

Review

Research Progress on Solid-State Fermentation Parameter Optimization and Related Technological Innovations

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Abstract

Organic waste causes severe pollution, while agriculture lacks quality fertilizers. Solid-state fermentation solves both issues. Nevertheless, traditional methods are slow and lead to nitrogen loss. They also emit greenhouse gases and yield uneven products. This fails to reach modern low-carbon standards. We urgently need efficient solid-state fermentation systems. Therefore, this review summarizes recent advances in parameter optimization and cutting-edge innovations. Firstly, key solid-state fermentation operational parameters, such as carbon-to-nitrogen ratio, aeration frequency, temperature, humidity and pH, are analyzed. The optimization of these parameters facilitates nitrogen retention and mitigates pollutant emissions. Secondly, emerging enhancement strategies are discussed. Elaboration on the electron-shuttle effect of modified biochar and advances in synthetic microbial consortia is provided. For process coupling, the mechanisms of hydrothermal carbonization (HTC) combined with solid-state fermentation are explored. Bioelectrochemically assisted solid-state fermentation (MCFT/BFC) based on Direct Inter-Species Electron Transfer (DIET) is also examined. Furthermore, feasible mitigation approaches for pollutants including greenhouse gases and antibiotic resistance genes (ARGs) are summarized. Subsequently, the applications of mathematical models, the Internet of Things (IoT), and artificial intelligence in solid-state fermentation are introduced. Finally, current challenges in large-scale application and risk management are analyzed. Future prospects involving multi-omics, life cycle assessment (LCA), and functional customization are discussed. Low-carbon solutions for high-value waste utilization are provided in this review.

Keywords: solid-state fermentation; biochar electron shuttle; bioelectrochemical; hydrothermal carbonization; IoT-based technologies; resource utilization



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1. Introduction

Solid-state fermentation is implemented to harness microbial metabolic activity for the remediation of organic waste and its transformation into stable organic fertilizers. Typical feedstocks for this process include straw, kitchen waste, livestock manure, and municipal sludge [1]. Microbial metabolism drives this technology. Microorganisms utilize organic waste as nutrients. They oxidize part of the organic matter into simple inorganic substances, releasing energy. The remaining organic matter synthesizes cellular materials for microbial growth [2]. Meanwhile, partially degraded organic substances are transformed into

humus, a complex organic colloid [3]. It significantly improves soil structure and fertility [4]. Solid-state fermentation proceeds with temperature changes. It divides into four stages: mesophilic, thermophilic, cooling, and maturation. Each stage exhibits distinct characteristics and microbial activity patterns [2].

The continuous growth of organic waste output renders the inherent advantages of solid-state fermentation increasingly prominent. This technology mitigates methane emissions from landfills, strengthens soil carbon sinks, and lowers chemical fertilizer consumption, thereby effectively cutting whole-chain carbon emissions [5]. Solid-state fermentation serves as the major pathway for nutrient recycling back to farmland. Developing green solid-state fermentation technologies supports low-carbon goals [6]. Nevertheless, traditional natural fermentation has practical limitations. Firstly, it features a lengthy fermentation cycle and requires large land occupation; dependence on spontaneous heating reduces site turnover efficiency [1]. Secondly, nitrogen is prone to volatilization in the form of ammonia, which triggers odor generation and devalues the final fertilizer product [7]. Thirdly, anaerobic organisms readily emerge within the compost pile, releasing greenhouse gases such as methane and nitrous oxide [8]. Finally, spatially non-uniform temperature distribution is frequently detected. Edge regions often fail to reach pathogen-killing temperatures. This results in inconsistent product maturity [9].

These drawbacks severely restrict industrial-scale implementation. This paper systematically reviews recent research advances aimed at resolving these bottlenecks, covering three major research directions. First, dynamic parameter regulation is explored, including the optimization of carbon-to-nitrogen ratios, aeration, temperature, moisture, and pH. Second, state-of-the-art enhancement technologies, such as membrane covering, fed-batch operation, modified biochar, synthetic microbial consortia, and hydrothermal carbonization, are summarized. Third, we introduce intelligent monitoring technologies and forecast industry trends. Core novelty of this integrative review: Organic solid waste solid-state fermentation is a multi-factor-coupled complex system. A single optimization measure often fails to achieve simultaneous goals of nitrogen retention, GHG reduction and pollutant elimination. This paper unifies parameter regulation, material synergy, synthetic microbial consortia, bioelectrochemical/HTC cross-process coupling and AI intelligent decision making into an integrated research framework. We systematically sort out their interaction mechanisms and coordinated application paths, which fills the gap of comprehensive whole-process reviews in this field. The classification and action mechanisms of common functional microbial inoculants are preliminarily summarized in Table 1.

Table 1. Classification and action mechanisms of common functional microbial inoculants for solid-state fermentation.

Inoculant Category	Representative Strains	Core Function	Applicable Scenarios	Advantages	References
Bacteria	<i>Bacillus subtilis</i> , <i>Bacillus licheniformis</i> , and <i>Azotobacter</i>	Rapidly decompose sugars and proteins. Promote nitrogen conversion. Reduce ammonia volatilization. Secrete antibacterial substances.	Kitchen waste, manure, and sludge.	Rapid heating in early stages. Fast solid-state fermentation initiation.	[10]
Fungi	<i>Trichoderma</i> , <i>Aspergillus</i> , and White-rot fungi	Secrete cellulase and ligninase. Efficiently degrade lignocellulose. Accelerate humification.	Crop straw, forestry waste, and garden leaves.	Specific degradation of lignocellulose. Maintain high activity later in solid-state fermentation.	[11]
Actinobacteria	<i>Streptomyces</i> and <i>Nocardia</i>	Tolerate high temperatures. Degrade complex aromatics. Generate natural antibacterial agents. Decompose odor precursors.	Mixed organic waste and high-organic sludge.	Strong thermophilic traits. Sustain metabolism during high temperatures. Reduce odors.	[12]

Table 1. Cont.

Inoculant Category	Representative Strains	Core Function	Applicable Scenarios	Advantages	References
Complex Consortia	Bacteria + Fungi + Actinobacteria	Rapidly increase temperature. Degrade complex organics. Deodorize and inhibit pathogens. Improve overall efficiency.	Industrial-scale solid-state fermentation. High-fiber straw and high-nitrogen sludge.	Adapt to complex materials. Shorten overall cycle. Stabilize maturity.	[13]

2. Process Parameter Optimization and Dynamic Regulation

2.1. Carbon-to-Nitrogen (C/N) Ratio and Co-Fermentation

The carbon-to-nitrogen (C/N) ratio fundamentally governs the startup and operation of solid-state fermentation [14]. Carbon supplies energy for microbial metabolism. Nitrogen is essential to synthesizing cellular components such as proteins and nucleic acids [15]. Appropriate C/N adjustment avoids nutrient imbalance and guarantees efficient organic-matter degradation.

