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Role of Temperature in Sludge Composting and Hyperthermophilic Systems: a Review

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Abstract
The utilization of nutrients in sewage sludge partly alleviates the economic and environmental constraints, and the composting process has been proved a cost-efficient and simple approach for the recycling of sewage sludge. During the bio-oxidative process, the thermophilic phase is considered to be the most effective stage for the biodegradation of organic matter in sewage sludge composting systems. However, the maximum temperatures of conventional thermophilic composting systems only reach approximately 55–60 °C because of the activity limitations of thermophiles at higher temperatures. Notably, increasing temperatures can accelerate the humification process and shorten the composting cycle. Therefore, the effect of rising temperature on sewage sludge composting was examined as a specific mechanism. Further, the consequent hyperthermophilic composting (HTC) system created by rising temperatures was reviewed. Moreover, the potential techno-economic advantages and future challenges of HTC systems were discussed. Finally, the microbial communities necessary to ensure the efficiency of HTC systems were analyzed and suitable hyperthermophiles for sludge HTC systems were proposed.

Keywords Bioconversion · Techno-economic · Microbial communities · Hyperthermophilic composting

Abbreviations

OM	Organic matter
TC	Thermophilic composting
HTC	Hyperthermophilic composting
CTC	Continuous thermophilic composting
RPBA	Recyclable plastic bulking agent
EPS	Extracellular polymeric substances
LB-EPS	Loosely bound EPS
TB-EPS	Tightly bound EPS
BVS	Biodegradable volatile solids
DO	Dissolved oxygen
HSs	Humic substances
ARGs	Antibiotic resistance genes
MGEs	Mobile genetic elements

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Introduction

The treatment and disposal of sewage sludge has become an increasingly critical environmental issue because of growing production and potential pollution risks. The total amount of sewage sludge (80 wt.% moisture) generated by the three major economies (the USA, China, and the European Union) was 137 million tons in 2018 according to GEP Research (2018). However, the harmless disposal rate is still relatively low because of the improper management strategies, such as direct dumping or simple landfills, and low treatment efficiency [1]. Further, the associated economic cost is also of growing interest as approximately 35–65% of the total wastewater treatment plant operating cost is used for the disposing sewage sludge in accordance with the conditions of different countries. Sewage sludge is a carrier of energy and nutrients, which can be employed as an organic fertilizer. In particular, the organic matter (OM) contained in sewage sludge varies from 50 to 70% of the total solids, including the proteins, carbohydrates, and lipids [2, 3]. It should be stated that many of the chemical constituents, including nutrients, are important when considering the ultimate disposal of sewage sludge [4–6]. However, the direct use of raw sewage sludge as an agricultural fertilizer may damage soil and plants because of the phytotoxic and pathogenic effects of unstable and harmful substances [7–9]. The sustainable sludge treatment that meets requirements of efficient recycling of resources without supply of harmful substances to humans or the environment has been the key alternatives [3–9]. Therefore, the conversion of raw sewage sludge into safe and stable products, such as soil amendments and fertilizers, which are promising energy carriers, has been encouraged in several countries.

A composting process, which has been proved a cost-efficient and simple approach for the disposal of sewage sludge, has always been employed in the sewage sludge recycling of sewage treatment plants [10, 11]. The bio-oxidative process mainly involves the mineralization and partial humification of OM, leading to a stabilized and detoxicated final products [1, 12, 13], that could be utilized as a potential source of organic fertilizers or in soil amendments [10, 14]. Composted sewage sludge, as the biofertilizer, has been successfully applied to farmland, woodland, grassland, municipal green, and fruit and vegetable land, so as to restore vegetation on serious disturbance land and promote soil ripening, enhancing soil fertility and quality of energy crops [12, 14]. Bioprocesses are heavily dependent on dynamic interactions between biological, chemical, and physical mechanisms. The exothermic process is mainly determined by the initial temperature, biodegradability of the substrates, and the microbial activity [15]. Moreover, the physicochemical parameters, such as temperature, pH, particle size, moisture content, aeration, and electrical conductivity, play an important role in OM decomposition and the transformation and synthesis of humus under the action of microorganisms during a continuous process [16–18]. Among the multiple interacting factors in a complex system, temperature is regarded as the most critical [16, 19] (Fig. 1). Temperature can not only change the physicochemical characteristics of substrates but also affect the properties of microbial communities, such as the sludge morphology, microbial activity and OM degradation, oxygen transfer, and microbial succession [19–24]. The effects of a rising temperature on the four main bioprocesses in sewage sludge composting are (1) increasing solubilization of dissoluble solid OM, (2) accelerating diffusion of dissolved matrix, (3) enhancing the permeation and transmission of oxygen, and (4) improving the oxidation rate of dissolved matrix using aerobic microorganism [25]. In addition, higher temperature can further accelerate moisture evaporation, which reduces the sewage sludge mass. The moisture content of compost end products in a special hyperthermophilic composting (HTC) system with a maximum temperature of 93.4 °C can reach 38.8%, which is lower than that in conventional composting systems, which have a maximum temperature range of 55–60 °C [16, 26, 27].

