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Composting: Turning waste into soil wealth

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Introduction

Waste production continues to rise in proportion to urbanization and the global population.

Economic expansion and the Industrial Revolution have profoundly altered people's consumeristic preferences, which has led to a sharp increase in amount of waste generated in recent years. With global waste output predicted to exceed 3.4 billion tons by 2050, projections show that this trend will continue. This is a substantial rise above the 2.1 billion tons that were reported in 2016 (Valavanidis, 2023). An estimated 1.3 billion tons of food waste are created annually, constitutes the largest portion of global waste (Awasthi *et al.,* 2020; Girotto *et al.,* 2015). At present, conventional methods like landfilling or incineration are utilized to dispose of solid organic wastes (SOW), such as animal manure, agricultural residue, MSW (municipal solid waste), etc. However, these techniques are not sustainable owing to space limitations (Soobhany, 2018). A major fraction of municipal solid waste (MSW) is made up of green waste (GW) and biowaste (BW) (Thi *et al.,* 2015; Zhang *et al.,* 2021). Up to 64% and 46% are composed of organic fraction in low-income nations and worldwide respectively (Lu *et al.,* 2020). BW and GW disposal in sanitary landfills or dumps produces high-strength leachate and leads to the release of greenhouse gases that may have a negative impact on the environment and human health (Oviedo-Ocąna *et al.,* 2016). Effective waste management could potentially reduce climate change emissions, improve environmental protection, and make better use of the resources of the world (Jensen *et al.,* 2016). Several technologies, including anaerobic digestion, pyrolysis, incineration, and gasification, can be used to efficiently handle the massive quantity of biodegradable wastes; nevertheless, composting is a better choice since it is relatively simpler to set up and maintain. Well-stabilized humus, which can be used as a soil conditioner, is the end result of biological processing of the waste stream (Adewumi *et al.,* 2005).

Therefore, composting is suggested as the best way to dispose organic waste since it adheres to circular economy principles and allows for material recovery (Oldfield *et al.,* 2018; Zhang *et al.,* 2021). Diverting waste to composting has great potential of developing a circular waste management framework, reducing greenhouse gas emissions, and mitigating the impact on the climate (Ng *et al.,* 2021). In this context, even small-scale or homemade composting efforts play a meaningful role in minimizing the volume of organic waste dumped in landfills, and enhancing soil health.

Composting processes

Composting is an aerobic, biochemical, and microbiological process that involves the hydrolysis of organic fractions into humus, a stable and sterilized residue (Wei *et al.,* 2017). While decomposition occurs naturally, human management can significantly accelerate this process. Composting systems can be broadly classified as either anaerobic or aerobic based on their O_2 needs. With the presence of O_2, aerobic composting breaks down organic matter (OM) more quickly, at higher temperatures, and with less offensive smells. This process begins by blending appropriate organic substances and making sure there is enough aeration. As they swiftly use up the O_2, microorganisms force air out of the pore spaces. In lack of a steady flow of oxygen, the process of breakdown slows down and finally ceases. Anaerobic composting, on the other hand, takes place without O_2 and includes the breakdown of organic waste in a restricted space with little intervention from humans. CH_4, CO_2, and low molecular weight organic acids are among the byproducts produced by this process. The finished product has the consistency of mud and requires post treatment for use. Various composting systems - Composting heaps, windrows, passive composting piles, aerated static piles, in-vessel composters, rotary drum composters, and bioreactors are among the most popular composting techniques employed globally (Tchobanoglous *et al.,* 1993; Ezzariai *et al.,* 2021)). Before initiating the process, it is necessary to regulate the fundamental composting parameters, such as moisture, pH, and C/N ratio, as they affect the microbial growth and organic matter breakdown (Mehta and Sirari, 2018; Hermann *et al.,* 2011). Additionally, the microbial population, which consists of worms, fungus, and bacteria can stabilize the compost's degradable organic matter. Furthermore, the substrate and physical parameters, such as the substrate's temperature, aeration, and moisture content, affect the characteristics of the microbial community.

Phases of composting: Composting process through three sequential stages: (i) a mesophilic phase in which mesophilic bacteria and fungi quickly raise the temperature to break down simple compounds like sugars, amino acids, etc.; (ii) a thermophilic phase in which thermophilic microbes break down organic matter (fats, cellulose, hemicellulose, and lignin). Metabolic activity of heat-tolerant microorganisms is responsible for the feedstock's decreased organic carbon content during this phase. Finally, (iii) the cooling and maturation phase which is distinguished by a decrease in temperature and a reduction in microbial activity. Mesophilic microorganisms recolonize the compost mass during this process, breaking down the remaining sugars, cellulose, and hemicellulose to produce compounds that are comparable to humic substances (Albrecht *et al.,* 2010). This final stage involves two processes: humification and mineralization (Kong *et al.,* 2023).

