar et al., 2024), whereas highly persistent contaminants such as microplastics are mainly redistributed and potentially fragmented rather than mineralized (Hassan et al., 2023; Chen et al., 2025; Shrivastava et al., 2025).

Overall, these biochemical trajectories – rapid mineralization of labile carbon, slower lignocellulose breakdown and humification, nitrogen stabilization from ammonium toward nitrate, and contaminant immobilization or partial transformation—explain why mature sludge co-compost behaves as a stable biofertilizer and soil amendment rather than as a fermentable waste (Manea and Bumbac, 2024; Mesbah et al., 2025; Almási et al., 2025).

Hygiene and safety: Pathogen reduction

Hygiene and safety are central motivations for selecting (co-)composting as a sewage-sludge valorization route, because untreated sludge can contain a broad spectrum of enteric pathogens originating from domestic and municipal wastewater, including bacteria, viruses, protozoa and helminth eggs (Sugurbekova et al., 2023; Almási et al., 2025). Direct land application of raw or insufficiently stabilized sludge therefore poses clear health risks for farmers, consumers and nearby communities. In co-composting systems, thermophilic hygienization becomes the primary barrier: as compost piles move from mesophilic to sustained thermophilic conditions, most vegetative bacteria and many viruses are rapidly inactivated by heat, competition and antagonism within the microbial community (Manea and Bumbac, 2024; Almási et al., 2025). Co-substrates that improve structure and aeration help maintain high temperatures throughout the mass, allowing reliable pathogen reduction compared with sludge-only piles that are more prone to cold, anaerobic pockets (Rani et al., 2024; Tsabedze et al., 2025; Almási et al., 2025).

Practically, pathogen control is implemented through time–temperature criteria and microbiological verification. International guidelines and recent European analyses emphasize that biosolids must remain above critical temperatures (typically ≥ 55 °C) for defined periods, with turning or forced aeration ensuring that all parts of the pile pass through the thermophilic core (Salva et al., 2025; Grobelak et al., 2024). The next step is to ensure compliance by testing for indicator organisms like *Escherichia coli* or fecal coliforms, *Salmonella* spp., and viable helminth eggs. The hygienic quality classes for land application are defined by threshold values or non-detection requirements (Elgarahy et al., 2024; Bünemann et al., 2024; Almási et al., 2025).

At the same time, authors stress that hygienization is not complete at the end of the thermophilic phase alone – a controlled curing and storage phase is needed to avoid recontamination, requiring separation of mature compost from fresh sludge streams, protection against animals and runoff, and periodic microbiological monitoring until use (Manea and Bumbac, 2024; Sugurbekova et al., 2023; Almási et al., 2025). In this sense, pathogen reduction in sludge co-composting is best understood as a chain of measures—from mixture design and process control to curing and handling practices—that jointly secure sanitary safety for agricultural reuse.

Contaminants: Classical and emerging

Contaminants are a critical dimension of sewage-sludge (co-)composting, because wastewater treatment not only concentrates nutrients and organic matter but also accumulates pollutants from domestic, industrial and urban runoff sources (Kominko et al., 2024; Elgarahy et al., 2024). For the “classical” group, potentially toxic elements such as Cd, Pb, Cr, Ni, Cu, Zn and Hg are routinely detected in sludge and sludge-derived products, with levels largely controlled by industrial inputs and sewer management (Kominko et al., 2024; Grobelak et al., 2024; Mesbah et al., 2025). Composting does not remove these metals; on the contrary, their total concentrations may increase as organic matter is mineralized. However, numerous studies and syntheses indicate that co-composting promotes a shift from more labile to more stable pools through sorption and complexation with humified organic matter or biochar-like phases, generally reducing bioavailability and plant uptake compared with raw sludge (Grobelak et al., 2024; Frišták et al., 2024; Bünemann et al., 2024). This is why heavy-metal risk in recycled nutrients is increasingly evaluated using speciation and bioavailability metrics rather than total contents alone (Bünemann et al., 2024; Leino et al., 2025).