Rich and Bharti [28] found that the optimum composting temperature range is from 40 to 65 °C, in which the highest activity of thermophilic microorganisms generally occurs at approximately 54 °C according to the levels of superoxide dismutase and catalase activity in thermophilic bacteria. Moreover, when the temperature is greater than 65 °C, most of the bacteria might be deactivated [16, 29]. In addition, higher temperature composting systems improve the deactivation of pathogenic bacteria and accelerate the moisture evaporation, which helps to achieve the quick recycling of small-scale and decentralized sewage sludge [26]. Therefore, the HTC system, which exploits a high temperature of about 80–100 °C, seems to have great advantages in the rapid recycling of sewage sludge. However, HTC systems have rarely been studied because most of the microorganisms are destroyed in their temperature range. Oshima and Moriya

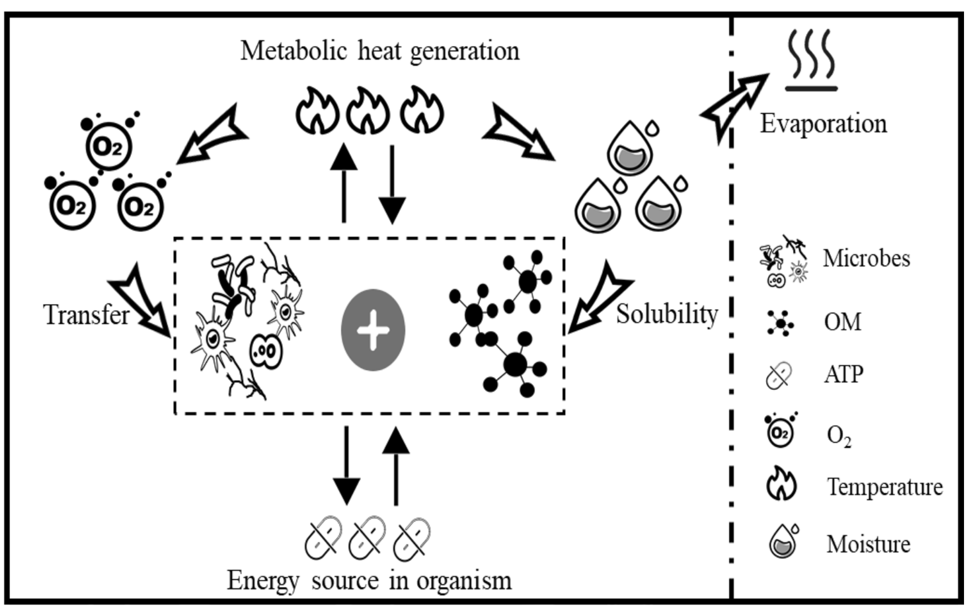

Fig. 1 The interaction between temperature and other main factors

[30] proposed a special HTC system with a high temperature of 90 °C that was driven by the *Calditerricola satsumensis* (YMO81^T) and *Calditerricola yamamurae* (YMO722^T) strains [31]. As pointed out by Trautmann and Krasny [32], when the compost temperature was greater than 65 °C, the composting process reached a hyperthermophilic phase. Furthermore, increased efforts have been made to the exploration of the novel HTC system that reach higher than 80 °C as the maximum temperature of their hyperthermophilic phase [22, 24, 26, 33, 34]. Therefore, with the development of this emerging sludge treatment technology, we aimed to review the role of temperature in sewage sludge composting with emphasis on the hyperthermophilic system.

Present Status of Sewage Sludge Composting

The sewage sludge composting systems have been widely investigated, wherein the main areas of focus have been the following:

1) The effects of various physicochemical parameters on the composting system, including temperature, pH, aeration, microbial activity, moisture content, and C/N ratio
2) The bioavailability of different OM in sewage sludge, including the biodegradable matrix (saccharide, humic acid, protein, and lipid) and refractory organics, and improving bioavailability with different bulking agents, such as lignocellulosic amendments, biochar, recyclable plastic bulking agent (RPBA), medical stone and lime, pig and cow manure, coal fly ash, municipal solid waste, spent mushroom substrate, and sucrose
3) Methods and technologies, including the continuous thermophilic composting (CTC) system, sequential anaerobic–aerobic composting, multistage inoculation strengthening composting, semipermeable cover composting, vermi-composting, and rotating-wall bioreactor composting
4) The optimization strategies of composting, which mainly involves the statistical approaches (e.g., one variable-at-a-time, factorial designs, fuzzy logic estimation model, Markov chain approximation, and modified Gompertz model) and the kinetic models (such as the first-order model for OM degradation, microbial growth rates and formation of humification, Monod or Monod-type model for the oxygen uptake rates, and empirical model for the carbon dioxide generation)
5) The maturity evaluation of composting, mainly including the changes of physical, chemical, and biological indexes, such as temperature, OM degradation, carbon mineralization, and germination index

This research has significantly promoted the efficacy of conventional thermophilic composting (TC) sewage sludge systems. Table 1 summarizes the effects of the aforementioned research focuses on regarding composting temperature; particularly almost all the improvements in composting efficiency are accompanied by a rise in temperature. This is because composting is driven by various microorganisms whose succession in community composition and population corresponds to temperature evolution.