The optimal initial C/N ratio generally ranges within 25–30:1. Optimization experiments have demonstrated that a C/N ratio of 25 delivers maximum degradation efficiency and humification performance [16]. The pile undergoes rapid temperature rise, and the thermophilic phase can persist for 14 days, facilitating humus formation and pathogen inactivation. This promotes humus formation and eradicates pathogens [17]. Deviating from this range hinders fermentation. A C/N ratio above 40:1 provides insufficient nitrogen. This suppresses microbial growth and prolongs the fermentation cycle [18]. By contrast, a C/N ratio below 20:1 results in relative carbon shortage, so that microorganisms cannot assimilate surplus nitrogen [19]. This unassimilated nitrogen readily volatilizes as ammonia gas. Ammonia volatilization is especially severe under hot, alkaline conditions. This causes nitrogen loss, odors, and greenhouse gas emissions [20].

In practical applications, single feedstocks can hardly reach the ideal C/N ratio. Multi-source co-fermentation is therefore widely adopted. Sludge, kitchen waste, and manure possess low C/N ratios and high moisture. They are often mixed with high-carbon structural conditioners like straw or sawdust [21]. This supplements carbon and improves pile porosity. Conversely, crop straws require blending with high-nitrogen materials to balance nutrients [22]. Organic carbon is continuously oxidized into CO₂ during solid-state fermentation. Nitrogen accumulates relatively. The C/N ratio drops continuously. A final C/N ratio of 15–20:1 is generally regarded as the maturity indicator for fermented products [23].

2.2. Aeration Strategies and Oxygen Supply

Aeration delivers oxygen to drive microbial metabolism. It regulates pile temperature and removes excess moisture [24]. Ideal aeration satisfies microbial oxygen demand. It also minimizes energy use and gas emissions [25]. Modern aeration strategies have evolved from constant continuous-airflow modes to intermittent and dynamic regulation frameworks.

2.2.1. Continuous vs. Intermittent Aeration

Forced aeration in solid-state fermentation includes continuous aeration (CA) and intermittent aeration (IA). These two methods differ significantly. They vary in their mechanisms for reshaping internal microenvironments and their application efficacy [26].

Continuous aeration (CA) delivers a constant 24 h airflow. It eliminates oxygen mass transfer resistance and accelerates early-stage degradation [27]. Nevertheless, CA suffers from prominent practical drawbacks. First, it removes excessive metabolic heat. The pile struggles to maintain temperatures above 55 °C. This severely weakens pathogen inactivation [28]. Second, persistent air stripping elevates the release of ammonia and volatile

organic compounds (VOCs). Such gaseous pollutants lead to environmental deterioration and reduce the nutrient value of final fermented products [25]. Third, long-term continuous fan operation brings about high energy consumption.

Intermittent aeration (IA) alternates between “aeration-on” and “aeration-off” cycles. This overcomes the defects of CA. Heat is accumulated during the off-aeration period, whereas oxygen supply and moisture adjustment are realized during the aeration-on phase, generating distinct operational merits. First, IA balances thermal and oxygen demand. The aeration-off phase suppresses convective heat loss. This reduces heat dissipation. Microbial metabolic heat accumulates internally. This helps the pile quickly reach the thermophilic phase. The subsequent on phase replenishes depleted oxygen [29]. Well-tuned IA parameters can effectively extend the thermophilic duration and boost degradation efficiency of recalcitrant substrates such as lignocellulose. Second, IA facilitates nitrogen conservation, promotes humification, and mitigates greenhouse gas emissions. During the aeration-off stage, residual oxygen is rapidly depleted, forming alternating aerobic–anoxic microzones within the pile. This unique microenvironmental condition selectively enriches typical facultative anaerobic taxa, including *Bacillus* and *Pseudomonas*, as well as diverse denitrifying bacteria. These functional microbes promote the decomposition of macromolecular organic matter, increase humic acid accumulation, and enhance compost humification [25]. Furthermore, appropriate on/off ratios weaken the persistent ammonia-stripping effect, lowering ammonia volatilization and nitrous oxide emissions via nitrification–denitrification processes within micro-anoxic niches [26].

2.2.2. Dynamic Oxygen Supply Model Based on Oxygen Uptake Rate (OUR)

Intermittent aeration (IA) possesses prominent engineering merits. Nevertheless, conventional IA adopts empirical fixed on-off durations, while microbial oxygen demand varies greatly across heating, thermophilic, cooling, and maturation phases. Fixed-time aeration causes issues. Oxygen supply becomes inadequate in the thermophilic phase, triggering local anaerobic zones and methane generation. Accordingly, over-aeration occurs during the cooling phase. This wastes energy [25,30]. Therefore, dynamic control models based on the oxygen uptake rate (OUR) are current research hotspots [31].

The oxygen uptake rate (OUR) serves as a core indicator that directly mirrors microbial metabolic activity. It quantifies the biological oxygen consumption per unit mass of organic matter per unit time [32]. The OUR curve presents an inverted “U” profile. Values rise rapidly during the heating phase. They peak during the thermophilic phase. This indicates massive mineralization of easily degradable organic carbon. Substrates decrease during cooling and maturation. Humus stabilizes. The OUR eventually drops to its lowest point [33].

The OUR-based dynamic oxygen supply model is a high-precision closed-loop feedback control system. It coordinates equipment operation with microbial oxygen demand [34]. Firstly, in situ sensing and computation are implemented. Sensors are placed inside the pile or exhaust ducts. They collect real-time data on exhaust oxygen concentration, flow rate, and pile temperature. The current instantaneous OUR is calculated. This uses mass conservation and gas state equations [35]. Secondly, intelligent parameter modulation is realized. The system compares the real-time OUR with set oxygen thresholds. It uses algorithms like PID, fuzzy logic, and machine learning. Based on deviations, the system adjusts the variable-frequency drive (VFD). This changes fan speed. Alternatively, it calculates optimal on/off ratios for the next aeration cycle [31].

The OUR-based model fundamentally achieves “on-demand oxygen supply”. Mechanistically, it maintains pile oxygen within an efficient and safe range, with exhaust oxygen kept at 10–15%. On one hand, exhaust oxygen data only reflect the average oxygen level of the entire compost pile. Local anaerobic microsites can still form due to material compaction

and airflow channeling. These microzones cannot be completely eliminated by overall exhaust oxygen control. This regulation strategy can substantially reduce anaerobic dead zones formed by material compaction and airflow channeling, yet cannot fully eradicate microscale anoxic pockets merely relying on exhaust oxygen detection [36]. On the other hand, the system automatically reduces aeration during late stages. Organic matter stabilizes here. This prevents moisture loss and ammonia volatilization [37]. Measured data prove its superiority. The OUR feedback model shortens the fermentation cycle by 15–20%. It reduces fan energy consumption by 30–50%. This maximizes economic benefits. It achieves multi-dimensional synergy in nitrogen conservation, emission reduction, energy saving, and humification [31].

2.3. Bi-Directional Feedback Mechanism of Temperature and Moisture

Among solid-state fermentation parameters, temperature and moisture do not function independently. Instead, they interact via thermodynamic principles and microbial metabolism to form a highly delicate bi-directional feedback system. Understanding and controlling this balance are crucial to ensuring efficient organic degradation and safe products.

2.3.1. Duration of Thermophilic Phase and Pathogen Inactivation

Temperature mirrors microbial metabolic activity and heat release. The solid-state fermentation process consists of heating, thermophilic, cooling, and maturation phases. Both temperature magnitude and the duration of the thermophilic phase determine final product safety.

