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Review

Recent trends and advances in composting and vermicomposting technologies: A review

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HIGHLIGHTS

- Composting is a feasible and economic method for managing organic waste.
- Improved reactor types mitigate greenhouse gas emissions of composting.
- Novel supplements offer ample potential to improve composting.
- Process efficiency is improved by mathematical modelling.
- Policymaking and legal frameworks are directive for future technological advances.

GRAPHICAL ABSTRACT

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ABSTRACT

Composting technologies have come a long way, developing from static heaps and windrow composting to smart, artificial intelligence-assisted reactor composting. While in previous years, much attention has been paid to identifying ideal organic waste streams and suitable co-composting candidates, more recent efforts tried to determine novel process-enhancing supplements. These include various single and mixed microbial cultures, additives, bulking agents, or combinations thereof. However, there is still ample need to fine-tune the composting process in order to reduce its impact on the environment and streamline it with circular economy goals. In this review, we highlight recent advances in integrating mathematical modelling, novel supplements, and reactor designs with (vermi-) composting practices and provide an outlook for future developments. These results should serve as reference point to target adjusting screws for process improvement and provide a guideline for waste management officials and stakeholders.

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1. Introduction

Bio-waste is the most abundant contributor to the municipal solid waste stream particularly in low and middle-income countries (Kaza et al., 2018). For streams of biological wastes, circular economy has gained recognition in current scientific literature and among international and national authorities as a key strategic environmental policy framework (Awasthi et al., 2019, 2021a, 2022d; Jain et al., 2022). New technologies and innovative steps are required to establish recycling practices, including composting and vermicomposting in business and community sectors (Chen et al., 2018; Girón-Rojas et al., 2020; Awasthi et al., 2022). Linear economy mechanisms still prevail at global level and lead to vast amounts of bio-waste landfilled with significant GHGs emissions. In less developed regions, where waste management infrastructure is rudimentary, bio-waste is in many cases illegally dumped or burnt, thereby polluting local environment particularly in rural and smaller urban areas.

Home composting and application as animal feed were traditional pathways to divert bio-waste fraction from environment or dumpsites (Chen et al., 2020a; Mihai and Ingrao, 2018). Advanced waste management systems use source-separated collection of bio-waste from the population and agri-food industries and treat these wastes in composting, vermicomposting, or anaerobic digestion facilities producing natural fertilizers (compost) and biogas as renewable energy source (Yuvaraj et al., 2020; Ddiba et al., 2022). Wastewater treatment plants produced sludge that required further treatment in similar ways as municipal bio-waste in order to prevent landfilling and related environmental issues. Previous review studies revealed that vermicomposting employing *Eisenia fetida* earthworms has become a widespread practice to transform sludge into soil improvement fertilizer (Ghorbani and Sabour, 2021). For the first time, sludge composting using hyperthermophilic bacteria demonstrated to be a promising strategy to *in-situ* biodegradation of micro-plastic (Chen et al., 2020; Zhou et al., 2022). Co-composting with microbial inoculants to increase the quality of natural fertilizers has been practiced for a long time (Greff et al., 2022), thus, engineering highly effective microorganisms able to improve the composting process is a key research challenge for bio-waste management (Chen et al., 2020b; Xu et al., 2021) beside preparation of organic fertilizers (Zheng et al., 2020; Liu et al., 2022).

On this background, this work highlights the current progress of small-scale (household) and large-scale composting and vermicomposting technologies with their features and challenges. This paper reveals the role of refining the design, the operation, and the technological intricacies of composting and vermicomposting practices in bio-waste and sludge diversion from landfills, with the ultimate goal of supporting sustainable mechanisms to achieve a circular economy transition in bio-waste management. Key related sectors are further investigated such as: (i) modeling and optimization of composting technology; (ii) Role of additives, bulking agents, and microbes on composting; (iii) recovery of value-added products from compost; (iv) economic evaluation and business models of composting for a circular economy; and (v) opportunities of end-product applications. The experimental initiatives and knowledge gaps are outlined, revealing the future research prospects in the field of composting and vermicomposting with advanced technological support.

2. Innovations in design, operation and technology development

Technology development based on research and innovation activities is going to play a crucial role in improving the role of composting and vermicomposting practices during the transition to a circular economy and to obtain high-quality natural fertilizers for sustainable agricultural practices (Awasthi et al., 2022c). Patents related to compost technology often focus on novel composting devices, with China having the highest share of global patents (44%) as pointed out by Zheng et al. (2020) using the Derwent Innovations Index database. An LCA study revealed that reactor composting is a promising solution in terms of eco-efficiency when compared to other traditional technologies such as static heaps, windrow composting, and membrane-covered composting (Chen et al., 2020c; Liu et al., 2022).

Co-composting of various bio-waste streams to obtain high-quality fertilizers is a mainstream research practice. Mathematical models could enhance the initial mixture of bio-waste streams and optimal amounts for composting (Golbaz et al., 2021) and thereby help to accelerate the process (Sokac et al., 2021). By simulating and predicting the process outcome, mathematical models could become a key tool for optimizing process performance in terms of costs, efficiency, and environmental impact associated with the practice (Walling et al., 2020). However, co-composting could play an additional role as a bioremediation method of organic contaminants (Mihai et al., 2020). For example, Liu et al. (2022) demonstrated that co-composting of food waste (FW), sawdust and mature compost could be a feasible option in degradation of benzophenone and these findings could be applied for other organic contaminants. Energy recovery from heat generated during the composting process is a complementary approach. For example, intelligent control technology such as fuzzy control could enhance the heat recovery of composting technology (Chen et al., 2020d; Guo, 2021). Another study reveals that an energy recovery system attached to an aerated static composting pile has an energy capture ranging from 17,700 to 32, 940 kJ/h with a compost vapor temperature range of 51–66 °C (Sokač et al., 2022). Enhancing compost production with energy recovery systems will improve circularity levels of both small- and large-scale composting practices. Beside mathematical models, inoculation of compost with specific microorganisms is another approach to reduce the cycle time of composting. For example, inoculation of municipal bio-waste with *Aspergillus niger* leads to reduction of the composting process to 18 days (Heidarzadeh et al., 2021), while other microorganisms are used to compost more specific bio-waste streams such as herbal residues from Chinese medicine (Wang et al., 2021). To address the problem of lipid-rich FW streams, a nitrogen-retaining and decomposition-promoting microbial agent (NRDPMA) is used to decompose refractory components, thereby enabling the decomposition of a diverse range of FW components (Wang et al., 2022). Biochar addition improves the compost operation parameters and reduces ecological risks (Awasthi et al., 2022a, 2022b; Zhou et al., 2022). Distiller grains is another option to catalyze the degradation of organic matter and to activate microorganisms that accelerate compost maturation (Ren et al., 2021). However, process automatization seems to have particular benefits for FW composting. An automated thermophilic composting technology applied for FW from the retail sector shows good performances in eliminating pathogens and reducing mass (88 %) while processing 2,235 kg of fruits in a 14 days-time frame (Nenciu et al., 2022). Simulation models combined with experimental data showed that the rate of air flow and the mass fraction of the substrate are key parameters to reduce the composting timeframe and improve the process (Sokac et al., 2021). Bio-filters could be used to remove ammonia and volatile organic compounds from composting of livestock waste and carcasses (Shang et al., 2020; Khoshnevisan et al., 2021). Artificial intelligence used in future composting modeling could scale up the optimization process by adjusting a wide range of parameters (Walling et al., 2020; Awasthi et al., 2021a).