Consequently, the process of sewage sludge composting can be divided into mesophilic, thermophilic, cooling, and maturing phases according to the temperature and microbial succession [41–44]. The maximum temperature of the thermophilic phase (55–60 °C) is consistent with the optimum growing temperature of thermophiles (45–60 °C) [10, 45, 46], in which the survived temperature of thermophiles is approximately equal to the upper temperature of composting system because of their thermostability, which is determined by their special protein [47, 48] and DNA structures [49]. Moreover, the thermophilic phase is the highest efficiency stage [46, 50, 51], as thermophiles have a high efficiency in degrading various pollutants, such as the long-chain alkane, benzopyrene, phenanthrene, azo dyestuffs, benzothiophene, petrol, etc. [52–55. Therefore, the interaction of temperature and microorganism activity has attracted the most composting research attention [16, 24, 26, 56]. A schematic illustration of the relationship between temperature and microbial communities is shown in Fig. 2. Notably, most of the microorganisms are deactivated when a composting system enters the hyperthermophilic stage, which has temperatures greater than 65 °C, with the exception of the distinctive hyperthermophilic microbial community in special HTC systems [16, 26, 29].

Effect of Temperature on Sewage Sludge Composting

Temperature is a critical factor in most chemical, physical, and biological processes. In the composting process of sewage sludge, a higher temperature has positive effects on water evaporation, deactivating pathogenic microorganisms, and degrading OM. However, if temperature is too high, most of microorganisms are destroyed, stopping the composting process. Therefore, the roles of temperature in the composting of sewage sludge should be further examined regarding its interaction with various factors.

Moisture Content and Dewatering Performance

Moisture removal determines the dewatering performance, which is important for reducing the sewage sludge mass. However, it is difficult to remove the capillary water, adhesive

Table 1 Summary of research focuses on sewage sludge compost temperatures

Research focuses	Parameters	System temperature	Comments	References
Variables optimization	Aeration rate, C/N ratio, moisture content, pH, and particle size	Maximum temperature is 55–60 °C	Optimization of variables leads to the rise of temperature	[16, 19]
Co-composting	Lignocellulosic amendments, biochar, RPBA, mineral stone, pig and cow manure, coal fly ash, and municipal solid waste		Co-composting with different amendments can improve the temperature and extend the thermophilic phase (> 50 °C)	[12–14, 35, 36]
Statistical approaches	One variable-at-a-time, factorial designs, fuzzy logic estimation model, and Markov chain approximation	Effective prediction temperature is approximately 30–60 °C	Effects of various factors on temperature can be simulated and a significant temperature gradient occurs	[16]
Kinetic model analysis	First-order models, Monod or Monod-type models, empirical models, and the Gompertz equation	Applicable temperature to the models is approximately 30–60 °C	Thermal balance can be estimated to provide proper temperature control and predict temperature profiles	[16, 37]
Composting technologies	CTC system, sequential anaerobic–aerobic composting, multistage inoculation strengthening composting, semipermeable cover composting, and HTC system	Maximum temperature is approximately 55–60 °C and only the HTC system is above 80 °C	Accelerates the rise of temperature and extends the thermophilic phase (> 50 °C). Especially, the hyperthermophilic phase of HTC system when above 80 °C	[23, 30–34, 38, 39, 40]

water, and internal water by mechanical force. Thus, more than 30% of the bound water cannot be removed effectively [57]. It was demonstrated that the key to achieving sludge dewatering is to destroy the structure of the flocculants in order to release the bound water [58]. Moreover, moisture removal is strongly dependent on temperature. The succession of microbial communities is continuous with rising temperature during the composting process. In particular, when the temperature exceeds the thermal limit of a microorganism, its cell structure is destroyed, causing cell lysis, and it releases a large number of extracellular polymeric substances (EPS) [59, 60]. EPS are mainly involved in microbial aggregation matrix formation, bacterial adhesion to solids, and microbial flocculation properties [61], which play key roles in the physicochemical and biological properties of sludge [62–64]. EPS mainly include the loose bound EPS (LB-EPS) and tightly bound EPS (TB-EPS), which are related to the sludge dewaterability. To date, the roles of EPS in dewatering sewage sludge can be divided into four different mechanisms, including (1) EPS has a high viscosity due to the amounts of polysaccharide and proteins that attach to the sludge surface, lowering the dewatering performance [65]; (2) sludge with a high EPS content has a strong shear resistance that is not easily broken, leading to a better filtration performance [66]; (3) an EPS content of 400–500 mg/L is most conducive to sludge dewatering whereas higher EPS concentrations diminish sludge dewaterability [63]; and (4) LB-EPS have a slight effect on the sludge dewatering, but excessive TB-EPS with a large amount of water can weaken the cell-to-cell binding and destroy the tight structure, resulting in a worse dewatering performance [64]. Therefore, the key to achieving extensive sludge dewatering is to destroy the moisture holding capacity of EPS. Moreover, it has been shown that higher temperature can destroy the links between EPS and water, causing the interstitial or combined water between sludge particles to be removed, thereby releasing the intracellularly bound water for either liquid separation or evaporation [67, 68]. However, a moisture content of 40–60% is necessary for composting. When the moisture content is lower than 40%, the microbial metabolic activity is inhibited as a certain moisture content is necessary for microorganisms proliferation and OM degradation [10]. In particular, for the HTC system, higher temperatures can further promote the reduction of sewage sludge mass, and the moisture content of the compost end product can be 38.8% [26].