Beyond metals, sewage sludge contains a broad range of organic micropollutants – pharmaceuticals, personal-care products, surfactants, PAHs, pesticide residues and industrial organics – that partition to solids during wastewater treatment (Elgarahy et al., 2024; Kominko et al., 2024; Leino et al., 2025). Their behavior under composting and co-composting is compound-specific – some pharmaceuticals and aromatic compounds can be substantially attenuated under thermophilic, well-aerated conditions and during curing, especially when co-substrates improve structure and oxygen transfer (Vráblová et al., 2024; Nahar et al., 2024; Grobelak et al., 2024). Others are more persistent and may survive into the final product at low but detectable

Table 2. Main contaminant groups in sewage-sludge (co-)composting: occurrence, behavior and management

Contaminant group	Typical behavior during (co-)composting	Main concern / management (with references)
Heavy metals (Cd, Pb, Cr, Ni, Cu, Zn, Hg)	Not removed; total contents may concentrate slightly, but often shift to less bioavailable forms via sorption and humification.	Long-term accumulation and plant uptake risk. Manage by source control, limits on cumulative load, and focusing on bioavailability/speciation (Kominko et al., 2024; Grobelak et al., 2024; Bünemann et al., 2024; Leino et al., 2025).
Conventional organic micropollutants (pharmaceuticals, PCPs, PAHs, pesticides)	Some compounds are significantly degraded under thermophilic, well-aerated conditions; others persist at low levels in mature compost.	Chronic toxicity and food-chain transfer. Manage with upstream reduction, optimized aerobic conditions and targeted monitoring of priority molecules (Vráblová et al., 2024; Nahar et al., 2024; Elgarahy et al., 2024; Bünemann et al., 2024).
PFAS and related fluorinated surfactants	Extremely persistent; largely unaffected by composting—co-composting mainly dilutes but does not destroy them.	Long-term soil and groundwater contamination. Manage via strict source control, selection of sludge sources and PFAS inclusion in monitoring/regulation (Arvaniti et al., 2024; Balkrishna et al., 2024; Leino et al., 2025; Bünemann et al., 2024).
Microplastics	Retained and often fragmented; particle size may decrease, increasing mobility and interaction surface.	Accumulation in soils and effects on soil biota; vector for other pollutants. Manage by reducing plastic inputs, better screening and integrating MPs into future risk frameworks (Hassan et al., 2023; Chen et al., 2025; Shrivastava et al., 2025; Bünemann et al., 2024).

concentrations, which is increasingly relevant for high-value or organic farming systems relying on recycled fertilizers (Bünemann et al., 2024; Lucia et al., 2025). Reviews underline that hydrothermal or thermal processes can modify contaminant speciation and, in some cases, enhance degradation, but may also produce transformation products that require careful assessment (Nahar et al., 2024; Grobelak et al., 2024).

The emerging contaminant frontier is currently dominated by PFAS and microplastics. PFAS are highly persistent fluorinated surfactants that accumulate in sludge and challenge both biological and thermal treatment processes, with land application now recognized as a potential pathway for their transfer to soils and food chains (Arvaniti et al., 2024; Balkrishna et al., 2024; Leino et al., 2025). Co-composting can dilute PFAS concentrations by mixing but does not destroy these molecules, so long-term risk management must rely on upstream source control and expanded monitoring (Arvaniti et al., 2024; Leino et al., 2025). Microplastics show a similar pattern: wastewater treatment retains a large fraction of particles, which then accumulate in sludge and later in soils when sludge-based products are applied (Hassan et al., 2023; Chen et al., 2025; Shrivastava et al., 2025; Das et al., 2025). Composting tends to fragment rather than mineralize plastics, creating smaller particles with potentially greater mobility and interaction surface (Hassan et al., 2023; Chen et al., 2025). Recent integrative reviews of contaminants in recycled nutrients conclude that while composting and co-composting can stabilize metals and attenuate some organics, they are not sufficient as stand-alone barriers for ultra-persistent pollutants; thus, safe agricultural reuse of sludge co-compost must be embedded in a risk-based framework that couples stringent feedstock control, optimized process conditions and broad-spectrum product monitoring (Bünemann et al., 2024; Kominko et al., 2024; Grobelak et al., 2024; Lucia et al., 2025) (Table 2).