2.1. Technological development of small-scale composting

Reuse of municipal and agricultural wastes in vermicomposting and composting practices to produce valuable natural fertilizers that support organic agriculture could act as a pathway for sustainable rural development. Especially new tools, bio-waste mixtures, and economically feasible technologies could improve the composting process for family farmers (Perreira et al., 2020). The takakura composting method accelerated by bio-activators (cow rumen, orgadec, stardec, and rice mole) is suitable for households and small businesses (Dewilda et al., 2021). Home composting plays a key role in rural regions in diverting bio-waste from dumpsites or open burning practices (Mihai and Ingrao, 2018; Awasthi et al., 2021b). However, the quality of natural fertilizers obtained from home composting and the emissions occurring during the process need to be improved. Combining four bio-waste mixture (rice straw, FW, swine manure, and human feces) using a simplex centroid design to facilitate the composting process shows possible solutions for managing various rural waste streams in China and beyond (Guo, 2021). Different geometric models of composting bins were analyzed in relation to composting performances using similar bio-mixtures and -proportions. The results showed that the hexagonal-prism and the cube-shaped bin have greater usability compared to the parallelepiped one despite having the same capacity (3 L) according to Dazzi et al. (2021). Another study proposes rapid-in house composters using a fixed mixture of FW and brown waste with fly ash addition (Mandpe et al., 2021).

On the other side, community participation in designing functional composting bins could be regarded as a complementary approach to increase responsibility and environmental awareness among residents concerning bio-waste management and composting challenges (Lunag et al., 2021). Better design of a composting-type toilet could be a response to local sanitation issues, but this option is suitable only for certain areas categorize as “green zone” where composting processes are prone to be successful (Lopez -Zavala, 2019; Awasthi et al., 2020). A holistic approach of on-site composting is required to speed up circular economy transitions. For example, excessive heat energy generated in on-site composting at household level (thermophilic phase) could be captured and used to heat a greenhouse in autumn season. Neugebauer et al. (2021) used artificial neural networks to predict the temperature inside the greenhouse to show that the composting process not only reduces bio-waste but also provides an opportunity for heat recovery, in line with circular economy goals. In fact, future research on small-scale composting practices should promote such integrative approaches.

2.2. Development of large-scale composting and vermicomposting

Large scale composting facilities often serve urban agglomerations where large amounts of bio-waste are produced by its inhabitants, tourists, and agri-food businesses. Good process performance of composting also relies on the feedstock’s quality, making it crucial to ensure clean source-separation of bio-waste in urban areas. Pre-treatment of FW such as using a decentralized bioreactor to reduce the volume and mass could be a reliable alternative for large urban areas to further supply centralized composting plants without the burden of increasing capacity (Sakarika, et al., 2019). On the other hand, black soldier fly larvae (*Hermetia illucens*) are used to faster biodegrade the food waste (Klammsteiner et al., 2021). The resulting frass could be directly applied to agricultural land or further treat through composting or vermicomposting process (Awasthi et al., 2020f; Lopes et al., 2022; Klammsteiner et al., 2020). Household-scale rearing units employing insect larvae for kitchen waste conversion that are able to generate larval biomass and frass have been tested in past (Awasthi et al., 2020g, 2020h; Walter et al., 2020). Improvement of sewage sludge composting derived from large municipal and industrial wastewater treatment plants is another key research to be further investigated. Modified pine wood as bulking agent has promising results on this bio-waste flow (Liu et al., 2021a).

In case of large composting facilities, the proper design of natural ventilating systems will improve and speed up the composting process. Inclined roof systems seem to provide the most benefits in terms of air flow and heat discharge compared to other designs such as hanging roof, wall vents, or chimney pipe (Tham et al., 2022). A large-scale study involving data from 28 composting systems fed from commercial pig farms showed that reactor composting had the best results in terms of material degradation, nitrogen loss, antibiotics, and antibiotic resistance genes compared to conventional methods such static heap and windrow systems (Awasthi et al., 2019c, 2019d; Liu et al., 2020b). This is in line with other studies where reactor technology (reactor drum) is found to be most sustainable compared with other enclosed (e.g. agitated bays/channels, and in-vessel tunnels) and open technologies (e.g. turned windrow, and aerated static pile) taking into account technical, environmental, economic, and social criteria (Makan and Fadili, 2020). Reactor technologies require larger investments in the first stage compared to open technologies, but in the long term these reactors are cost-efficient and offer significant environmental benefits.

The relation between composting or vermicomposting and bioenergy should be further investigated in line with circular economy principles. For example, Chaher et al. (2020) revealed that the food waste digestate from an anaerobic reactor could be used as moisturizing agent for in-vessel composting. On the other side, the in-vessel vermicomposting technologies are suitable for colder regions when taking into account additional measures such as insulation techniques, additives, and substrate pre-treatment (Kumari et al., 2022). One of the key problems related to large-scale vermicomposting technologies is that the extraction of earthworms is often performed manually. Manual extraction is labor- and time-intensive and linked to low efficiency. On this regard, Walling et al. (2020) propose a new technology where earthworms can be separated via centrifugation with a worm recovery rate of approximately 84%. To enhance the stabilization process of dewatered sewage sludge, a mixed approach such as vermicomposting (10 days) with room drying (10 days) is proposed to achieve a good maturity (Huang et al., 2022). Vermicomposting reactor is another route of technological development to enhance the operating parameters and to speed up the biodegradation process (Ramprasad and Alekhya, 2021). A smart vermicompost reactor was proposed where it took 50% less time to generate compost with a simultaneous 30% increase of worm growth rate compared to a conventional container (Ghorbani and Sabour, 2021). Therefore, research studies related to reactor technologies on both composting and vermicomposting shows to produce faster and qualitative fertilizers in a more sustainable way. As future options, thermal cameras could replace temperature sensors and water supply could be regulated by a microcontroller using machine learning in large scale vermicompost facilities (Solanki and Mahore, 2021). Urban farming is expected to be further developed in the coming years and vermicomposting is already examined as reliable technology to provide high-quality fertilizers for growing lettuce (Schröder et al., 2021).