Microbial Activity and Organic Matter Degradation

Microbial activity is a good indicator of the biotransformation and mineralization of organic waste because the enzyme catalytic reaction of microorganisms is an essential process in composting [69]. The effects between microbial activity

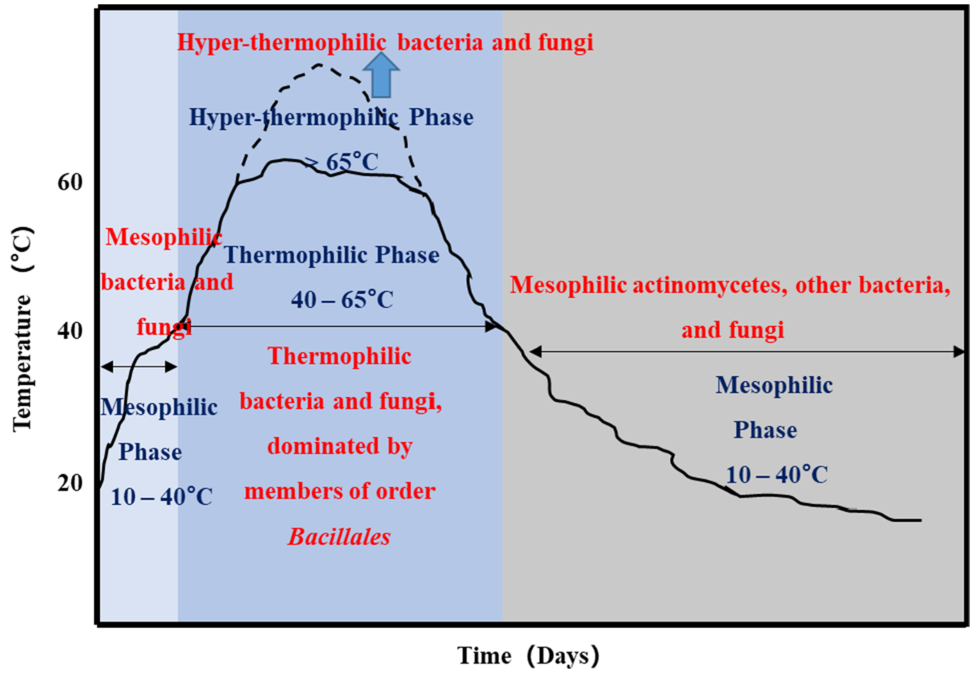

Fig. 2 Schematic illustration of prevailing microbial communities at certain temperature in the compost system [56]

and temperature are dynamic, wherein higher microbial activity can accelerate OM decomposition, thereby raising the temperature with metabolic heat. Meanwhile, the continually changing temperature may cause a certain succession of microbial communities, and various organic substrates can be decomposed and further humified by microbes in different phases. During the bio-oxidative process, OM is first adsorbed on the surface of enzymes, followed by a biocatalytic degradation reaction. According to the Michaelis–Menten mechanism, for the steady-state sewage sludge composting system, if excessive OM is provided, the maximum reaction rate can be derived:

$$V_{max} = \frac{[S]}{K_m + [S]} \quad (1)$$

where V_{max} is the maximum degradation rate of OM, S is the OM, and K_m is the Michaelis constant, which is a characteristic constant of enzyme in the steady-state sewage sludge composting system. Considering the redox reaction of enzymes, the K_m increases gradually as a result of competitive inhibition when excessive OM is provided. As various substrates compete for the same enzyme binding sites, the V_{max} is not affected. Therefore, the availability of sewage sludge is mainly affected by the content of biodegradable OM, in which the main restrictive degradation step is the oxidation of dissolved matrix [70].

The temperature dependence of biodegradable volatile solids (BVS) reaction rates in different composting systems follows the Arrhenius equation, in which the degradation of organic solids waste can be quantitatively predicted using a first-order reaction model [69]. According to typical Arrhenius plot of ln(k) versus 1/T, to determine the activation energy, the reaction rate constants and percentage of BVS degradation can be calculated as follows:

$$K = e^{(17.73 - \frac{6688.5}{T})} \quad (2)$$

$$\frac{\Delta BVS_n}{BVS_0}\% = 100\left(1 - e^{-Kt}\right) \quad (3)$$

where K is the reaction rate constant, T is the reaction absolute temperature (K), ΔBVS_n is the amount of BVS degraded (kg), BVS_0 denotes the amount of initial BVS (kg), and t is the degradation time. Therefore, the percentage of BVS degradation at different temperatures can be determined. As shown in Fig. 3, increasing the temperature accelerates the

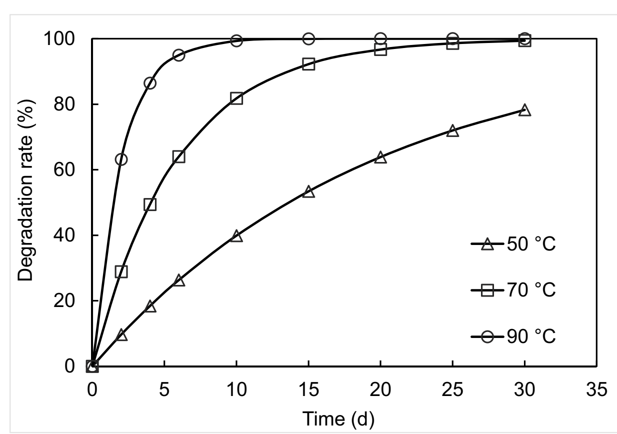

Fig. 3 The percentage of BVS degradation at different temperatures based on the first-order reaction model

degradation process and improves the percentage of BVS degradation when the temperature is suitable for microorganisms [71].