Biologically, heat inactivation of harmful organisms is a cumulative process. It is not instantaneous. When pile temperature exceeds 55 °C, cell membranes break down. This affects *Salmonella*, *E. coli*, parasite eggs, and weed seeds. Intracellular proteins and metabolic enzymes undergo irreversible denaturation and lose their biological functions [38]. Instantaneous high temperatures differ from sustained high-temperature exposure. Standards mandate that composting must maintain temperatures above 55 °C for at least 3 days. Static composting requires over 15 days of high temperatures [39]. Short thermophilic phases are dangerous. Harmful organisms survive in edge regions and cold spots. They may multiply during the cooling phase using residual nutrients. This causes a microbial rebound. It poses severe safety risks [40]. Accordingly, extending the thermophilic phase is a primary engineering goal.

2.3.2. Dynamic Balance Between Moisture Evaporation and Dry Matter Degradation

Extending the thermophilic phase faces a physical contradiction. This is the bi-directional feedback between organic degradation heat and moisture evaporation heat loss.

Moisture is a prerequisite for degradation. Microbes cannot decompose dry solids directly. They utilize dissolved nutrients. The material surface must maintain a complete water film. A moisture content of 50–65% guarantees smooth degradation performance. Nevertheless, high temperatures cause moisture loss. Intense microbial metabolism releases abundant heat energy. Much of this heat vaporizes moisture. Studies indicate that over 80% of total heat loss originates from water evaporation [33].

Moisture evaporation dissipates large amounts of heat, preventing pile temperature from rising above 75 °C, protecting thermophilic microorganisms from thermal damage and maintaining the thermal stability of the system [33]. However, rapid evaporation causes moisture to drop below 40%. This destroys the water film on solid particles [41]. Although undegraded organics remain, liquid mass transfer ceases. Osmotic pressure inhibits microbial exchange and extracellular enzymatic reactions. Metabolic activity stalls [28,42]. Once degradation ceases, heat generation terminates, and pile temperature drops sharply.

Premature termination of fermentation leads to “pseudo-maturity” [43]. This highlights the tight bi-directional feedback among temperature, moisture, and microbial metabolism.

Therefore, process control must balance these factors. It must ensure efficient degradation and heat production. It must control aeration to prevent excessive moisture loss. The goal is coordinating multiple factors to achieve a dynamic balance of degradation, heat production, evaporation, and insulation: securing sufficient degradation and heat generation while modulating aeration intensity to avoid excessive moisture loss.

2.3.3. Practice of Dynamic Fed-Batch Process

Conventional single-batch solid-state fermentation suffers from inherent limitations. Readily available carbon substrates are rapidly depleted, leading to substrate starvation and metabolic decline of the microecosystem in later stages [44]. The thermophilic phase is brief, as the depletion of easily degradable substrates and moisture loss lead to rapid cooling. Pathogen inactivation and recalcitrant organic degradation are compromised [45]. To overcome this, the dynamic fed-batch process was introduced. It adopts dynamic regulation concepts from bioengineering. Fresh organic materials are added in stages. This continuously provides efficient metabolic substrates. It sustains pile heat and degradation efficacy [46].

The fed-batch strategy delivers prominent engineering advantages. First, it prolongs the thermophilic phase. When the temperature begins to drop, fresh degradable materials are added, thereby restoring metabolic activity and heat production. The phase with temperatures above 55 °C can last for two weeks or more. This thoroughly inactivates pathogens. It accelerates the degradation of antibiotics and microplastics [44]. Second, it preserves moisture balance. Fresh feedstocks such as kitchen waste or sludge possess high moisture content and replenish evaporated water. The system adjusts moisture naturally without extra watering. It aligns with temperature-moisture feedback rules. This ensures sustained metabolism. Third, it improves space utilization and treatment capacity. Substantial volume reduction (>30%) occurs after early-stage high-temperature degradation. Step-wise feeding takes advantage of the newly available void space and maximizes reactor capacity [45]. The overall processing efficiency and capacity increase by over 40% compared with traditional batches. This holds high promotional value.

However, staged feeding also raises potential biosafety risks. Newly added raw materials cannot undergo the same long-term high-temperature treatment as the original compost matrix. Local under-treated zones may remain, carrying residual pathogens. Thus, regular monitoring is required for practical operation. After each feeding cycle, representative sampling should be performed; further, material mixing uniformity should be checked and pathogen indicators should be tested. These measures ensure sufficient pathogen inactivation and reduce biosafety risks in fed-batch composting.

2.4. Spatiotemporal Evolution of pH and In Situ Buffer Regulation

In aerobic composting, pH indicates dynamic changes in physicochemical properties. It regulates microbial succession, humification, and nitrogen transformation.

2.4.1. “V-Shaped” Dynamic Evolution of pH

The classic V-shaped pH dynamic profile is typically observed in compost systems dominated by carbon-rich raw materials, yet this pattern is not universal and is highly dependent on feedstock characteristics.

Early fermentation is the acidification phase. Mesophilic microbes degrade soluble sugars. Metabolism generates abundant volatile fatty acids (VFAs). Rapid organic acid accumulation makes the pH drop and stabilize in the slightly acidic range of 5.5–6.5. Insufficient aeration or excessive easy carbon causes acid buildup. This leads to over-acidification, which suppresses core microbial activity and halts fermentation [47]. However, high-ammonium

and inherently alkaline feedstocks (e.g., poultry manure) show distinctly different pH trajectories. Their initial pH remains near-neutral or weakly alkaline from the start, without an obvious early acidification stage.

For typical carbon-rich compost matrices, the system shifts to alkaline during the thermophilic and maturation phases. Microbes degrade recalcitrant substrates like ligno-cellulose and proteins. Proteins undergo intense ammonification. This releases abundant free ammonia (NH₃). This is the main cause of nitrogen loss [48]. Free ammonia hydrolyzes into ammonium (NH₄⁺). This consumes hydrogen ions (H⁺) [49]. Meanwhile, accumulated VFAs degrade under high temperatures and strong oxidation. They also volatilize. Consequently, the pH rises rapidly. It peaks at 8.5–9.0 during the thermophilic phase. It drops slightly later. It finally stabilizes in the weakly alkaline range. This completes the V-shaped evolution for carbon-dominant compost systems.

2.4.2. Mechanisms of Dynamic Buffer Regulation and Ammonia Inhibition

When the pH reaches 8.5–9.0, nitrogen loss and pollution occur. This is a major bottleneck. From a chemical perspective, nitrogen exists in the forms of ammonium (NH₄⁺) and free ammonia (NH₃). Under conditions of pH > 8.0 and high temperature, the chemical equilibrium shifts sharply, driving the conversion of ammonium ions into volatile ammonia gas. This loses valuable nitrogen and causes pollution. Adding biochar or fulvic acid inhibits ammonia volatilization [50]. “In situ pH buffer regulation” using exogenous additives is a key solution. It introduces specific buffer materials early on. These include modified biochar, phosphogypsum, superphosphate, and magnesium salts. Their active surface functional groups buffer hydrogen ions. This stabilizes the system pH at 7.0–8.0 throughout fermentation. This suits microbial metabolic needs [50].