The subsections (2.1. and 2.2) reveal the current trends in composting bin designs and optimization of the composting process (microbial inoculants, co-composting of various bio-waste streams, bulking agents). They also point out the benefits and perspectives of advanced technologies (reactor composting/vermicomposting) over conventional open air options for both small- and large-scale composting practices. New research is expected in developing mathematical models and sensors to optimize a wide range of composting/vermicomposting parameters including artificial intelligence.

3. Modeling and optimization of composting technology

Similar to other engineering disciplines, numerous mathematical models for composting have been developed during the past few decades to advance the systemic understanding of the composting process and to optimize composting procedures at different scales (Onwosi et al., 2017; Walling et al., 2020). Compared with laboratory and pilot-scale investigations, the application of modelling can dramatically reduce the cost and provide timely solutions when exploring new composting practices (Kabak et al., 2022). Composting models can be classified as 1) mechanism-derived models and 2) empirical-based models (Table 1). Mechanism-derived models are ideal for revealing the mechanisms governing organic decomposition and mineralization during composting. By comparison, mechanism-derived models generally have more comprehensive applications than empirical driven models. First-order kinetics and the Monod type kinetics are typical mechanism-derived models utilized to simulate substrate degradation during composting (Wang et al., 2018; Walling et al., 2020). The first-order kinetics believed that the organic matter degradation during composting is enzyme-mediated while the reaction rates were determined by the concentration of the substrate (Wang et al., 2016).

Furthermore, different limiting variables, such as ambient temperature, moisture content, and oxygen concentration were generally utilized to adjust the models for higher accuracy (Walling et al., 2021). In contrast, Monod type kinetic models describe substrate degradation as a function of substrate, oxygen, depth of composting, moisture, and airflow rate, and is governed by microbial activities (Ajmal et al., 2020). Although, the accuracy of Monod models was higher than first-order-kinetics, the application of Monod kinetics was restricted for the excessive stimulation parameter required. So far, both models have been successfully utilized to simulate organic solid mineralization, oxygen uptake, heat transfer, nitrogen dynamic and carbon dioxide emission (Fig. 1). By categorizing the substrate into different species (e.g. readily, moderately, and slowly hydrolysable solid carbon), based on the accessibility of organic substance in the compost, the accuracy of models can be dramatically improved (Komilis, 2006). In addition, the mechanisms-derived models are developing with the growing understanding of composting process from physicochemical and biological aspects.

Empirically driven models are usually based on experimental data and specifically developed to establish the correlations between parameters or variables and composting quality/process indices (Yang et al., 2021). They can be linear, nonlinear, polynomial, exponential, and statistical in forms and specifically developed to establish the correlations among several composting parameters and results, such as the correlations between organic matter degradation and pile temperature or the content and species of elements through composting (Hosseinzadeh et al., 2020). Other examples are correlations between oxygen consumption rate or the moisture content and pile temperature or organic matter degradation and microbial activities (Varma et al., 2017). These models were generally developed for specific feedstock and composting techniques and thus usually demonstrated high accuracy, although their utilization was restricted. Due to the complexity of the composting system it is challenging to establish an empirical model (Sokac et al., 2022). Recently, the fast development of data analysis methods and techniques, such as neural networks, decision trees, and regression analyses greatly facilitated the development of composting modelling. By employing an original neural model, Boniecki et al. (2012) successfully developed a model that can precisely predict the ammonia emission from sewage sludge composting. Bibuecki et al. (2013) also found that neural modelling can effectively simulate the heat balance in the pig manure (PM) composting process. Among them, statistical-based models like Response Surface Methodology (RSM) and machine learning models like Artificial Neural Networks (ANNs) are the most frequently utilized data optimization and verification techniques. Sharma et al. (2021) found models developed with RSM and ANNs both high accuracy for the maturity parameters for vermicomposting with R^2 near 1. However, models simulated by ANNs generally achieve higher reliability and validity than RSM models (Sharma et al., 2021). For example, Kabak et al. (2022) found that a hybrid cascade forward neural network prediction model (H-CFNN-PM) had a much lower mean absolute percentage error (1–2% on all data points) compared to Response

Table 1

Utilization of mathematical models for composting process prediction and optimization.

Composting methods	Scale	Substrate	Model	Model type	Factors Optimized	Input data	Findings	Reference
In-vessel reactor	Pilot scale	Poultry waste and food waste	Hybrid cascaded prediction model	Empirical model	Nitrogen loss	Duration, Moisture content, EC, Temperature, pH, C/N, Poultry and food waste ratio (PRW) and PWR × duration, PWR × MC, PWR × C/N, duration × MC, and EC × C/N	The optimal values were found as PWR of 17% and a duration of 98 days	(Kabak et al., 2022)
Windrow composting piles/ cylindrical reactors	Pilot/ lab scale	Oily sludge	Neuro-evaluative methodology based on artificial neural networks (ANNs) and differential evolution (DE)	Empirical model	Petroleum hydrocarbon (TPH) and organic carbon (OC) degradation	Duration, initial petroleum content		(Dragoi et al., 2021)
Multiple composting system	Pilot/ lab scale	Multiple feedstocks	Modified first-order kinetic model	Mechanisms-derived models	Mass loss	Degradation rate, ratio between the duration of mesophilic and thermophilic phases	Data is not required, while an accurate mass loss can be obtained. Dividing composting into three separate phase elevated the accuracy of the model.	(Walling et al., 2021)
Compost reactor	Lab scale	Pig manure	Coupling mass-heat-momentum transfer mode	Mechanisms-derived models	Dynamic changes and spatial distribution of temperature and oxygen concentration in compost pile	Degradable organic matter, microbial concentration, Temperature, oxygen concentration	The coupled transfer model combined with the microbial mechanism of aerobic composting may offer a more accurate simulation of the aerobic composting process.	(He et al., 2018)
Compost reactor	Pilot-scale	Olive mill waste	Monod kinetics model, first-order kinetics model, mass and energy balance model	Mechanisms-derived models	Evolution of temperature, organic matter, volume and nutrients	Particulate components, soluble substrates, gas components, moisture content, temperature, biomass, volume of compost	Model can be used for predicting a wider variety of compost mixtures	(Muhammad et al., 2021)