Furthermore, the OM solubility and degradation pathway are dependent on temperature [72]. In particular, most OM fractions (except those that are gaseous) increase with increasing temperature, which improves its biodegradability and thus accelerates the metabolism of microorganisms and promotes the decomposition of metabolic or intermediate products [73–75]. Temperature also plays a vital role in the OM degradation pathway by affecting dissolution/hydrolysis, diffusion, active transport, and intracellular respiration during the compost process. Further, it has been confirmed that increasing temperature enhances OM degradation [76]. The succession laws of microbial communities also reveal the domination effect of temperature in the composting process [43]. It is generally agreed that when the temperature enters the thermophilic phase (temperatures above 45 °C) [39, 43, 77], most of the OM is degraded because of the interaction between higher temperature and thermophiles [11]. In the process, water-soluble OM is decomposed first, followed by the decomposition of refractory organics (such as cellulose, hemicellulose, and lignin) [78]. In particular, the removal of pollutants that are toxic to humans, such as antibiotic resistance genes (ARGs), mobile genetic elements (MGEs), and heavy metals, is significantly affected by temperature. Moreover, thermophilic conditions realize rapid antibiotic removal, including tetracyclines and chlortetracyclines [79, 80]. Further, the HTC system was found to be efficient in removing ARGs, MGEs, and heavy metals [81, 82]. Note that the microbial community composition plays a crucial role in removing such human-toxic pollutants [81].

Oxygen Transfer

In a sewage sludge composting system, microbial enzyme activity strongly depends on the oxygen content because the level of dissolved oxygen (DO) affects the microbial metabolic pathways, resulting in the deviation of target products [83]. A stabilized DO concentration can avoid not only metabolic abnormalities caused by insufficient oxygen supply but also the excessive energy consumption caused by oxygen supply. In general, an increasing temperature has a negative effect on the transfer of oxygen to water in gas–liquid system. However, the existence of solid particles, hydrocarbons, and some vegetable oils greatly increases the oxygen diffusion rate by increasing the transfer coefficient and effective surface area in the complex composting system [84]. Also, Fick's law has revealed the effect of oxygen transfer on aerobic reaction, emphasizing the oxygen concentration and oxygen consumption rate [85]. However, both the temperature and viscosity of sewage sludge affect the mass transfer of oxygen in the complex aerobic composting systems. Therefore, Fick's first law and Stokes–Einstein equation were combined to correlate temperature and oxygen diffusion, generating the diffusion flux J as follows:

$$J = -\frac{RT}{6\pi N_A \eta r} \cdot \frac{dC}{dX} \tag{4}$$

where N_A is the Avogadro's number, R is the gas constant, η denotes the liquid viscosity coefficient, r represents the radius of oxygen, T is the temperature of oxygen transfer, and $\frac{dC}{dX}$ is the concentration gradient. Thus, in a steady-state sewage sludge composting system, a positive relation was found between diffusion flux and the rising temperature when the excessive oxygen is provided.

Succession of Microbial Communities

The composting process is a complex, and involves several dynamic interactions, including the biological, chemical, and physical mechanisms, and the microbial communities succession laws that can reflect changes in temperature [38, 42, 44]. During this bioprocess, the microbial communities mainly comprise bacteria and fungi [86, 87]. The growth situation of microorganisms can be greatly affected by rising temperatures, as summarized in Table 2. Different microorganisms dominate different temperature ranges, wherein their continuous metabolism and rising temperature stabilize the community structures and microbial activity by eliminating the competition of other bacteria. In the mesophilic phase, most microorganisms are mesophilic degrading bacteria and fungi, such as *Bacillus licheniformis* and *Thermoactinomyces*, which can decompose the hydrolyzable substrate quickly, and the resultant metabolic heat can further increase temperature. In the thermophilic phase, *Bacillus* become the dominant bacteria, which can hydrolyze complex OM (such as proteins), and

Table 2 Microorganism growth at different temperatures

Microorganisms	Temperature, °C								References
	25–38	38–45	45–55	55–60	60–70	70–80	80–105	> 105	
Mesophile	Excitated	Inhibited	Destroyed	–					[92–96]
Moderate thermophile	Unadapted		Excitated			Inhibited	Destroyed	–	[92, 93, 97–99]
Hyperthermophile	Unadapted						Excitated	Inhibited	[100, 101]

rising temperature can easily eliminate the potential pathogenic microorganisms by the heat generated in this stage [88]. Fungal populations play an intricate role in the early stages of composting. However, some fungi can also tolerate high temperatures. For instance, *Aspergillus*, *Corynascus*, *Trichoderma*, *Penicillium*, *Phanerochaete*, and *Pseudallescheria* were found in the thermophilic composting stage [89]. In the cooling phase, the exhaustion of easily degradable substrates leads to a decrease of heat production and thus a lower temperature. Meanwhile, in the maturing phase, the mesophiles (e.g., actinomycetes, bacteria, and fungi) revive and continue growing. Specifically, in this stage, the fungal community experiences a stronger ability to utilize amines, amino acids, and carbohydrates [90], while some nondegradable compounds (such as lignin-humus complexes) form [35, 39, 44, 75]. The results showed that temperature is crucial to changing the composition of both bacterial and fungal communities [35], and that changes in their community structure were dynamic and parallel [91]. Moreover, for the conventional sludge composting, the thermophilic phase is considered to be the most suitable stage as it has an abundance of heterogenic members belonging to the genus *Bacillus*, because it can decompose more extensive organic substances because it has a higher activity and metabolic rate, as compared with others [16]. Though the fungal species richness is relatively low during the composting process, maintaining a favorable fungal composition is vital for efficient and successful composting because the thermophilic fungal genus could potentially degrade carboxylic acids and polymers [90]. To date, several moderate functional thermophiles have been found to improve composting efficiency (as listed in Table 3). However, when temperature was greater than 65 °C, a decrease in bacterial abundance was observed because the high temperature might deactivate fungi, actinomycetes, and most of the bacteria that are essential in degradation during the thermophilic stages [16, 29]. Particularly for the special HTC system, the metabolized heat of special microbial communities gradually increases the temperature, revealing a distinctive microbial community in the hyperthermophilic phase. The results of high-throughput sequencing of microbial communities in the HTC system with a maximum temperature of 93.4 °C revealed that bacterial abundance decreased greatly, and *Thermaceae* (35.5–41.7%) became the predominant family species under hyperthermophilic conditions [22, 26]. However, as HTC systems are still not common because of their unique start-up inoculants from the volcanic region in Kagoshima, only a few studies have been published regarding their special microbial communities [26, 30].