Exogenous additives realize simultaneous nutrient retention and rapid maturation. In terms of physicochemical retention, acidic buffers such as superphosphate directly neutralize alkaline ammonia and convert it into stable inorganic salts. Synergistic addition of magnesium and phosphate salts triggers chemical precipitation. This reacts with free ammonia to form highly stable struvite crystals. This firmly fixes volatile ammonia [51]. Biochar combined with microbial consortia regulates community structure. This significantly reduces nitrogenous greenhouse gases and ammonia [52]. This regulation also ensures maturation. The stable, weakly alkaline buffer environment prevents early acidification. It provides an optimal environment for lignin-degrading enzymes (laccase and manganese peroxidase) and thermophilic actinobacteria. This dramatically accelerates macromolecule cleavage and humus synthesis [53].

In brief, in situ buffering regulation against pH fluctuation is of great importance for nitrogen conservation, emission abatement and maturation acceleration. The optimal regulation ranges and bi-directional impact mechanisms of these key parameters are systematically summarized in Table 2.

Table 2. Optimal regulation ranges and bi-directional impact mechanisms of key composting parameters.

Core Parameters	Optimal Regulation Range	Impact of Below-Ideal-Range Parameter Values	Impact of Above-Ideal-Range Parameter Values	Core Regulation Goal	References
Carbon-to-Nitrogen Ratio (C/N)	25–30:1 (optimal: ~25:1)	<20:1: Nutrient excess. Insufficient carbon energy. Excess nitrogen easily converts into escaping ammonia under hot, alkaline conditions. This causes nitrogen loss and odor.	>40:1: High energy, low nutrients. Lack of nitrogen hinders microbial reproduction. Slow heating, significantly prolonged cycle. Poor maturation.	Prevent nutrient imbalance. Ensure efficient degradation. Prevent nitrogen loss at the source.	[19,54]

Table 2. Cont.

Core Parameters	Optimal Regulation Range	Impact of Below-Ideal-Range Parameter Values	Impact of Above-Ideal-Range Parameter Values	Core Regulation Goal	References
Temperature	Thermophilic phase (>55 °C)	Fails to reach target or too short: Incomplete pathogen and parasite inactivation. Harmful microbes rebound during cooling.	>75 °C: Excessive heat kills beneficial microbes and halts biological degradation.	Thoroughly kill pathogens and weeds. Accelerate recalcitrant pollutant cleavage. Achieve safe product.	[40]
Moisture	50–65%	<40%: Surface water film breaks. Microbes stop working due to “thirst”. Fermentation terminates prematurely (false maturation).	Excess moisture: Microbial metabolism hindered. Slow heating. Incomplete degradation. Excessive evaporation removes massive latent heat, causing rapid cooling.	Excessive water evaporation removes large amounts of latent heat, resulting in a sharp drop in compost temperature.	[33]
Aeration and Oxygen Supply	OUR-based dynamic IA. Exhaust oxygen maintained at 10–15%.	Blind stoppage/insufficient oxygen: It creates local anaerobic dead zones, triggers methanogenesis, and slows degradation.	Continuous/excessive aeration: It causes “overcooling” and shortens thermophilic phase. Stripping effect worsens ammonia/VOC loss. It increases energy use.	Meet true metabolic oxygen demand. Balance heat accumulation. Minimize energy use and gas emissions.	[43]
pH Value	7.0–8.0	Early phase < 5.5: Organic acid buildup causes over-acidification, kills beneficial microbes, and halts composting.	Thermophilic phase > 8.0: Violent equilibrium shift. Soluble ammonium massively converts into escaping ammonia gas. This causes severe pollution.	Forcefully block violent ammonia volatilization (conserve nitrogen). Provide optimal environment for degrading enzymes.	[55]

3. Composting Enhancement Technologies and Cutting-Edge Process Innovations

Conventional parameter optimization can ameliorate the basic microenvironment of solid-state fermentation. Nevertheless, it cannot overcome the physicochemical bottlenecks of slow recalcitrant degradation and gas emissions. Introducing physical and chemical materials has become a core strategy to break these limits and achieve high-value conversion.

3.1. Synergistic Enhancement by Physical/Chemical Materials

Exogenous functional materials no longer merely improve the macroscopic physical properties of fermentation piles. They now penetrate the micro-level. They affect electron transfer dynamics, interface-specific adsorption, and biochemical pathways [56,57]. Such microlevel intervention effectively eliminates intrinsic bottlenecks restricting microbial metabolic activity.

3.1.1. Modified Biochar Synergy: Evolution from Physical Water Retention to Electron-Shuttle Effects and Targeted VOC Adsorption

Biochar has abundant pores and a huge surface area. It was previously used purely as a physical conditioner. It increased porosity, optimized oxygen transfer, and retained moisture. However, modification technologies (acid/base modification, metal loading) have advanced. Biochar’s role has evolved. It has changed from a single physical medium to a multi-dimensional catalytic system with targeted adsorption functions.

It should be noted that Direct Inter-Species Electron Transfer (DIET) is originally a metabolic mechanism identified in anaerobic methanogenic syntrophic systems, rather than the dominant reaction pathway under aerobic solid-state fermentation conditions. Modified biochar acts as an electron shuttle to accelerate oxidative transformation of lignin aromatic structures, which provides favorable precursors for humus formation. This electron transfer function mainly facilitates lignin degradation, and there is no solid research evidence proving that DIET can directly promote the hydrolytic cleavage of the

glycosidic bond [58]. Targeted Adsorption and Pollution Control: Biochar's network shows targeted interception of gas pollutants after surface modification [59]. For NH_3 and VOCs, grafted oxygen-containing functional groups (carboxyls and hydroxyls) exhibit strong capture abilities [60]. Biochar physically traps pollutants via micropores. It also anchors gaseous pollutants chemically via hydrogen bonds, electrostatic attraction, and surface complexation. This synergistic mechanism cuts off odor and greenhouse gas emissions at the source. It fixes free nitrogen, enhancing fertilizer efficacy [61].

3.1.2. Application of Nanomaterials and Novel Inorganic Conditioners

Nanomaterials and novel inorganic minerals provide new routes for precise biochemical intervention at the microscale.

Nanomaterial Enzyme Stimulation and ARG Regulation Mechanism: Nano-metals and -oxides (nano-zero-valent iron, nano- TiO_2 , and nano- ZnO) have high specific surface reactivity. They are widely used in composting [62]. At proper concentrations, nano-metal ions act as co-factors for core degrading enzymes (e.g., laccase and peroxidase). They stimulate enzyme expression. This accelerates polymer degradation and humification. Notably, reactive oxygen species (ROS) generated by nanomaterials act as non-specific oxidants and cannot selectively target ARG-carrying microbial cells. Moderate ROS stress reshapes the overall composition of the microbial community during solid-state fermentation. Furthermore, nanomaterial-induced environmental pressure alters microbial co-selection effects, thereby indirectly regulating the total abundance of ARGs in the system. This interpretation conforms to the mainstream research consensus on nanomaterial-mediated ARG dynamics. Moderate ROS stress reorganizes microbial community succession and alters microbial ecological niches, thereby indirectly regulating the overall ARG abundance of the compost system. In addition, nanomaterial-induced environmental stress alters microbial selective pressure. This regulates ARG abundance via microbial co-selection effects, which conforms to the mainstream understanding of ARG variation in compost systems [63,64]. This approach effectively reduces the horizontal spread risk of antibiotic resistance genes in compost.