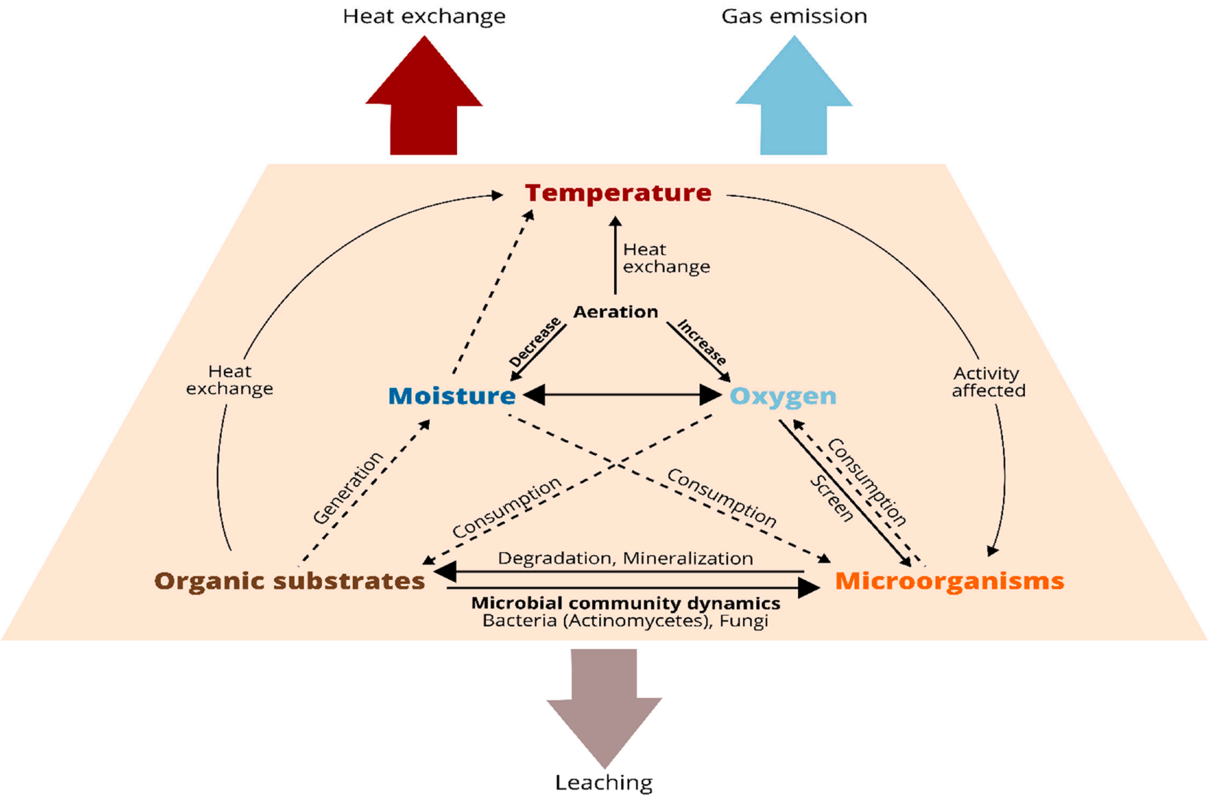
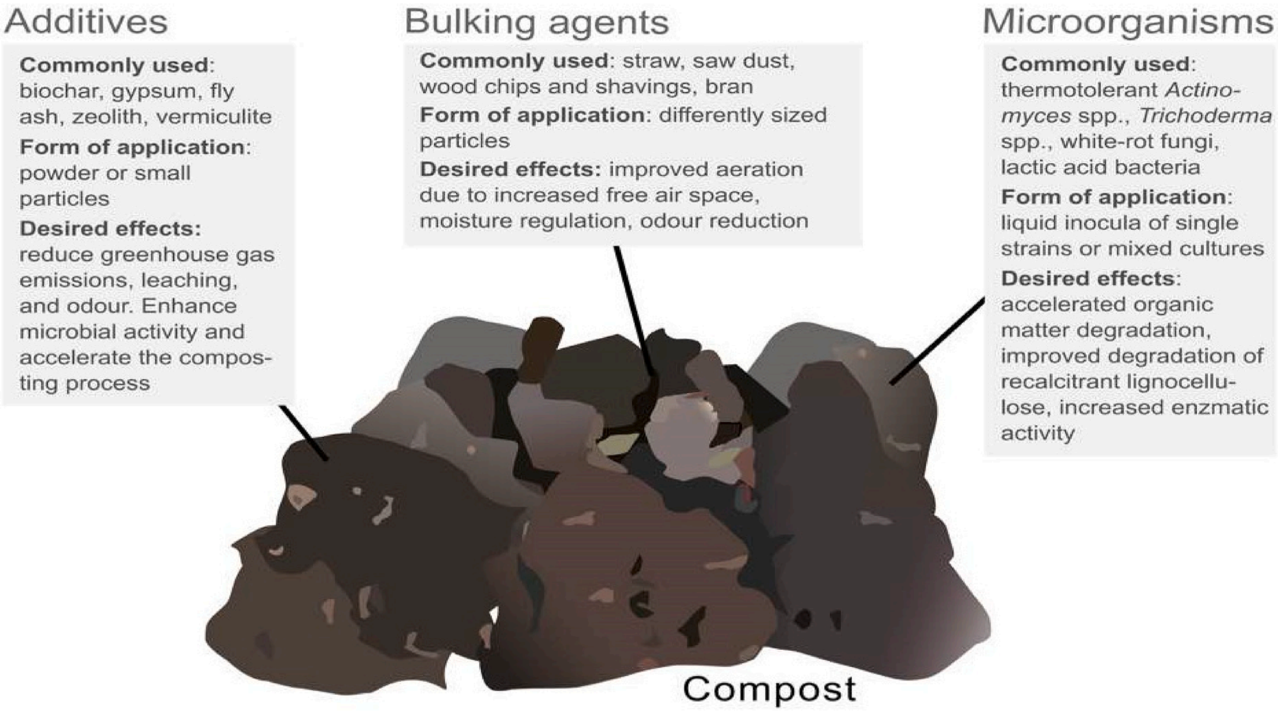


Fig. 1. Interaction of main variables during composting and modelling.

Surface Methodology (RSM, ~15% on all data points) when simulating the nitrogen losses based on a laboratory co-composting of pig manure (PM) and food waste.