Nitrogen Loss

Nitrogen emissions (N_2O and NH_3) from composting are also of concern as they contribute not only to greenhouse gas emissions but also to nutrient loss and lower nutrient quality of final compost products [103]. The volatilization of NH_3 during chemical reactions, the emission of N_2O from microbial mediated denitrification processes, and draining by leaching are the main causes of nutrient loss [104, 105]. Notably, NH_3 volatilization consists of 40–80% of the total nitrogen loss during composting [106]. Therefore, decreasing NH_3 volatilization may be an effective way to control nitrogen loss during composting. Regarding conventional TC processes, many studies have demonstrated that high temperatures could affect nitrogen metabolic processes, including nitrification and denitrification [107–109], and that higher temperatures could cause a higher emission rate of NH_3 by enhancing the solubilization of non-dissolved nitrogen and evaporation of NH_4^+-N as NH_3 gas. For example, the emissions of nitrogen as NH_3 at 60 and 70 °C were 14.7 and 15.6%, respectively, which

Table 3 Various functional microorganisms isolated from sewage sludge composting system

Strain	Temperature, °C	pH	Characteristics	References
Thermus	40–78	7–8	Aerobic, oxidase and catalase positive, penicillin sensitive, yellow, orange or reddish colonies	[102]
Bacillus stearothermophilus	40–75	6–7.5	Aerobic, oval endospore formation, growth inhibition with 3% NaCl, growth inhibition with NaN_3	[102]
Ammoniibacillus agariperforans	50–65	7.5–9	Ammonium was required as a nitrogen source, while nitrate, nitrite, urea, and glutamate were not utilized. Catalase and oxidase activities were weakly positive and positive, respectively	[97]
Bacillus thermoamylovorans	60	7	The strain is facultative anaerobic bacteria and can improve the bioconversion of the mixture of sewage sludge and food waste	[98]
Bacillus sp. strain T3	55	7–9	The strain can oxidize the ammonia	[99]
Microbacterium luticocti	27–45	5.5–9.7	Aerobic, nitrate reduction, starch, gelatin, and aesculin are hydrolyzed	[92]
Candidimonas	15–40	5–8	Facultative anaerobic, nitrate reduction, amino acids, and organic acids are used as sole carbon sources	[93]
Humibacter albus	22–36	5.5–8	Nitrate reduction	[94]
Massilia umbonate	37	7–8	Accumulate poly-β-hydroxybutyrate as intracellular granules	[95]
Pichia guilliermondii	28	–	Uptake the copper	[96]

is much higher than that at 50 °C (9.0%) [14, 104]. Nitrogen emissions (e.g., NH_3) are mainly derived from an incomplete OM humification process, especially the proteins. However, rising temperatures can accelerate the humification process, and high-molecular-weight recalcitrant humic substances (HSs), such as fulvic acids, humic acids, and humins, are major reservoirs of recalcitrant nitrogen in the compost and are mainly formed during the humification process [74, 75]. Thus, it may be ideal to reduce nitrogen loss by raising the composting temperature in order to accelerate the humification process and reduce the substrate for ammonification reactions. Recently, some studies have shown that the HTC system can accelerate the formation of HSs and contribute to the reduced nitrogen loss by decreasing NH_3 emissions, ammonification enzyme activities, and the ammonifier relative abundance [22, 24]. Moreover, Peng et al. [110] revealed that a high temperature was key for lowering N_2O emissions in an HTC system, mitigating approximately 90% of N_2O emissions compared with that of a conventional TC system. This decrease was mainly due to the inhibition of the abundance of the bacterial *amoA* and *norB* genes, which decrease the nitrification rate and N_2O formation, respectively [110]. Therefore, the special hyperthermophilic microbial communities play an important role in reducing nitrogen loss in sludge composting.