Ion Anchoring and Chemical Phase Transition of Inorganic Conditioners: Nanomaterial research focuses on enzyme/stress catalysis. Novel inorganic minerals utilize 3D lattice cavities and spatial retention. They stabilize system nutrients via chemical equilibrium shifts. Minerals like zeolite, medical stone, and phosphogypsum possess natural ion exchange and acid-base buffering capabilities. They build efficient "ion capture traps" in the microenvironment. They convert volatile ammonia nitrogen into slow-release nutrients via chemical phase transition. This profoundly reshapes physicochemical properties and enhances fertilizer efficiency [65].

3.2. Biological Enhancement and Precise Control of Functional Microbes

Microorganisms govern material transformation and energy cycling during solid-state fermentation. Natural fermentation relies on spontaneous succession. Nevertheless, environmental fluctuations and recalcitrant materials cause slow startup, long cycles, and severe nitrogen loss. Bioaugmentation, defined as the exogenous addition of specialized microbial inocula, constitutes a core strategy for upgrading fermented product quality.

3.2.1. Classification and Mechanisms of Functional Consortia

According to microbial taxonomy and core metabolic functions, inoculants applied in solid-state fermentation can be classified into three major functional consortia:

(1) Macromolecule Degradation Consortia: Lignocellulosic raw feedstocks such as straw contain compact crystalline structures that are difficult to degrade. Fungi including *Trichoderma* and *Phanerochaete chrysosporium* form extensive hyphae to penetrate rigid lignocellulose matrices. These fungi secrete cellulase and lignin peroxidase to break down

aromatic structures and glycosidic bonds, facilitating preliminary decomposition of recalcitrant organic fractions [11]. The initial temperature rise of the fermentation system mainly depends on mesophilic bacteria rather than fungi. *Bacillus subtilis* and other fast-growing bacteria consume soluble oligomers and amino acids produced by fungal degradation. Their rapid metabolic activity generates heat, driving the system into the thermophilic stage, and establishes a high-temperature fermentation environment [66,67]. Fungal lignocellulose degradation functions predominantly in the later cooling and maturation stages to promote humification.

(2) Nitrogen Conservation and Odor Control Consortia: High-nitrogen substrates such as sludge release large amounts of free ammonia under high-temperature conditions, causing severe odor and nitrogen loss. Nitrifying bacteria are highly sensitive to sustained high temperatures, so AMO-mediated nitrification rarely proceeds effectively during the peak thermophilic phase. Functional strains including *Pseudomonas* and nitrogen-fixing bacteria mainly mitigate ammonia loss via microbial nitrogen assimilation in the thermophilic period. They convert free ammonia into microbial biomass protein, directly reducing volatile nitrogen loss. Nitrification processes occur mainly during the subsequent cooling and maturation phases, further converting nitrogen into stable nitrate [68]. This staged nitrogen transformation pattern balances odor suppression and total nitrogen preservation across the whole fermentation cycle.

(3) Humification and Biocontrol Consortia: The quality and biosafety of final fermented products are largely determined by late-stage humification and pathogen suppression. Heat-tolerant actinobacteria (e.g., *Streptomyces* and *Nocardia*) adapt to the sustained high-temperature environment of the thermophilic phase. They maintain stable metabolic function and continuously secrete polyphenol oxidase. This enzyme catalyzes oxidative condensation of lignin-derived phenolic precursors and accelerates polymerization toward stable humic acid skeletons during maturation [37]. Such humification pathways convert fragmented organic moieties into recalcitrant humus, improving fermentation stability and the soil-amending potential of end-products. Beyond humification, these actinobacteria, together with *Bacillus* strains, synthesize bioactive secondary metabolites including lipopeptides and antibacterial peptides. Rather than directly disrupting pathogen cell membranes, these metabolites interfere with pathogen proliferation and build a sustainable antagonistic microhabitat. This microbial antagonism suppresses harmful pathogens such as *Salmonella* and *E. coli*, reducing disease risks and ensuring safe agricultural application.

3.2.2. Microbial Evolution Innovation: From Single Strains to Synthetic Consortia

Specific functional strains exhibit unique metabolic advantages under stable laboratory culture conditions. However, bioaugmentation using single strains or randomly mixed microbial preparations frequently exhibits poor colonization performance in complex practical solid-state fermentation environments. Exogenous inoculated strains face intense thermal stress and fierce resource competition from indigenous microorganisms, making them vulnerable to competitive exclusion by native microflora.

Evolution of synthetic microbial consortium bioaugmentation. To mitigate such colonization barriers, bioaugmentation strategies have evolved gradually. The technical route has shifted from simple strain isolation and screening to rationally constructed synthetic microbial consortia guided by multi-omics profiling [69]. A synthetic microbial consortium is not merely a random physical mixture of individual strains; it represents a manually assembled microecosystem underpinned by compatible metabolic interaction networks. Its key functional mechanisms depend on metabolic cross-feeding and biofilm-supported synergistic defense to enhance microbial fitness within fermentation substrates [70].

Metabolic cross-feeding. Synthetic consortia establish tightly coupled nutrient circulation loops. Metabolic intermediates generated by upstream fungal species serve as available

carbon and nitrogen substrates for downstream bacteria. Such complementary substrate exchange alleviates end-product inhibition and improves energy conversion efficiency under well-controlled lab conditions [71]. Even with this synergistic advantage, the delicate nutrient balance is vulnerable to field-scale disturbances. Fluctuating temperature, variable pH, and uneven raw material composition disrupt coordinated cross-feeding, weakening consortium metabolic activity during full-scale operation.

Synergistic defense and biofilm colonization. Strains in synthetic consortia mediate inter-species communication via quorum-sensing signals and jointly secrete extracellular polymeric substances (EPSs). The secreted EPSs encapsulate microbial cells to form compact biofilm matrices [72]. This biofilm layer can partially buffer abrupt fluctuations in temperature and moisture and mitigate competitive pressure exerted by indigenous microorganisms. Nevertheless, this protective effect has clear limitations. Biofilm cannot fully insulate inoculated strains from long-term resource competition with native microbiota, and gradual functional decay of exogenous strains is commonly observed in continuous industrial fermentation systems.

Bottlenecks for large-scale field promotion. Overall, rationally designed synthetic consortia show promising potential to improve solid-state fermentation performance under controlled conditions. Nevertheless, large-scale field application still faces critical challenges, including complex environmental variability, inconsistent long-term microbial activity, high production costs, and difficulty in continuous colonization against indigenous microbiomes. Further validation through full-cycle pilot-scale and industrial trials is needed to confirm the robustness and economic feasibility of synthetic microbial consortia. The categories, representative strains, and application characteristics of these typical inoculants are summarized in Table 3.

Table 3. Categories, representative strains, and application characteristics of common composting inoculants.