The humification stage, involving the polymerization of humus, takes the most time, during composting phases (Gao *et al.,* 2019). Consequently, it is essential to encourage resource recycling of organic waste by reducing the composting period and allowing composting to mature more rapidly in light of the growing volume of organic waste.

Prerequisite for composting of waste materials: Successful composting depends on maintaining optimal environmental and nutrient conditions. The carbon to nitrogen rate, or C/N ratio of feedstock, is a measure of nutrient balance, which is important to support microbial activity during composting. Since microorganisms require 30 parts of C for every unit N, a good C/N ratio must be between 25 and 35 for them to develop and function (Bernal *et al.,* 2009). When the ideal pH range for the feedstock is 5.5 to 8.0, it no longer influences the process to guarantee high microbial activity throughout the composting process. N losses are impacted by ammonia volatilization when the pH is higher than 7.5 (Bernal *et al.,* 2009; Miller and Melting, 1996). Aeration regulates temperature, eliminates CO_2 and moisture, and provides microorganisms with oxygen. O_2 content of 15-20% is ideal during composting (Miller and Melting, 1996). The feedstock and/or mixes typically require a moisture level of between

50% and 60% at the start of the composting process. High moisture content creates anaerobic conditions and reduces the O_2 transfer which aeration provides. The pace of decomposition is adversely affected when the moisture level drops. According to the US EPA (United State Environmental Protection Agency), in order to eradicate pathogens in an aerated static pile or during in-vessel composting, the temperature needs to be higher than 55 °C for three days. However, the microbial activity slows down if the temperature rises over 63 °C, which is the tolerance limit of many thermophilic microbes. For composting to produce superior compost products, choosing high-quality organic waste is essential. Using organic waste that has been source-separated and uncontaminated as the raw material is the first step in achieving this. This comprises rich and clean organic waste from urban solid waste collection systems, parks, gardens, and marketplaces.

Additives and bulking agents: The use of additives and bulking agents (BAs) has become increasingly important for optimizing compost quality and performance. BAs are essential for enhancing the C/N ratio, bulk density, and porosity, among other aspects of the composting process. Meanwhile, it has been demonstrated that a number of additives, such as chemical, microbial, and mineral types, improve nutrient retention, regulate pH, and affect the dynamics of microbial communities, all of which contribute to higher-quality compost. A variety of different BAs can be used to accelerate the composting process. Rice husk, paper, coffee grounds, tea waste, straw, bean dregs (Yang *et al.,* 2020), sawdust (Ding *et al.,* 2019), grain hull (Wang *et al.,* 2017), fly ash, minerals, and green waste (mowed grass, grass clippings, fallen leaves, tree trimming, branch cuts, and weeds) (Arrigoni *et al.,* 2018; Williams *et al.,* 2019) are some examples of these BA. The use of fly ash, such as biomass fly ash (Karnchanawong *et al.,* 2017; Karnchanawong and Najarut, 2014) and coal fly ash (Manyapu *et al.,* 2018; Muhammad *et al.,* 2024), has been extensively documented in the literature. Fly ash helps reshape and promote the growth of microbial communities (Muhammad *et al.,* 2024), neutralizes acidic soil, decreases the amount of exchangeable aluminium and hydrogen ions (Karnchanawong and Najarut, 2014), decreases the bio-availability of heavy metals (Manyapu *et al.,* 2018), and lowers lignin in compost more effectively than control (Karnchanawong *et al.,* 2017).

Additionally, natural zeolites and biochar have been drawing more attention as a mineral additive for composting, due to their distinct physicochemical properties (Chaher *et al.,* 2020). The application of biochar increases microbial activity, which hastens up the breakdown of even the more resistant lignocellulosic components of organic matter. When combining raw materials for composting that have weak physical qualities, this becomes even more crucial.