Compost maturity and quality assessment

Compost maturity and quality assessment are pivotal for sewage-sludge co-composts because the final product is intended for direct contact with soil, crops and, indirectly, the food chain. In this context, stability refers to the extent to which readily degradable organic matter has been consumed and biological activity has decreased to a level that no longer causes self-heating or odor, whereas maturity additionally implies that the compost is humified, phytotoxin-free and agronomically safe (Manea & Bumbac, 2024; Almási et al., 2025; Tsabedze et al., 2025). Several authors emphasize that sewage-sludge compost can appear "stable" based on temperature alone while still exhibiting salinity, ammonium toxicity or residual organic intermediates that inhibit seed germination and root development, so multi-indicator quality assessment is recommended rather than relying on a single parameter (Tsabedze et al., 2025; Rani et al., 2024).

In practice, maturity is evaluated through a combination of physical, chemical and biological indicators. Operationally, a mature compost no longer reheats after turning and presents a dark, crumbly structure with an earthy odor rather than putrid or ammoniacal smells (Manea and Bumbac, 2024; Almási et al., 2025). Chemically, commonly used indices include a reduced and stabilized C/N ratio, low NH_4^+ concentrations and a low NH_4^+/NO_3^- ratio, which together indicate progression from ammonification to nitrification and lower risk of ammonia toxicity (Almási et al., 2025; Mesbah et al., 2025). Stabilized pH and electrical conductivity within crop-tolerable ranges are particularly important for sludge-based composts that may be saline or alkaline depending on upstream treatment (Tsabedze et al., 2025; Sugurbekova et al., 2023). Maturity is also linked to humification, often inferred from increases in humic-like substances and shifts in organic-matter quality, which underpin the long-term soil-ameliorating effect of sludge co-composts (Lucia et al., 2025; Mesbah et al., 2025).

Biological and eco-toxicological tests provide the most direct evidence that a compost is safe for plants. Respiration indexes (e.g., CO_2 evolution or O_2 uptake) are used to quantify residual microbial activity, with low values indicating that the material will not undergo further intense decomposition after field application (Manea and Bumbac, 2024; Almási et al., 2025). Phytotoxicity tests, especially seed germination and root-elongation assays in compost extracts, are widely recommended for sewage-sludge and green-waste composts, and germination index thresholds are often used to distinguish immature from mature products (Tsabedze et al., 2025; Rani et al., 2024). Recent reviews on recycled nutrient products and contaminant risks argue that maturity and quality criteria should be integrated with contaminant and pathogen checks into composite quality classes, particularly when composts are destined for organic or high-value agriculture (Bünemann et al., 2024; Grobelak et al., 2024; Almási et al., 2025).

Finally, these technical indicators are interpreted within regulatory and market frameworks. European and international discussions increasingly link biosolids-derived compost quality to both classical parameters (stability, maturity, nutrients) and contaminant ceilings, while also calling for harmonized methods to assess phytotoxicity and compost performance (Salva et al., 2025; Grobelak et al., 2024; Bünemann et al., 2024). Case studies from sewage-sludge composting plants show that products meeting stringent stability, maturity and eco-toxicological criteria are more readily accepted by farmers and can be credibly positioned as circular-economy biofertilizers (Almási et al., 2025; Aguado et al., 2025; Lucia et al., 2025) (Table 3).

Agronomic value as biofertilizer

The agronomic value of sewage-sludge co-compost lies in its dual role as a source of nutrients and stable organic matter. Sewage sludge concentrates nitrogen, phosphorus and micronutrients during wastewater treatment, and co-composting with suitable bulking agents stabilizes these elements into a humified matrix that can be applied as a biofertilizer (Lucia et al., 2025; Balkrishna et al., 2024). Field and pot studies show that sludge-based composts increase soil organic matter and total N and P, improving fertility indicators relative to unamended controls (Mesbah et al., 2025; Almási et al., 2025). In many cases, yields under composted sludge are comparable to, or higher than, those obtained with conventional mineral fertilization when application rates are adjusted to crop demand, supporting the use of sludge co-compost as a genuine agronomic input rather than merely a waste disposal route (Sugurbekova et al., 2023; Lucia et al., 2025).