Functional Category	Representative Microbial Communities	Core Action Mechanisms	Applicable Scenarios	Advantages	References
Macromolecule Degradation Consortia	Fungi: <i>Trichoderma</i> and <i>Phanerochaete chrysosporium</i> . Bacteria: <i>Bacillus subtilis</i> .	Fungal targeted cleavage: Secrete cellulase and lignin peroxidase. Break glycosidic bonds and aromatic networks. Bacterial synergistic heating: Rapidly metabolize cleavage monomers (oligosaccharides).	High-carbon/recalcitrant materials (e.g., crop straw and garden waste).	Break lignocellulose barriers. Rapidly start fermentation and enter thermophilic phase.	[11]
Nitrogen Conservation and Odor Control Consortia	Bacteria: Nitrifying bacteria, <i>Pseudomonas</i> , and nitrogen-fixing bacteria.	Nitrification: Express ammonia monooxygenase (AMO). Oxidize volatile ammonia to stable nitrate. Assimilation: Convert nitrogen into cellular proteins.	Thermophilic phase of low-carbon, high-nitrogen materials (e.g., sludge and kitchen waste).	Block ammonia volatilization. Massively cut odors and greenhouse gases. Increase total nitrogen retention.	[68]
Humification and Biocontrol Consortia	Actinobacteria: <i>Streptomyces</i> and <i>Nocardia</i> . Bacteria: Specific Bacilli.	Accelerated humification: Secrete polyphenol oxidase. Catalyze condensation of phenolic precursors. Accelerated humic acid synthesis. Biocontrol: Produce lipopeptides, targeting pathogen membranes.	Quality improvement and biosafety control during hot and late phases.	Extremely heat-tolerant. Strongly kill <i>Salmonella</i> , <i>E. coli</i> . Ensure safe fertilizer application	[68]
Synthetic Microbial Communities	Cross-kingdom artificial microecosystems designed via multi-omics and metabolic calculations.	Metabolic cross-feeding: Upstream fungal intermediates serve as downstream bacterial carbon. Relieve inhibition. Biofilm colonization: Quorum sensing coordinates EPS secretion for dense biofilms.	Complex open real-world engineering with severe heat stress and intense indigenous competition.	Build “physical ecological shield”. Break single-strain colonization limits. Maximize energy conversion.	[69]

3.3. Cross-Field Coupling: Bioelectrochemically Assisted Composting (BFC/MCFT)

Traditional solid-state fermentation relies on natural thermodynamics and biochemistry. It suffers from slow temperature rise and low recalcitrant degradation efficiency. Recently, bioelectrochemical systems were integrated into solid-state fermentation. This created “Microbial Compost Fuel Cells (MCFT/BFC)”. Such cross-field coupling between physical electric fields and microecological environments overcomes thermodynamic constraints [73].

3.3.1. In Situ Micro-Electric Field Construction and Electrogenic Heating Mechanism

MCFT establishes an in situ micro-electric field within the fermentation pile. For engineering configuration, conductive materials (e.g., carbon felt and graphite) are embedded in the anoxic zone of the pile to serve as the anode, whereas the cathode is installed on the pile surface or ventilation channels (aerobic zone). Both electrodes are linked through an external circuit. During fermentation, electroactive microbes (e.g., *Geobacter* and *Shewanella*) act as “micro-generators”. While degrading organics, they transfer stripped electrons to the anode via extracellular respiration. Electrons flow through the circuit to the cathode. They combine with oxygen and protons to form water. This generates a continuous weak current inside the pile [74].

This in situ micro-electric field induces prominent electrogenic heating. Low-intensity current flowing across the resistive solid-state fermentation matrix produces Joule heat. Furthermore, the electric field stimulates overall microbial metabolic activity and accelerates heat output. This dual physical–biological heating mode enables rapid temperature increase in fermentation piles under cold conditions and addresses the bottleneck of low-temperature startup [75].

3.3.2. Core Role of Direct Inter-Species Electron Transfer (DIET) in Accelerating

Degradation of Recalcitrant Organics

Beyond macroscopic heating, the micro-electric field profoundly transforms the microecology. It fundamentally reshapes microbial energy transfer by inducing and enhancing Direct Inter-Species Electron Transfer (DIET).

In traditional solid-state fermentation, microbial collaboration relies on chemical carriers like hydrogen or formate. This diffusion mode is slow and vulnerable to environmental changes. It is the main reason why lignocellulose degrades slowly. In MCFT-coupled solid-state fermentation systems, the micro-electric field stimulates microorganisms to synthesize conductive nanowires (pili) or enables them to directly utilize anode materials as electron conduits. Upstream acidogenic bacteria and downstream degrading bacteria establish physical connections. Electrons bypass chemical carriers. They transmit directly across cells as point-to-point electrical signals [76].

DIET greatly improves microbial electron transfer efficiency. This efficient energy transfer lowers the activation energy required to cleave complex chemical bonds (e.g., aromatic rings and glycosidic bonds). Studies show that DIET increases recalcitrant macromolecule degradation rates by over 30%. It accelerates the oxidative condensation of precursors. It significantly boosts humic acid generation and humification indices in the final product [77]. The mechanisms of bioelectrochemically assisted composting and in situ micro-electric field construction are illustrated in Figure 1.

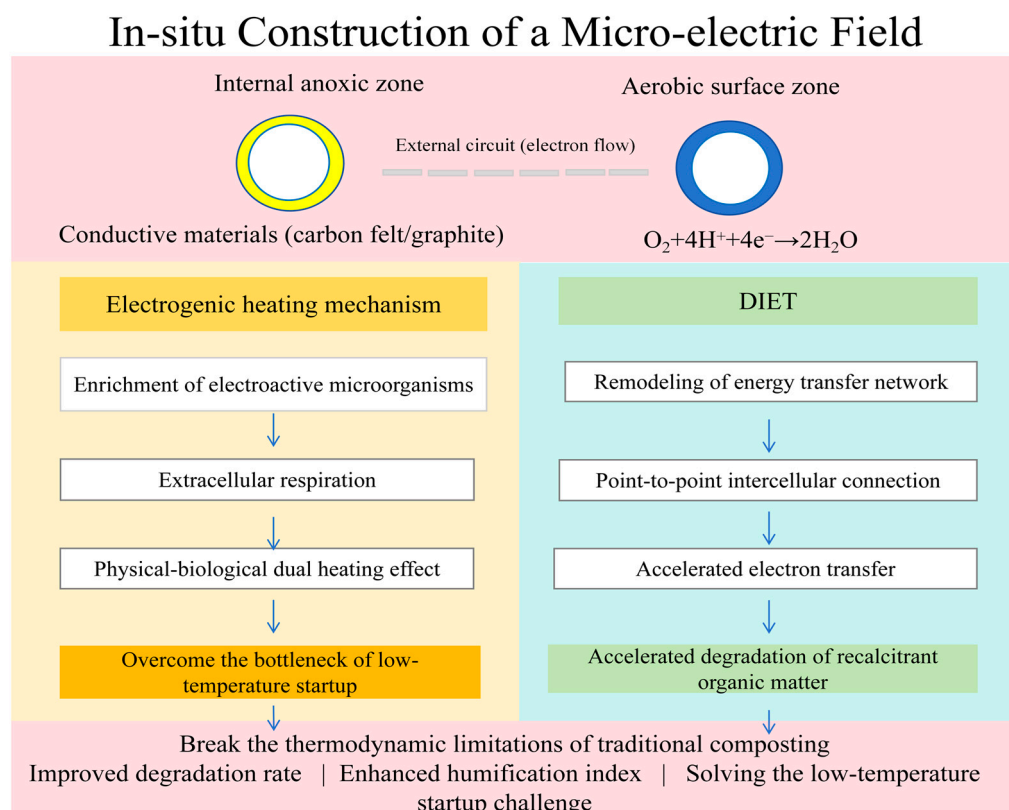


Figure 1. Cross-field coupling: bioelectrochemically assisted composting (BFC/MCFT) and in-situ micro-electric field construction [74,77].