Role of Hyperthermophiles in the Hyperthermophilic Composting System

As the temperature of a HTC system is 20–30 °C higher than that of the conventional TC process, it significantly enhances the compost maturity and shortens the composting period. HTC systems can accelerate the formation of humic acid at the molecular level and improve the removal of ARGs and MGEs [24, 54, 109]. The enhanced humification process may increase the recalcitrant nitrogen reservoir, thereby decreasing the substrate content for the ammonification reactions, leading to 40.9% reduction of nitrogen loss in the HTC system [22]. Furthermore, OM loss in the HTC system in 24 d can reach 66.8%, which is higher than that of a TC system in 48 d (63.8%) [26]. These results are mainly because of the HTC system's special hyperthermophiles, which can drive the process under hyperthermophilic condition. However, the proper hyperthermophiles are difficult to be directly isolated from the sludge composting because of their special growth environment. To date, many moderate functional thermophiles have been identified (Table 2), but of the hyperthermophiles with growth temperature above 80 °C, only *Calditerricola satsumensis*, *Calditerricola yamamurae*, and *Thermaerobacter* were isolated from the volcanic region in Kagoshima by Oshima's group [26, 31, 38]. Note that *Thermaerobacter* is closely related to *Thermaceae* [26]. Therefore, the critical issue in the HTC system is the lack of suitable hyperthermophiles for the continuous degradation of OM. Thus, the other hyperthermophiles with a good performance in hyperthermia condition may have applicability in the HTC system. While more than 90 hyperthermophiles have been isolated from different environment conditions [112], there are no relevant researches regarding the proper hyperthermophiles to employ in an HTC system. Most microorganisms are inhibited when the temperature is above 65 °C as a result of thermal denaturation. However, hyperthermophiles have optimum growth temperature greater than 80 °C, and the *Pyrodictium occultum* strain can even survive in 121 °C for 1 h [100, 102, 113, 114]. Most hyperthermophiles belong to the archaea domain, while only a few exceptions (such as *Aquificales* and *Thermotogales*) belong to bacteria [115]. Hyperthermophiles have attracted significant attention because of their extreme thermostability, which can be explained using evolutionary theory [116, 117] and their special molecular structure [118]. Because of the extreme growth environment, the anaerobic is the main metabolic mode for most hyperthermophiles [114, 117, 119], wherein oxygen can be severely toxic to anaerobic hyperthermophiles at their growth temperature [101]. For the aerobic organotrophic metabolism mode, the main metabolic mechanism is the modified Embden-Meyerhof-Parnas pathway, in which the carbohydrates (such as sugars) can be completely oxidized to CO_2 through the citric acid cycle [116]. Research regarding hyperthermophiles mainly focused on basic biology fields, including the growth environment, cell characteristics, proteins, thermostable hydrogenases, and genetic systems [115, 120]. Industrial applications of hyperthermophiles primarily involve detergent production, sugar chemistry, oil chemistry, food production, cellulose degradation and ethanol production, paper pulp bleaching, and molecular biology [118, 120]. Compared with other microorganisms, hyperthermophiles have numerous application advantages, including reduced costs of cooling large-scale thermophilic fermentations and less contamination in thermophilic conditions [120]. These advantages have stimulated efforts to explore their potential applications in thermostable protein nanostructures, robust biosensor devices, and hyperthermophile cell engineering [115]. However, their applications in biosolids recycling are limited because of their slow-evolving features and special growth conditions [116]. The proper strains for aerobic, organotrophic, and hyperthermophilic conditions may have potential application in HTC system. According to the characterizations of the *Calditerricola satsumensis* strain, several proper strains with the similar properties have been summarized, such as *Pyrobaculum aerophilum*, *Aeropyrum camini*, and *Aeropyrum pemix*, as listed in Table 4.

Table 4 Comparison of several proper heterotrophic hyperthermophiles with *Caldothrix satsumae* YM081^T strain

Strains	Domain	Temperature (optimal) °C	pH (optimal)	Relation to oxygen	Metabolism	Carbon sources	References
Pyrobaculum aerophilum	Archaea	74–104 (100)	7.0	Facultative anaerobic	Mixotrophic	Complex proteins can be used as carbon sources, such as tryptones, gelatin, yeast extract, and beef extract	[111]
Aeropyrum camini		70–97 (85)	8.0	Aerobic	Heterotrophic		[117]
Aeropyrum pemix		80–100 (90–95)	7.0				[98]
Thermus	Bacteria	40–78 (65)	7.0				[100]
Bacillus stearothermophilus		40–75 (60)	7.0				[100]
Calditerricola satsumensis		50–85 (75)	7.2				[31]

Techno-economic Analysis of Hyperthermophilic Composting System

The prominent advantages of an HTC system's techno-economic costs were evaluated based on the currently available theoretical and practical research. To evaluate the techno-economic cost, the technological process of sewage sludge composting is shown in Fig. 4. Various technological characteristics including sludge transportation, composting additives, energy consumption, land-use efficiency, and end-product quality were considered for this analysis. Consequently, a comparison between HTC and TC systems was conducted, as summarized in Table 5. First, the HTC system significantly shortens the composting period, thereby lowering the energy consumption and raising the land-use efficiency. In addition, an HTC system can start with a C/N ratio lower than 10 [26], while a conventional TC system requires a ratio between 25 and 30 [26, 121, 122], which means the HTC system has a lower composting additive cost. Moreover, an HTC system only requires a space of 45 m^2 (t wet sludge)$^{-1}$, which is 40 m^2 less than that required to treat the same volume of sludge using a conventional TC system [26]. Moreover, the HTC system can greatly decrease the sludge mass (41.2%), leading to lower end-product transportation costs. In addition, the agricultural value of a compost increases when a high nutrient content was obtained which requires a high degree of OM humification and reduction of N loss during the process [123]. Obviously, the HTC system's lower N loss and higher OM degradation rates could lead to higher end-product quality and fewer odor emissions [22, 110]. At present, the immediate conversion of biowastes into bioenergy is the high cost of processing, rather than the cost or availability of biomass feedstock. Thus, to improve the utilization rate of bioenergy that can be produced sustainably by using biowastes has been a promising challenge [124]. Significantly, except the bioenergy potential of the compost production, the HTC system also has a huge advantage in heat recovery because of the extreme high temperature. For conventional TC system, the amount of heat recovery can be 1.2 to 2.6 × 10^5 kJ, about 12–24% of total heat production [125]. Especially, the direct heat recovery makes more sense for HTC system, because its temperature is 20–30 °C higher than that of the conventional TC process which means more heat production. Based on these findings, an HTC system may be employed as a novel technology for future sewage sludge treatment project.