The progressive release of nutrients, particularly nitrogen, is a big advantage. Composting transforms nitrogen from its readily mineralizable state into organic and nitrate forms, making it more stable than raw sludge or highly soluble fertilizers. Soil mineralization of this pool as it is applied helps synchronize nitrogen supply with crop absorption and decreases the possibility of volatilization and abrupt leaching pulses (Almási et al., 2025; Mesbah et al., 2025). Organic-mineral complexes containing micronutrients and phosphorus enhance the retention and availability of these nutrients in soils that are either nutrient-poor or have been degraded (Mesbah et al., 2025; Lucia et al., 2025). The majority of evaluations also stress the need of careful dose and timing in maximizing agronomic benefits: With the help of mineral fertilizers, soil fertility, structure, and biological activity may be improved with modest applications of mature sludge co-compost (Grobelak et al., 2024; Almási et al., 2025; Tsabedze et al., 2025). Additionally, this method is able to control pollutant buildup, nitrate leaching, and salinity to a tolerable level. Circular economy

Table 3. Main indicators used to assess the maturity and quality of sewage-sludge co-composts

Indicator	What it indicates	Typical criterion / trend for “mature” sludge co-compost	References
Temperature profile	Process stability and end of active phase	Pile no longer self-heats after turning; temperature stabilizes close to ambient	Manea and Bumbac (2024); Almási et al. (2025)
Visual aspect and odor	Qualitative stability / maturity	Dark, crumbly, soil-like structure; earthy odor without putrid or strong NH_3 smell	Manea and Bumbac (2024); Almási et al. (2025)
C/N ratio	Degree of organic matter stabilization	Decrease and stabilization, often in the mid-teens to low-20s range	Almási et al. (2025); Mesbah et al. (2025)
NH_4^+ concentration	Residual ammonium / risk of ammonia toxicity	Marked reduction compared with active phase; low NH_4^+ in final product	Almási et al. (2025); Mesbah et al. (2025)
NH_4^+/NO_3^- ratio	Nitrification / maturity index	Low NH_4^+/NO_3^- ratio with NO_3^- dominant, indicating advanced curing and reduced phytotoxicity	Almási et al. (2025); Mesbah et al. (2025)
pH	Process evolution and plant compatibility	Stabilized pH within crop-tolerable range; no significant drift over time	Tsabedze et al. (2025); Sugurbekova et al. (2023)
Electrical conductivity (EC)	Salinity and phytotoxicity risk	Stabilized EC; below crop- and soil-specific salinity thresholds	Tsabedze et al. (2025); Sugurbekova et al. (2023)
Respiration index (CO_2 evolution / O_2 uptake)	Biological stability (residual biodegradability)	Low respiration values indicating absence of intense further decomposition after application	Manea & Bumbac (2024); Almási et al. (2025)
Germination index (GI)	Phytotoxicity and eco-toxicological maturity	High GI (non-inhibitory or stimulatory to seed germination and root growth; threshold test-dependent)	Tsabedze et al. (2025); Rani et al. (2024)
Humification indicators	Formation of humic-like, stable organic matter	Evidence of increased humic-like fractions and more stable organic carbon forms in compost	Lucia et al. (2025); Mesbah et al. (2025)
Pathogens (e.g. E. coli, Salmonella)	Hygienic quality and sanitary safety	Indicator organisms and pathogens below legal or guideline limits for land application	Grobelak et al. (2024); Almási et al. (2025)
Contaminants (metals, organics, PFAS, microplastics)	Chemical safety and suitability for agriculture	Concentrations within regulatory or recommended thresholds; acceptable risk for soil and crops	Bünemann et al. (2024); Leino et al. (2025); Kominko et al. (2024)

research (Yu et al., 2023; Aguado et al., 2025; Lucia et al., 2025) shows that this pattern of use brings sludge management in line with broader sustainability goals and links urban and agricultural nutrient and carbon cycles. Synthetic fertilizers are also used less often as a result.

Effects on soil physical structure and health

Soil physical structure is often improved quickly and quantitatively after applying sewage-sludge co-compost, thanks to the addition of relatively stable organic matter that binds and aids in the reconstruction of the soil pore network. Soil organic carbon, aggregation, total porosity, and water-holding capacity may all be enhanced using sludge-based composts, according to both laboratory and field studies (Almási et al., 2025; Lucia et al., 2025; Mesbah et al., 2025). Concurrently, the composts can decrease bulk density and the likelihood of crusting and erosion. In degraded or compacted soils as well as semi-arid areas where water is frequently the primary constraint, these structural alterations lead to improved infiltration and decreased runoff, improved aeration for roots and microbes, and increased plant-available water (Ghacha et al., 2020; Sugurbekova et al., 2023; Benlemlih et al., 2024). Humified carbon from co-compost, when applied moderately and repeatedly, helps create soil that is more stable, crumbly, and well-aerated, rather than only providing temporary benefits (Lucia et al., 2025; Mesbah et al., 2025).