3.4. System-Level Coupling of Hydrothermal Carbonization and Composting Processes

High-moisture (>80%) solid wastes such as municipal sludge and food waste present considerable practical challenges. Conventional aerobic solid-state fermentation suffers from heat loss induced by water evaporation, slow temperature rise, and high demand for excessive structural bulking agents. Coupling hydrothermal carbonization (HTC) with aerobic solid-state fermentation has become a cutting-edge series process. It achieves efficient reduction and safe resource recovery for wet waste [78].

3.4.1. Route of High-Moisture HTC Treatment Combined with Hydrochar Recirculation

HTC is a thermochemical conversion technology. It operates in a closed, high-temperature (180–250 °C), high-pressure aqueous environment. It bypasses energy-intensive pre-drying. It uses free water in wet materials as the reaction medium. Within hours, it dehydrates and decarboxylates complex organic macromolecules. It converts them into solid, carbon-rich “hydrochar” [79].

In this coupled path, extremely recalcitrant, high-moisture waste first enters the HTC reactor. It undergoes rapid volume reduction and carbonization. Subsequently, the dehydrated hydrochar is recycled as a functional additive. It enters conventional aerobic fermentation tanks for synergistic co-fermentation. This system-level coupling reduces the strict moisture and C/N requirements of front-end composting. The hydrochar’s catalytic action enhances the subsequent fermentation process [79].

3.4.2. Synergistic Effects of HTC Coupling on Humification and Heavy Metal Passivation

Hydrochar recirculation is not simple physical mixing. It generates significant synergistic effects at the microecological and chemical levels. This accelerates humification and passivates heavy metals [80]. (1) Electron mediation and accelerated humification: Unlike regular high-temperature biochar, hydrochar retains abundant oxygen-containing func-

tional groups (carboxyl, hydroxyl, and carbonyl) and aliphatic structures. Once introduced into the fermentation system, these functional groups endow hydrochar with favorable redox activity. Hydrochar serves as an effective electron shuttle that mediates DIET and accelerates oxidative cleavage of recalcitrant precursors (e.g., lignin derivatives). It also uses abiotic catalysis to lower the activation energy for polyphenolic and amino acid condensation. This accelerates the synthesis of core humic macromolecules and shortens the cycle. (2) Dual physicochemical heavy-metal passivation: Municipal sludge contains high heavy-metal (Cu, Zn, Pb, and Cd) contents. Direct composting risks pollution. In the coupled process, the high-temperature and high-pressure HTC environment destroys organic–metal complexes. It physically encapsulates metals within the dense hydrochar carbon skeleton. This provides primary immobilization. During the subsequent recycling-based solid-state fermentation, humification proceeds at an elevated rate. Newly synthesized humic macromolecules, rich in carboxyl and phenolic hydroxyl groups, act synergistically with the active sites of hydrochar. They produce extreme chemical complexation and chelation with free heavy-metal ions. This “physical encapsulation plus chemical chelation” converts highly toxic heavy metals into stable residual fractions. It fundamentally eliminates application risks. The synergistic effects of this system-level process coupling are illustrated in Figure 2.

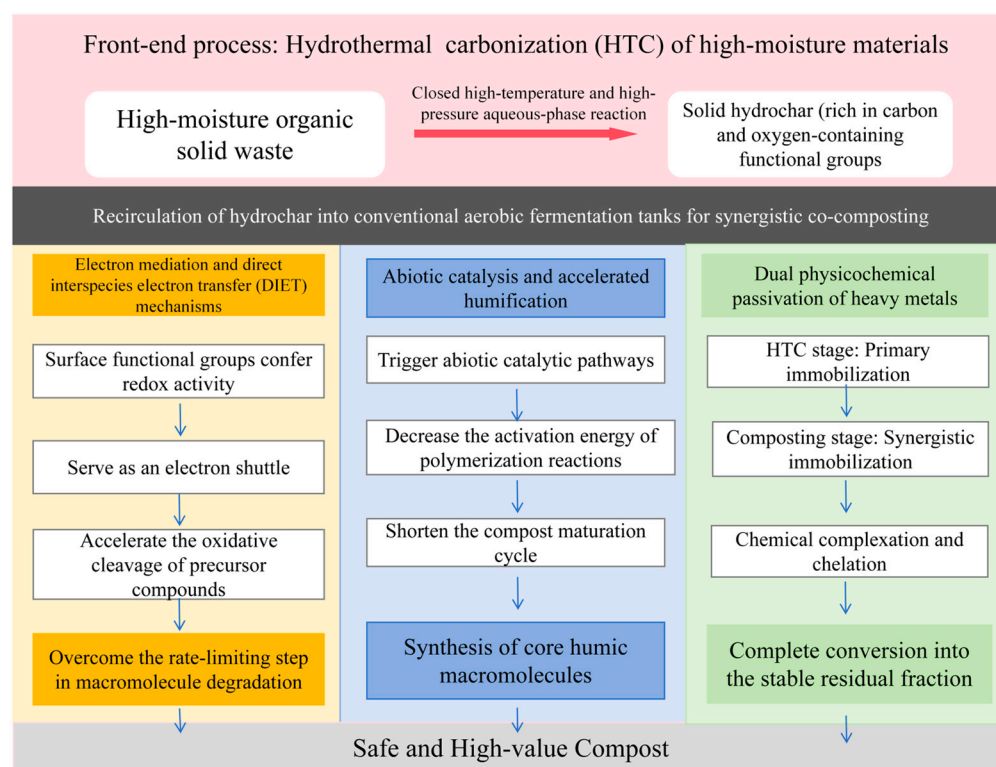


Figure 2. System-level process coupling: hydrothermal carbonization (HTC) and composting [79,80].

3.5. Goal-Oriented Innovation: Mitigation of Emerging Contaminants and Greenhouse Gas (GHG) Abatement

The objectives of conventional solid-state fermentation are shifting from basic maturation and pathogen inactivation toward targeted removal of emerging contaminants (ECs) and effective greenhouse gas (GHG) abatement [81].

3.5.1. Degradation and Inhibition Mechanisms of Antibiotic Resistance Genes (ARGs) and Microplastics (MPs)

In complex matrices (e.g., livestock manure and municipal sludge), the enrichment of ARGs and MPs poses massive safety risks. Modern solid-state fermentation tackles these

distinct pollutants via “genetic information blocking” and “macromolecular skeleton cleavage” [82]. Biochemically regulated inhibition of horizontal gene transfer (HGT) for ARGs: The dynamic microecological interface within solid-state fermentation systems serves as a hotspot for ARG horizontal gene transfer (HGT) [83]. Different from thermal degradation, thermophilic temperature primarily causes DNA denaturation rather than complete DNA breakdown. High heat damages the cell membranes of ARG host microorganisms. It releases intact free DNA into compost matrices. Notably, such thermally denatured DNA can partially recover its structural integrity during the cooling phase and still maintain transformable activity. These residual DNA fragments remain biologically available. They can be taken up by microbes during the cooling stage, potentially increasing the risk of transformation-mediated HGT. Therefore, high temperature cannot thoroughly eliminate ARG dissemination risks [84]. Furthermore, adding specific conditioners passivates heavy metals and antibiotic residues. This removes the “co-selection pressure” on microbial communities. It cuts off the cross-species transmission of ARGs via mobile genetic elements (MGEs) like plasmids and integrons at the source [85].