4. Role of additives, bulking agents, and microbes on composting

To start the composting process, four main components are generally required: organic matter, moisture, oxygen, and microorganisms. The starting material is defined by its physicochemical and microbiological


Additives

Commonly used: biochar, gypsum, fly ash, zeolith, vermiculite

Form of application: powder or small particles

Desired effects: reduce greenhouse gas emissions, leaching, and odour. Enhance microbial activity and accelerate the composting process

Bulking agents

Commonly used: straw, saw dust, wood chips and shavings, bran

Form of application: differently sized particles

Desired effects: improved aeration due to increased free air space, moisture regulation, odour reduction

Microorganisms

Commonly used: thermotolerant *Actinomyces* spp., *Trichoderma* spp., white-rot fungi, lactic acid bacteria

Form of application: liquid inocula of single strains or mixed cultures

Desired effects: accelerated organic matter degradation, improved degradation of recalcitrant lignocellulose, increased enzmatic activity

Fig. 2. Role of additives and microbes for composting purposes.

features, which in turn determine the course of the composting process (Fig. 2). However, an extensive variety of supplements can be applied to enhance the composting process by improving temperature and pH profiles, carbon and nitrogen content and ratio, cellulase and dehydrogenase activity, mineral nutrient availability, and bulk density of the compost (Barthod et al., 2018). Commercial supplements for composting are often branded as composting “accelerators”, “activators”, or “starters”, however, they strongly diverge in their composition and typically consist of a mixture of additives, bulking agents, and microorganisms (Table 2).

4.1. Additives

Additives are often added to improve the composting process by reducing leaching, greenhouse gas emissions, and odor while at the same time enhancing microbial activity and, thus, composting speed (Awasthi et al., 2020b). The application of such additives may not only influence key parameters of the process, but also increase the agronomic value of the end product (Barthod et al., 2018). Biochar, ashes, zeolites, or vermiculite find frequent use as additives. Biochar is a porous carbon rich material generated by the pyrolysis of organic matter at temperatures between 400 and 600 °C or even higher in case of fast pyrolysis (Manyà et al., 2018; Awasthi et al., 2020d; Zhou et al., 2021b). Its large surface area, water holding and cation exchange capacity is capable of positively influencing soil nutrient dynamics and microbial activity (Chung et al., 2021). A recent *meta*-analysis of 876 samples from 84 studies found that the addition of 10–15% biochar from straw is ideal to improve physicochemical features of the mature compost. This includes increased pH, higher seed germination, favorable nitrogen retention (both total and nitrate nitrogen) while at the same time reducing the bioavailability of heavy metals (Awasthi et al., 2020e; Zhou et al., 2021a; Zhou et al., 2022). Organic additives that boost microbial metabolism and growth by serving as readily available carbon source (e.g., jaggery and polyethylene glycol) tend to induce a faster and higher rise in temperature, while mineral additives such as gypsum and lime do not immediately affect temperature profiles. However, small concentrations of lime (1% on dry matter basis) in combination with 30% Zeolite may have beneficial effects on the composting process by reducing greenhouse gas emission and preventing loss of ammonia (Awasthi et al., 2016). Additives with high water holding capacities such as fly ash may even inhibit high temperatures in cases of high dosing by inhibiting enzymatic activity (Mandpe et al., 2019). Yet, He et al. (2018) found that adding 10% of vermiculite, a non-toxic, water-binding clay mineral, can prolong the thermophilic phase by 2–4 days and reduce

Table 2
The effect of frequently used additives, bulking agents, and microbes on compost. dwb = on dry weight basis.

	Material	Composting material	Optimum concentration	Observed effect	References
Additives	Biochar	Various organic wastes	10–15% (w/w)	Increased pH, germination index, nitrate and total nitrogen content; decreased heavy metal bioavailability	(Zhou et al., 2022)
		Manure	10% (w/w)	Increased temperatures during thermophilic stage, reduction of gaseous emissions, inhibition of potential pathogens	(Chung et al., 2021)
	Zeolite	Sewage sludge	30% (dwb) (+1% lime)	Reduced greenhouse gas emissions and loss of ammonia, improved compost maturity	(Awasthi et al., 2016)
	Vermiculite	Synthetic food waste	10% (w/w)		(He et al., 2018)
Bulking agents	Rice husks	Manure	20% (	Safe compost supplement that increases thermophilic temperatures and yields higher quality compost in terms of pH, C/N ratio, and particle size distribution	(Duan et al., 2021)
	Sawdust	Food waste	1:2.6 ratio (w/w)	Reduced ammonium-nitrogen, higher germination index, addition of mature compost further increased the beneficial effects	(Song et al., 2021)
		Vegetable waste with cow dung inoculant	10%	Increased water absorption capacity, composting rate, and germination index; stable progression in humic acid formation and less leaching	(Rich et al., 2018)
	Wood chips	Sewage sludge	1.05 kg in 7 kg waste	Lower methane emissions than other bulking agents due to high total and aeration porosity	(Wang et al., 2022)
	Wheat straw	Food waste	19–22% (w/w)	High water absorption capacity, neutral pH and suitable carbon/nitrogen ratio for food waste composting	(Adhikari et al., 2008)
Microorganisms	Actinomycetes mixed culture (*Streptomyces* sp. H1, *Streptomyces* sp. G1, *Streptomyces* sp. G2, *Actinobacteria* bacterium T9)	Manure	2% (dwb) (10^9 CFU ml^{-1})	Increased cellulase activity, accelerated degradation of cellulose, and changed the structure of actinomyceties community	(Zhao et al., 2017)
	Actinomycetes mixed culture (*Streptomyces* sp. H1, *Mycobacterium* sp. G1, *Micromonospora* sp. G7, *Saccharomonospora* sp. T9)	Various straws (wheat, corn, rice, soybean) co-composted with cabbage residues	3 ml kg^{-1} (10^9 CFU ml^{-1})	Increased degradation of cellulose, hemicellulose, and lignin; further adding urea enhanced the activity of key enzymes involved in lignocellulose degradation	(Wei et al., 2019)
	Consortium of thermophilic fungi (*Trichoderma viridae, Aspergillus niger, Aspergillus flavus*)	Municipal solid waste	6.8×10^6, 4.5×10^4, and 4.5×10^4 spores ml^{-1}, respectively in 14 kg waste	Increased carbon and nitrogen mineralization, faster compost maturation, elimination of phytotoxicity factors	(Awasthi et al., 2014)
	Thermotolerant ammonia-oxidizing bacteria (especially MT-AOB-2–4)	Manure	5% (v/v) (1×10^8 CFU ml^{-1})	Promotion of total and dissolved organic carbon conversion, increased bioavailable phosphorus, potassium, and humification	(Xu et al., 2022)

nitrogen loss during the composting of food wastes. Vermiculite already finds wide application in agriculture as it is known for its absorption and swelling properties as well as its ion binding capacity helpful for nitrogen conservation (Awasthi et al., 2018).