The physical advantages of healthy soil are closely related to its biological vitality. In general, sludge co-compost enhances nutrient turnover and functional fertility by increasing microbial biomass and stimulating enzyme activities involved in carbon, nitrogen, and phosphorus cycling. This is achieved by improving moisture and aeration regimes and providing organic substrates (Mesbah et al., 2025; Sugurbekova et al., 2023; Lucia et al., 2025). Soil biota and long-term soil functioning are benefited by composts made from biosolids, according to reviews of recycled nutrient products (Bünemann et al., 2024; Grobelak et al., 2024), provided that metal and organic-contaminant loading are maintained below acceptable limits. While these benefits may be short-lived, the literature cautions that they are very dose- and context-dependent; for example, crops that are sensitive to stress may experience an increase in salinity or ammonium levels if applications are not fully matured, and cumulative loading needs to be carefully monitored to prevent the accumulation of contaminants over time (Bünemann et al., 2024; Almási et al., 2025; Tsabedze et al., 2025). Thus, the most favorable outcomes for soil physical structure and health are reported when well-matured sludge co-compost is applied in moderate, repeated doses, integrated into nutrient management plans and adapted to local soil and climate conditions—a strategy that fits well with circular-economy approaches to sludge valorization in agriculture (Aguado et al., 2025; Lucia et al., 2025).

Environmental impacts and risk management

Environmental impacts are inseparable from sewage-sludge (co-)composting because the process sits at the interface between waste management, air quality and soil–water protection. Gaseous emissions from aerobic biodegradation, which occurs during composting, include CO_2 from carbon mineralization, CH_4 and N_2O from local anaerobic microsites and imbalanced nitrogen transformations, as well as NH_3 and volatile organic compounds (Nordahl et al., 2023; Yu et al., 2023). The feedstock's attributes (structure, moisture, C/N ratio, and aeration rate) and operational decisions (aeration rate, turning frequency, and pile shape) have a significant impact on these fluxes (Manea and Bumbac, 2024; Noor et al., 2024). Early on in the composting process, sludge is particularly susceptible to NH_3 losses because of its low carbon to nitrogen ratio and high ammonium content. Almási et al., (2025) found that deficient structural properties in compacted zones can lead to increased CH_4 and N_2O production. Reviews and life-cycle assessments have shown that these emissions can be significantly reduced through the use of bulking agents in mixture design, optimized aeration strategies, and, if needed, additives such as biochar or covers that reduce nitrogen volatilization and improve process stability (Grobelak et al., 2024; Noor et al., 2024; Aguado et al., 2025). When such measures are in place, co-composting typically performs better compared with uncontrolled dumping or landfilling, particularly after avoided fertilizer output and avoided landfill emissions are accounted for (Yu et al., 2023; Aguado et al., 2025).

The environmental profile changes after land application to focus on soil, water, and long-term contaminants. According to many studies, sludge co-composting has the potential to enhance soil carbon stocks and structure while also reducing the requirement for synthetic fertilizers (Sugurbekova et al., 2023; Lucia et al., 2025; Mesbah et al., 2025). Consequently, this helps in controlling erosion and retaining water. Treatments that are either applied too often or not timed properly can exacerbate nitrate leaching, phosphorus runoff, and the cumulative loading of metals and organic pollutants (Bünemann et al., 2024; Grobelak et al., 2024; Mesbah et al., 2025). Soluble salts in sludge-based composts may raise soil electrical conductivity and damage stress-sensitive crops when applied at high rates without drainage management or leaching (Ghacha et al., 2020; Benlemlih et al., 2024; Tsabedze et al., 2025). This poses an additional concern in semi-arid regions, such as several agro-ecosystems in Morocco. Applying sludge to wastewater has the potential to move new pollutants like PFAS and microplastics into soils, where they might stay for a long time. Because of this, there is a lack of clarity on the future (Hassan et al., 2023; Arvaniti et al., 2024; Chen et al., 2025; Leino et al., 2025). Given these facts, it is claimed in recent studies that risk-based management chains should be implemented. Improving treatment and co-composting circumstances, regulating upstream sources, and meticulously allocating field-level nutrients and pollutants are all links in these networks (Bünemann et al., 2024; Grobelak et al., 2024; Kominko et al., 2024; Salva et al., 2025).