Prospects of the Hyperthermophilic Composting System

The HTC system was first developed in 2008, but it is not commonly used because of its special microbial inoculants, which contain large numbers of hyperthermophilic

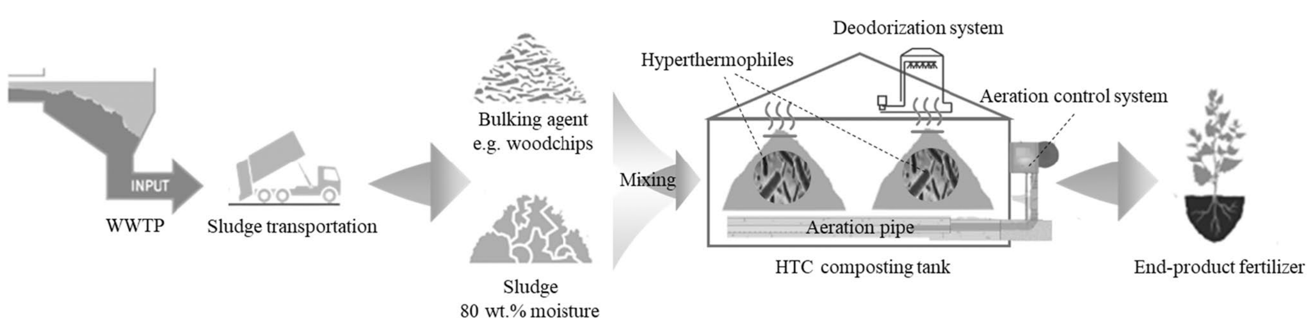

Fig. 4 The main technological process of HTC system of sewage sludge

Table 5 Techno-economic analysis of HTC system as compared with the TC system for sewage sludge treatment

Indexes	Technological characteristics		Economic savings	References
	HTC	TC		
Composting period	24 d	48 d	Lower energy consumption and higher land-use efficiency	[6]
Start-up C/N ratio	< 10	25–30	Less composting additives	[26, 121, 122]
Aeration volume	45 m^2 (t wet sludge)$^{-1}$	80 m^2 (t wet sludge)$^{-1}$	Lower energy consumption	[26]
Moisture loss	41.2%	36.9%	Greater sludge decrement and lower transportation costs	[6]
N loss	26.2%	31.0%	Higher end-product quality	[22, 110]
OM loss	66.8%	63.8%	Greater mineralization rate of OM and less odor emission	[26]

bacteria. Therefore, the characterization of microbial communities associated with HTC systems remains unclear. In total, only two studies have evaluated some characteristics of its distinctive microbial communities [26, 30], in which the bacteria *Calditerricola satsumensis*, *Calditerricola yamamurae*, and *Thermaerobacter* were identified as the predominant families in the hyperthermophilic phase of a sewage sludge HTC system. Though several studies have evaluated HTC systems, all of them were based on these special inoculants and only focused on its superior performance. Thus, the change mechanism of the special microbial communities associated with sewage sludge HTC systems also remains unclear. Moreover, a critical issue in the HTC system is the lack of suitable hyperthermophiles for continuous OM degradation. Notably, more than 90 hyperthermophiles have been isolated from different environment conditions, but their bioavailability is seldom involved in the sewage sludge HTC system. Therefore, to obtain suitable hyperthermophiles for the sewage sludge HTC system, different amounts of hyperthermophiles were investigated, and several strains, such as *Pyrobaculum aerophilum*, *Aeropyrum camini*, and *Aeropyrum pemix*, may be suitable for the sludge HTC system, because they share similar features with *Calditerricola satsumensis* in degrading complex carbohydrates at hyperthermophilic conditions. Therefore, their application feasibility for the HTC system is a useful research topic. In addition, the isolation and culture conditions must be further studied as they remain challenging because of the strict growth environment required by hyperthermophiles.

Conclusions

Higher temperatures have positive effects on the sewage sludge composting process because increased temperatures can accelerate the humification process and shorten the composting cycle. However, most microorganisms degrade in higher temperature ranges, thereby limiting composting temperatures. Specifically, an HTC system, which has a high working temperature of approximately 80–100 °C, has greater techno-economic advantages in the rapid recycling of sewage sludge as compared with that of conventional TC systems. However, HTC systems are not yet widespread because of their special microbial communities. The lack of suitable hyperthermophiles for HTC systems is thus a critical issue restricting their development. Consequently, the application feasibility of other hyperthermophiles for the HTC system should be evaluated in future research.

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Deyi Wu: methodology, formal analysis, and investigation.

Xinze Wang: methodology, formal analysis, and investigation.

Yan Lin: methodology, writing (review and editing), visualization, supervision, and funding acquisition.

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Data Availability The datasets generated and/or analyzed during the current study can be found from the corresponding author and the data will be released on reasonable request.

Code Availability Not applicable

Declarations

Conflict of Interest The authors declare no competing interests.

Ethical Approval Not applicable

Consent to Participate Not applicable

Consent to Publish Not applicable

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