4.2. Bulking agents

The surface area resulting from the shape and size of the raw material's particles is a decisive factor for water and air flow and, thus, also affects microbiological activity (aerobic, micro-aerobic, and anaerobic) as well as temperature dynamics (Awasthi et al., 2020a; Duan et al., 2021). Bulking agents are materials that are added to the compost to alter its physical structure including water absorption capacity, air space and flow between particles, and carbon/nitrogen ratio. Thus, dry fibrous and carbon-rich materials (e.g. lignocellulose) are used to improve free air space, C/N ratio and pH, and regulate moisture holding properties of compost (Sardá et al., 2019). Resources such as sawdust, wood chips, straw, or bran find frequent application as bulking agents. The capacity of the composting mixture to absorb water and increase porosity is a key physical parameter that drives composting rate due to enhanced microbial activity (Wang et al., 2021). Although, most bulking agents serve a similar purpose, not all help to generate a safe compost that supports germination. Sawdust was found to be an excellent regulator of free air space and moisture content, with greater capacity to reduce leaching than other comparable bulking agents (Rich et al., 2018).

Among organic bulking agents, wood chips were found to have high total and especially aeration porosity, while wheat straw tends to have higher water-holding porosity. This is critical, as higher water-holding capacities seem to have a elevating effect on ammonia and methane emissions most likely due to the creation of anaerobic niches (Wang et al., 2022). Adhikari et al. (2008) however, emphasized that wood shavings could be problematic when used for food waste composting, as they have a relatively low pH and could induce fermentation problems. Wheat straw, with its neutral pH and moderately high carbon/nitrogen ratio as well as good water absorption capacity, was suggested as more appropriate bulking agent alternative especially when dealing with food wastes.

4.3. Microbes

Tolerance to high temperatures is an important criterion for microorganisms that are meant to stay active throughout the composting process as peak temperatures during the thermophilic phase can reach up to 70 °C. Inoculation with thermo-tolerant *Actinomycetes* strains including *Streptomyces* sp. H1, *Mycobacterium* sp. G1, *Micromonospora* sp. G7, and *Saccharomonospora* sp. T9 has shown promising effects on enhancing the degradation of recalcitrant lignocellulose (Wei et al., 2019; Muhammad et al., 2021). By applying this mixture of cultures, the activity of CMCase, xylanase, manganese peroxidase, lignin peroxidase, and laccase responsible for the various steps in lignocellulose degradation was increased. Zhao et al. (2017) similarly applied a mixed culture of thermotolerant *Actinomycetes* with high cellulase activity (*Streptomyces* sp. H1, *Streptomyces* sp. G1, *Streptomyces* sp. G2, and *Actinobacteria* bacterium T9) and pointed out an increased concentration of humic substances and greater cellulolytic dynamics. More recently, the supplementation of newly isolated thermo-tolerant ammonia oxidizing bacteria (AOBs) was found to improve the humification process in composted cattle manure. Along with humification factors, the abundance of *Bacillaceae* increased significantly (Xu et al., 2022). AOBs are important players in the conversion of ammonia nitrogen-containing compounds and the preservation of nitrogen for humus formation. Alternatively, the supplementation of thermotolerant fungi may offer a low-cost approach to improve both the compost process and quality. Inoculating municipal solid waste with a fungal consortium consisting of *Trichoderma viridae*, *Aspergillus niger*, and *Aspergillus flavus* exhibited increased carbon and nitrogen mineralization and accelerated compost maturation as was shown by Awasthi et al. (2014).

5. Principles of sustainable composting and recovery of value-added products from compost

5.1. Principles of sustainable composting

Composting has been favored as an important alternative for the treatment of organic waste (Yang et al., 2020; Liu et al., 2021a). It plays an important role in material recycling and resource recovery actions that promote sustainable development. However, a certain amount of ammonia NH_3 and greenhouse gases (CO_2, CH_4, and N_2O, etc.) are inevitably produced during composting (Liu et al., 2020a). The emission of these gases will not only cause environmental pollution, but also cause the loss of nutrients and energy (Wu et al., 2019). In addition, compost products are not popular with farmers. The publicity and promotion of organic fertilizer need to be further strengthened (Ayilara et al., 2020). Therefore, sustainable composting requires to improve composting efficiency and quality, control by-product gas emissions and losses, and enhanced compost production management and application promotion (Fig. 3a).

5.1.1. The efficiency and quality of composting need to be improved

Improving the efficiency and quality of composting is the primary issue for sustainable composting. Although composting has many advantages in the treatment of organic waste, there are still many problems and challenges associated with both conventional composting and vermicomposting (Ayilara et al., 2020). Conventional composting is slow, potentially contains heat-tolerant pathogens, and poor nutrient content; Vermicomposting has problems with phytotoxic substances and low decay quality as well, and the high salinity of vermicompost limits organic fertilizer quality (Ayilara et al., 2020; Lim et al., 2015; Singh and Singh, 2017). Composting is a dynamic and complex decomposition process in which microbial life activities and enzymatic activities play a major role (Xie et al., 2021; Wang et al., 2022). Unsuitable composting environments and material compositions are the key factors limiting the activity of microorganisms, enzymes, and earthworms in case of vermicomposting as well as the quality of final products. Therefore, efficient and high-quality composting requires to appropriately regulate the composting environment and material composition.

As has been summarized by a large number of studies, temperature, water content, and aeration rate are the main environmental constraint factors for efficient and high-quality composting. Especially the initial C/N ratio is a key factor in determining the final quality of compost, whereby C/N ratio in the range of 25–30 generated the best results (Wang et al., 2022). By adjusting the material and C/N ratio, adding additives, swelling agents, and microbial agents, compost efficiency and quality can be improved (Wang et al., 2022). Additives and swelling agents are beneficial for improving the environmental parameters of composting (temperature, water content, and aeration rate). Microbial agents can accelerate the decomposition of organic matter. Appropriate compost mixtures can provide abundant nutrients and enrich microbial communities (Verrillo et al., 2021; Wang et al., 2020; Jia et al., 2021). In addition, the combination of earthworms and microorganisms can obtain efficient and high-quality composting. By adjusting physico-chemical parameters of compost and the fertilizing ratio, the negative effect of high salinity from vermicomposting can be solved (Lim et al., 2015).