Comprehensive risk management is in place throughout the whole cycle, beginning with the sewage treatment plant and ending in the field. Industrial pretreatment, focused monitoring, and regulatory limitations on discharges are examples of upstream measures that reduce heavy metals and ultra-persistent organics before they reach the sludge line (Kominko et al., 2024; Salva et al., 2025). Aeration control and recipe design are used throughout the plant and composting phases to decrease emissions and promote the immobilization of pollutants by humification and sorption

(Frišták et al., 2024; Manea and Bumbac, 2024; Noor et al., 2024). Following crop and soil-specific guidelines, applying nutrient-based rates, creating buffer zones near bodies of water, and monitoring soil salinity and contaminant stocks over an extended period of time are crucial for ensuring environmental safety while enjoying the agronomic benefits of sludge co-compost (Ghacha et al., 2020; Bünemann et al., 2024; Almási et al., 2025). When these measures are implemented within a circular economy perspective, sewage-sludge co-composting can improve soil quality, close nutrient and carbon loops, and keep risks to air, water, and soil within acceptable, transparently managed bounds (Yu et al., 2023; Aguado et al., 2025; Lucia et al., 2025).

Regulations, standards, and the Morocco case

Regulations and standards act as the final gate that determines whether sewage-sludge co-composting can move from pilot projects to routine agricultural practice. Across regions, the regulatory logic is broadly similar: sludge-derived products must be stabilized and hygienized, must comply with contaminant thresholds, and must be applied under controlled agronomic conditions to protect soils, water and the food chain (Kominko et al., 2024; Grobelak et al., 2024; Bünemann et al., 2024). Recent European analyses emphasize a combined approach based on process requirements (e.g., time–temperature conditions for pathogen reduction), end-product quality criteria (pathogens, heavy metals, sometimes organic pollutants) and land-application controls (cumulative loadings, crop and soil restrictions, record-keeping) (Salva et al., 2025; Grobelak et al., 2024). At the same time, new work on contaminants of emerging concern in sludge is pushing standards beyond a "metals-only" focus toward broader risk frameworks that also consider pharmaceuticals, PFAS and microplastics, as well as their fate in soils (Bünemann et al., 2024; Leino et al., 2025). This shift is closely aligned with the growing interest in life-cycle and circular-economy perspectives, in which sludge use in agriculture is judged not only on local safety but also on its contribution to nutrient recycling and greenhouse-gas mitigation (Yu et al., 2023; Aguado et al., 2025; Lucia et al., 2025).

Because of its immense technological potential and its still-evolving institutional and regulatory framework, Morocco is seen as a "transition case" in this global context. The country's investments in wastewater treatment have led to an increase in sludge volumes and a push for more sustainable disposal methods like composting and agricultural reuse, rather than uncontrolled disposal (Ghacha et al., 2020; Sugurbekova et al., 2023). Existing legislation on waste and water provides a general basis for valorizing biodegradable residues, yet several authors note that the specific status of sewage sludge, as well as detailed standards for sludge-derived fertilizers, remain incomplete or fragmented, which slows down large-scale, formalized reuse (Ghacha et al., 2020; Benlemlih et al., 2024). In practice, sludge co-composting fits well with national objectives for soil restoration, water-saving agriculture and circular economy, but scaling requires clearer product categories (e.g., types of sludge compost), explicit contaminant and pathogen thresholds adapted to local soils and cropping systems, and guidance on application rates in salinity- and drought-prone environments (Ghacha et al., 2020; Lucia et al., 2025). From a policy perspective, the literature suggests that Morocco's pathway forward lies in integrating sludge co-composting into a risk-based, circular-economy framework similar to that emerging in Europe—coupling source control, process quality assurance and long-term soil monitoring—so that recycled nutrients from wastewater can be used safely and credibly in agriculture (Aguado et al., 2025; Grobelak et al., 2024; Lucia et al., 2025).