Compost quality: The maturity and stability indexes are essentially used to evaluate the quality of compost. Stability refers to a specific state of organic matter (OM) or stage or decomposition of compost, whereas maturity indicates the extent to which the composting process is finished. The "aging" and "curing," or after-maturation, of the compost, results in a better quality that may be used for a variety of purposes. Compost's stability index provides information on the condition of organic matter during the composting process. It explains a particular compost breakdown stage (Kranz *et al.,* 2020; Exaco USA, 2022). In essence, stability is a measure of the biological breakdown attained by composting feedstocks, and it is correlated with the compost's microbial activity (Bernal *et al.,* 2017; Samal *et al.,* 2022). The various stability and maturity indices are used to assess the quality of compost (Mahapatra *et al.,* 2022), including:

1) Temperature profile (fluctuations in temperature throughout the composting process),

2) Organic matter (degree of humification),
3) C/N ratio,
4) B_c/B_n ratio (ratio between microbial biomass C and N),
5) Dehydrogenase activity,
6) Microbial respiration and respiration indices,
7) Nitrifying activity, and
8) Biological test such as germination and phytotoxicity test.

Together, these indicators provide a comprehensive evaluation of compost's biological stability and agricultural suitability.

Composting and Soil Health

Maintaining soil health is vital in view of climate change because robust soil ecosystems are essential for sequestering carbon, which reduces greenhouse gas emissions and the effects of climate change. Compost enriches organic matter, increases microbial activity, provides essential nutrients, and improves physical characteristics of soil (Cao et al., 2023).

When applied to soils, compost enhances the bulk density and water-holding capacity of soil (Lee *et al.,* 2019). Applying an organic fertilizer (OF) improves the physicochemical characteristics of soil, such as its structure, water retention capacity, and microbial activity (Abdelilah *et al.,* 2019). These improvements support the long-term fertility and health of the soil, strengthening its resistance to erosion and degradation and safeguarding groundwater resources, which is a natural remedy for this issue (Azim *et al.,* 2017). This natural process makes compost a vital resource for sustainable land management as it protects soil from erosion and prevents water resources from being contaminated. Manure-based compost has been shown to improve soil structure, aeration, water-holding capacity, infiltration capacity, and porosity (Goldan *et al.,* 2023). The nutrient cycle is enhanced by this compost, which also gives plants a slow-release method to get nutrients when they require them (Moral *et al.,* 2009). Therefore, compost contributes to the preservation of healthy, balanced ecosystems by improving soil fertility and crop yield (Masmoudi *et al.,* 2020). Composting has shown several advantages, such as better crop nutrient availability, higher carbon sequestration (CS), improved soil fertility, and reduced salt stress (Pergola *et al.,* 2018; Sanad *et al.,* 2024). Compost showed potential as an effective soil additive for raising soil fertility and agricultural yield, even under difficult circumstances like those posed by calcareous soils. Compost enhances soil fertility by raising OM content, enriching exchangeable cations, and improving the availability of macro and micronutrients (Manirakiza and Seker, 2020). In calcareous soils, where high pH levels frequently lead to decreased nutrient availability and poorer crop output, its slow-release nutrient characteristic is advantageous in such conditions.

Additionally, composting has been investigated recently for the bioremediation of soils containing organic contaminants along with potential hazardous metals (Neher *et al.,* 2022). OW compost is also essential for reducing soil erosion and limiting pollutants from infiltrating into and leaching into groundwater. The study highlights how compost's higher water-holding capacity and high organic matter content greatly improve soil aggregate stability (Zgallai *et al.,* 2024). This is because the compost contains humus, a stable residue that forms from a high degree of organic matter decomposition, which binds to the soil and functions as the "glue" that holds the soil particles together (Epelde *et al.,* 2018). As a natural filter, these stabilized aggregates hold onto water and capture any contaminants, prevent them from leaching into groundwater (Huang *et al.,* 2016; El Moussaoui and Bouqbis, 2022). These organic practices show promise for long-term agricultural sustainability that is consistent with preserving the long-term health of the soil.

Conclusion

Composting is a simple yet effective technique to turn one of our most pressing environmental concerns into a source of renewal. What starts as discarded organic waste becomes a living resource that fertilizes the soil, nourishes crops, and restores ecological equilibrium. Composting through biological processes, turns waste into humus-rich material that improves soil structure, fertility, and microbial communities – all of which are essential for healthy ecosystems. Composting, in addition to decreasing waste, helps to build climate resilience by sequestering carbon and lowering greenhouse gas emissions. It contributes to the closure of the loop between consumption and regeneration, hence embodying circular economy concepts.

Finally, composting is an act of environmental care and responsibility, not just a waste management. By turning waste into soil wealth, we are investing in the health of our planet, food systems, and future generations.

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