5.1.2. Emissions and losses of by-product gases need to be controlled

The degradation of organic matter is a complex process that generates unpleasant gases that affect the surrounding environment during composting and vermicomposting. Not only NH_3, volatile organic compounds (VOCs), hydrogen sulfide (H_2S), etc. are released by these processes, but also some greenhouse gases (CO_2, CH_4 and N_2O) are also produced during the microbiological decomposition of organic

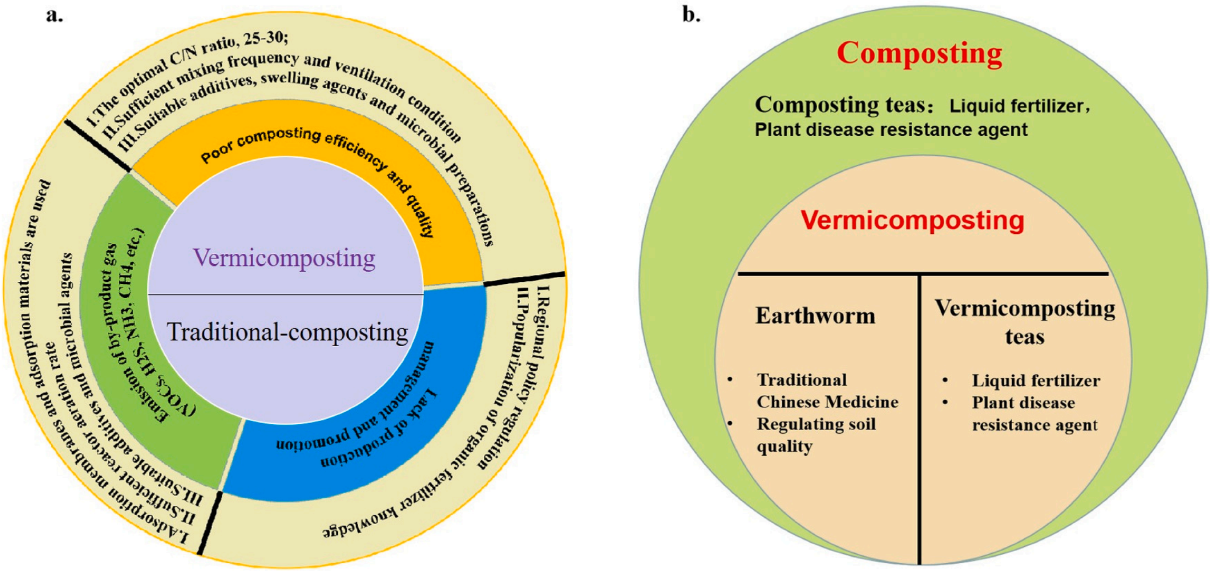


Fig. 3. Principles of sustainable composting (a); the inner ring shows the existing problems of composting and vermicomposting, and the solutions to those problems are described in the outer ring. Value-added products recovered from compost and (b); The inner and outer circle respectively introduces the value-added products extracted from vermicomposting and composting.

compounds (Andraskar et al., 2021). The management of CO_2 and VOCs is usually achieved by means of adsorption, such as covering the compost with adsorption membranes or adding adsorbents (Andraskar et al., 2021). NH_3 can be controlled by using struvite as buffer medium, fixing phosphorus and reducing nitrogen loss at the same time (Wu et al., 2019; Li et al., 2020; Awasthi et al., 2020c). H_2S and CH_4 are generated under anaerobic conditions during composting. Therefore, the aeration rate needs to be increased by adding bulking agents or increasing the aeration rate of the compost (Cayuela et al., 2015; Yuan et al., 2019; Awasthi et al., 2019a). A low C/N ratio in the compost substrate favor the emission of N_2O, CO_2, and CH_4, thus, selecting appropriate compost mixture is crucial (Awasthi et al., 2019b; Ren et al., 2021). In conclusion, gas emission problems occurring as by-products of composting processes can be effective solved by optimizing composting process parameters using additives or microbial agents, and pre-treating the compost substrate (Andraskar et al., 2021; Qiu et al., 2016).

5.1.3. *Compost production management and application promotion need to be strengthened*

Sustainable composting has several problems in management and promotion, besides low composting efficiency and quality and by-product gas emissions. Compost standards and compost quality indicators are still vague and do not support the establishment of a reliable composting industry chain (Liu et al., 2021b). Therefore, composting still needs improved management as well as strict and clear commercial organic fertilizer standards (Fan et al., 2016). In addition, compost production needs to overcome the problem of long-distance transportation, while the establishment of decentralized composting plants increases the risk of environmental pollution and is ultimately not conducive for the development of sustainable composting. Therefore, composting plants need to be set up and operated in alignment with regional characteristics. This could alleviate the pressure of organic waste treatment and organic fertilizer sales at the same time, and reduce the cost of collecting waste and transporting organic fertilizer (Fan et al., 2016; Singh and Singh, 2017). Finally, it is necessary to promote the advantage of organic fertilizer to local farmers. Organic fertilizer is a slow-release fertilizer, which can effectively improve the quality of farmland and cultivated land, improve crop quality, and avoid the risk of soil degradation caused by perennial application of chemical fertilizer (Gai et al., 2018; Wang, 2021; Ayilara et al., 2020; Fan et al., 2016).

5.2. *Recovery of value-added products from compost*

During composting, humus and other substances beneficial to plants and soil gradually increase, toxic substances and harmful pathogens gradually decrease. Therefore, composting cannot only produce organic fertilizer, but also recover other added-value products such as compost extracts (Ma et al., 2021; Zouari et al., 2020) (Fig. 3b). Currently, the use of compost extracts, often referred to as compost tea (CT), is gradually being unraveled and their development is moving towards liquid fertilizers and replacing chemical pesticides. CT is the aqueous solution extracted after soaking the compost in water and either fermenting for several days (Verrillo et al., 2021). The extracted residue can be directly applied to the soil. CT is rich in soluble nutrients and a large number of microorganisms that contribute to fertilizer efficiency and improve soil quality. In addition, both aerated and non-aerated CT have good ability to inhibit plant pathogenic microorganisms and have the potential to replace chemical pesticides (Verrillo et al., 2021; Zouari et al., 2020). CT contains high microbial diversity as a result of the composting process and with the soaking fermentation further increasing the proportion of beneficial microorganisms. These beneficial microorganisms might be the key for CT to inhibit plant diseases (Din et al., 2018). During vermicomposting, the earthworm's ability to secrete enzymes and to mechanically mix the compost with their movement are combined with microbial fermentation to produce composting products (Table 3). After the compost is mature, earthworms can be introduced into the soil to improve its quality by enhancing soil porosity, promoting the formation of soil aggregates, and improving the transformation of soil nutrients (Yuvaraj et al., 2021). Earthworms can also be turned into products including medicinal substances or fishing bait. In addition, vermicomposting tea can also be used as liquid fertilizer and plant disease resistance agent (Yatoo et al., 2021; Singh et al., 2017; Lim et al., 2015; Agapit et al., 2018; Ghorbani and Sabour, 2021).

6. Economic evaluation and business models of composting for a circular economy

The circular economy focuses on the recycling and reuse of materials and waste, reducing the loss of resources (Stahel, 2016). Engaging in composting to deal with organic matter is a win–win option that not only deals with the pollution of organic waste, but also recovers the nutrients

Table 3
Existing compost business models and their advantages.