Techno-economic, life-cycle, and circular-economy perspective

From a techno-economic standpoint, sewage-sludge co-composting occupies an intermediate position between low-cost but unsustainable options (stockpiling, uncontrolled spreading, and landfill) and capital-intensive routes such as incineration or advanced thermal treatments (Manea and Bumbac, 2024; Kominko et al., 2024). Cost structures are largely driven by dewatering performance, bulking-agent supply and preparation, land and infrastructure needs, energy for aeration/turning, and quality monitoring (Novak, 2006; Sen et al., 2024; Almási et al., 2025). Case studies and reviews indicate that windrow and aerated-pile systems can be economically favorable when co-substrates (green waste, agro-residues) are locally available and when there is an organized outlet for the compost, for example via municipal–farmer agreements or partial substitution of mineral fertilizers (Sugurbekova et al., 2023; Almási et al., 2025; Lucia et al., 2025). Conversely, where sludge remains highly wet or poorly dewaterable, additional pre-treatment and longer residence times can raise operational costs, reinforcing the importance of integrating sludge dewatering, composting technology and market development into a single business model (Sun et al., 2023; Sen et al., 2024; Manea and Bumbac, 2024).

Life-cycle assessment (LCA) and circular-economy analyses broaden this view by comparing sludge co-composting with alternative management pathways and accounting for indirect effects such as avoided fertilizer production and avoided landfill emissions. Recent LCAs show that composting and co-composting can perform well in terms of resource recovery and climate impact when process control limits NH_3, N_2O and CH_4 emissions and when the nutrient value of compost is effectively utilized in agriculture (Yu et al., 2023; Nordahl et al., 2023; Aguado et al., 2025). Research in the domain of circular economy has shown that sewage co-composting may help reduce the nutrient and carbon gap between urban and rural regions. According to many studies, this method helps regenerate soil and reduces dependency on synthetic inputs by transforming wastewater leftovers into a standardized biofertilizer (Balkrishna et al., 2024; Aguado et al., 2025; Lucia et al., 2025). For nations like Morocco, where organic matter levels are low and sludge volumes are increasing, this is an important consideration (Ghacha et al., 2020; Benlemlih et al., 2024; Lucia et al., 2025). However, techno-economic and LCA studies also underline that these benefits are contingent on robust contaminant and pathogen management: if heavy metals, PFAS, microplastics or other pollutants are not adequately controlled, environmental risks can offset circular-economy gains (Kominko et al., 2024; Bünemann et al., 2024; Leino et al., 2025). Overall, the literature converges on the idea that sludge co-composting delivers the greatest net benefit when it is designed and governed as an integrated, risk-based circular-economy system linking source control, optimized treatment performance and secure agricultural reuse (Grobelak et al., 2024; Aguado et al., 2025; Lucia et al., 2025).

CONCLUSIONS

Composting—and especially co-composting—of sewage sludge is a strong circular-economy route that turns a difficult wastewater residue into a hygienic, mature, and agronomically useful product. According to the information that has been examined, co-composting is technically necessary. This is because the presence of carbon-rich and porous co-substrates allows for the stable aerobic thermophilic operation, quick stabilization, and reliable elimination of pathogens in sludge, which is otherwise affected by its excess moisture, poor porosity, and low carbon-to-nitrogen ratio. Soil organic carbon, aggregation, porosity, and water retention are all improved with proper curing of the co-compost, making it humified and chemically stable. This improves crop productivity and microbial activity, particularly in semi-arid and degraded soils, and it delivers slow-release nitrogen and durable phosphorus.

On the other hand, residual risk management is essential for safe agricultural reuse. While co-composting is effective in reducing the bioavailability of heavy metals by passivation and humic complexation, and in attenuating numerous legacy organics, it is not effective in destroying ultra-persistent pollutants like PFAS and microplastics; hence, it is essential to implement upstream source management and increase monitoring. Recipes and aeration that reduce gaseous losses and secure compost outputs optimize sustainability, according to techno-economic and life-cycle studies. Due to increasing sludge volumes and an abundance of local co-substrates, co-composting is a promising strategy for soil restoration and nutrient security in Morocco. However, in order to scale up, a specific risk-based framework is required to define product classes, establish contaminant thresholds (which should gradually include emerging pollutants), and establish application rules tailored to soils that are sensitive to salinity, guarantee traceability, and conduct long-term soil surveillance.

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