Composting modes	Business model	Advantages	Reference
Distillery waste + urban waste	Compost as a by-product of wine industry, at the same time, urban wastes can be treated.	1. Complementary advantages of materials; 2. Reducing the distillery's cost on wastes disposal.	(Hungria et al., 2017)
Livestock manure and crop straw	Based on regional characteristics, integrating livestock and poultry industry, organic fertilizer manufacturers and farms	1. The raw materials are within the same region; 2. Reducing the cost of farms and livestock farms on wastes disposal; 3. Reducing selling pressure of organic fertilizer manufacturers.	(Zhang et al., 2021)
Food waste + other wastes	Compost as a by-product of catering industry, at the same time, other wastes can be treated.	1. Reducing the cost of catering industry on wastes disposal; 2. Food wastes and other wastes can be treated jointly.	(Wang et al., 2016)
Biogas residue + other wastes	Anaerobic digestion and compost are combined to treat organic wastes	1. The resource utilization efficiency of organic waste is higher; 2. The problem of biogas fermentation residue can be solved.	(Ren et al., 2021)
Municipal Sludge + other wastes	Compost as a by-industry of sewage treatment plant, other wastes can be treated.	1. Reducing the cost of sewage treatment plant on sludge disposal; 2. The heavy metal pollution in sludge can be avoided.	(Tang et al., 2019)

necessary for plants and enables resource utilization. Taking an important place in the circular economy (Ayilara et al., 2020; Bekchanov and Mirzabaev, 2018).

6.1. Economic evaluation and business models of composting

Although using composting as means to deal with organic waste achieves relatively good results, there are still some challenges in its commercial production, such as high transportation costs, difficult collection, and high sales pressure. The operators of organic fertilizer production plants need the promotion and support of policies (Ayilara et al., 2020; Ye et al., 2020; Girotto et al., 2015). Under the guidance of circular economy and sustainable development, the current business model of composting should focus on two directions (Table 1 shows the existing models). First, composting can be used as the end treatment for other industries, and the residual materials or waste from other industries can be resourcefully utilized to realize "waste treatment - organic fertilizer production". For example, composting can centralize the treatment of food waste pollution and solve the problem of obtaining organic fertilizer raw materials (Cerda et al., 2017). Secondly, the value of composting is considered in the context of regional characteristics to realize "waste treatment - composting production - organic fertilizer application". Organic fertilizer producers and local farms are combined under the support of the local government, resulting in a comprehensive plan for balancing farming activities and livestock breeding. The problem of livestock and poultry manure treatment, the pressure of raw materials and sales from organic fertilizer plants, and fertilizer demand on local farms are simultaneously solved. Among them, vermicomposting can not only produce organic fertilizer but can also be employed as a pretreatment in anaerobic digestion, accelerating the decomposition of chitin (lignocellulose) and increasing methane production by 63%-65% compared to untreated crop straw (Chen et al., 2010; Singh and Singh, 2017). This way, vermicomposting can be combined with anaerobic fermentation industry and resulting in a multi-win model.

Under the guidance of circular economy, the economic evaluation of composting needs to consider several aspects comprehensively (Stahel, 2016). The costs of environmental pollution control, disposal of waste from farmers and production operations, raw material costs for organic fertilizer producers, and fertilizer for farmers can all be reduced under both composting business models of operation (Table 3). Potential economic benefits emerge from the improved quality of agricultural products, the resolution of organic fertilizer marketing pressure, and the enhanced environment of farming plants and production operations. In addition, new opportunities for jobs can be generated under this joint business model to solve the employment problem which may include transportation, management, composting operation, organic fertilizer and agricultural products sales.

6.2. Business value of compost value-added products

Compost generates value-added products with various roles and effects. Compost teas can be used to produce a new liquid fertilizer and plant disease resistant agent. The effectiveness of compost tea has been demonstrated in a variety of plants such as herbs, tomatoes, and fenugreek (Din et al., 2018; Ibrahim, 2019; Verrillo et al., 2021). It was also mentioned earlier that earthworms could be recycled from vermicomposting. The price of commercial earthworms varies from approx. US$ 180 to US$ 897 per ton (Singh and Singh, 2017). The value further increases for earthworms that are processed into medicinal herbs as they are thought to possess antioxidant, hepatoprotective, and antibacterial effects and may promote wound and neurological repair (Wang et al., 2018). In addition, earthworms are effective in remediating soil quality and heavy metal contamination, and can be used in applications that treat wastewater (Singh and Singh, 2017). Therefore, the economic value of recycling earthworms from vermicomposting is vast and the production of mature compost is accompanied by a high-value industry. Partaking in this industrial sector can provide an interesting business opportunity for manufacturers of organic fertilizer, as it does not require a lot of extra equipment (Verrillo et al., 2021).

7. Challenges and opportunities associated with composting and end-product applications

The lack of effective and efficient implementation of waste management technologies across the globe stems from inadequate knowledge about organic waste resource management. This creates the need to establish a new economic model of producing, consuming, reusing, recycling, and avoiding waste. Government agencies, countries, and people should be aware of the advantages of composting as an environmentally friendly technology for organic waste management and the potential of compost in a circular economy. Based on this review of composting processes, further research should focus on the following aspects: (1) the reduced bioavailability of antibiotics and heavy metals during composting stages that are characterized by high temperature and high microbial activity, including changes of antibiotic concentrations, antibiotic resistance genes abundance and the mobilization of heavy metals in the compost-soil–plant system after compost application in agriculture ; (2) the disadvantages of composting that include the generation and emission of greenhouse gases and volatile fatty acids, which are also an area of extensive research. Microorganism-based compound additives have shown a better nitrogen conservation and could reduce the need for physical and chemical additives. More work should be focused on reducing these downsides without reducing compost quality; (3) the fertilizers generated from the composting process can only be exploited if the compost has turned mature and stable. To improve compost applicability, it is necessary to expand research on compost maturation; (4) Compost contains less nutrients than chemical fertilizers, but its organic matter is an indispensable component to soil. It is important to analyze soil and fertilizer characteristics before their integration to supply nutrients to fields and crops in a targeted manner, and (5) To accelerate the large-scale utilization of additives in composting, the economic viability of additives need to be evaluated. The support from local policy makers and legal framework is decisive for creating the necessary industry standards and promoting the acquisition of equipment. This has the capacity to boost the efficiency of composting operations and ecological problems could be prevented.

8. Conclusions

Composting is an environmentally friendly and effective method for recycling organic waste into stable and mature fertilizers. As the emissions of CH_4, NH_3, and N_2O are a major downside of traditional composting, many successful approaches have been determined to improve composting, including the addition of various additives, bulking agents, and microbial inoculants. Further research is also needed to mitigate gas emission, antibiotic resistance genes, and heavy metals mobilization. By further deciphering how additives affect the composting process and influence key microbes, the efficiency of composting systems can be improved.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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