Multi-phase surface weathering and fragmentation of microplastics: Microplastics have stable polymer carbon chains and strong biochemical resistance. Previous overestimation of enzymatic depolymerization in conventional composting is revised here. Under composting conditions, high temperature mainly induces thermal-oxidative aging on plastic surfaces [86]. Indigenous fungi and actinobacteria secrete extracellular enzymes to act on plastic amorphous regions. This process only triggers superficial weathering and physical fragmentation, rather than thorough depolymerization. Large-size microplastics are broken into smaller particles. This process even produces nanoplastics, introducing additional potential environmental risks [87].

3.5.2. Integrated Strategies of Smart Semi-Permeable Membranes for NH_3 and N_2O Abatement

Forced aeration leads to continuous gas stripping, which facilitates ammonia (NH_3) volatilization and nitrous oxide (N_2O) emission. Integrated multi-phase blocking strategies based on smart semi-permeable membranes address this problem.

Physical interception and condensate reflux driven by interfacial phase transition: Smart semi-permeable membranes (e.g., expanded polytetrafluoroethylene (ePTFE)) construct specific separation boundaries above the fermentation pile [88]. The ePTFE membrane features unique micropores. Oxygen (O_2) and carbon dioxide (CO_2) pass freely to maintain aerobic conditions. Nevertheless, it blocks large aerosol molecules and odor gases. High-temperature steam condenses on the inner membrane surface to form a dense condensate water film. Volatile NH_3 rapidly dissolves into this film to form ammonium (NH_4^+). It drips back into the pile. Such gas-liquid phase-transition reflux achieves physical interception and in situ nitrogen recovery and improves nitrogen-retention efficiency [89].

It is noteworthy that this continuous ammonia reflux brings potential feedback risks. The continuous backflow of dissolved ammonium gradually increases pile pH during long-term operation. The elevated pH further promotes NH_3 volatilization, which weakens the long-term ammonia control effect of membrane systems. To sustain stable nitrogen retention, auxiliary pH buffering regulation is essential throughout the whole composting period. Full-cycle operational monitoring data confirm that reasonable pH stabilization can offset the alkaline feedback effect and maintain the long-term effectiveness of membrane ammonia control. Cascade synergistic reduction network—“inhibition and external blocking”: Physical membranes block aerosols but struggle against small, poorly soluble N_2O molecules. Advanced engineering strategies combine membrane covering with in situ chemical matrix modification [89]. For instance, nitrification inhibitors or functional biochar are pre-mixed. Biochar optimizes oxygen transfer and substantially reduces anaerobic dead

zones. Nitrification inhibitors specifically block N_2O generation pathways. Such system-scale “internal biochemical source inhibition plus external physical airflow interception” enables effective abatement of pollutant gases and greenhouse gas emissions. An integrated overview of these goal-oriented innovations for contaminant mitigation and GHG control is presented. A comprehensive overview of these goal-oriented innovations for contaminant mitigation and GHG abatement is illustrated in Figure 3.

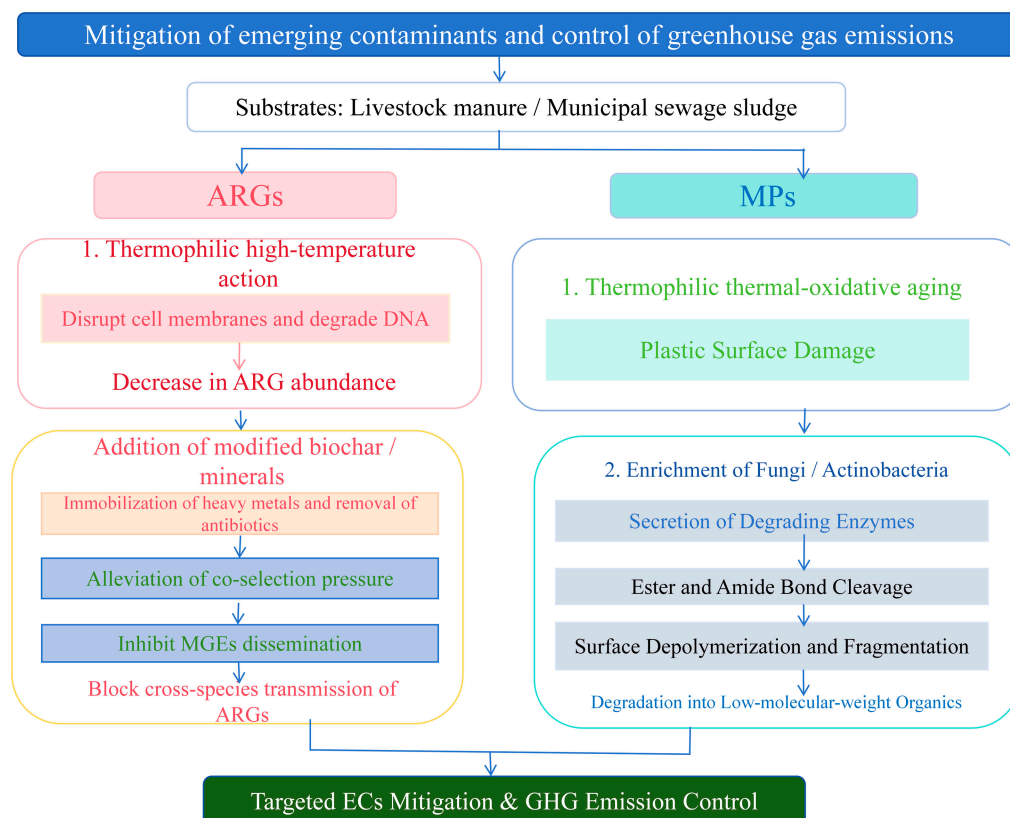


Figure 3. Goal-oriented innovation: mitigation of emerging contaminants and control of greenhouse gas emissions [82].

4. Mathematical Models and Intelligent Development of Solid-State Fermentation

4.1. Solid-State Fermentation Kinetics and Mass–Heat Transfer Models

Conventional solid-state fermentation depends on empirical black-box operations, which hinders precise process control. Establishing mathematical models that couple microbial metabolism with macroscopic physical fields is critical to intelligent-oriented process development.

4.1.1. Progressive Refinement of Carbon–Nitrogen Kinetic Models

Early kinetic models used simple first-order reactions. They treated complex solid waste as a uniform carbon source. However, degradation rates vary massively. Single models produce huge deviations [90].

Multi-component kinetic models have advanced rapidly. They divide organic matter by degradability: easily degradable (sugars and soluble proteins), slowly degradable (cellulose), and inert (lignin). These models integrate modified Monod equations to rigorously characterize the nonlinear coupling among substrate concentration, oxygen thresholds, temperature-dependent inhibition, and microbial proliferation. For complex nitrogen transformation processes, multi-component models adopt ammonification rate constants and

dynamic pH/temperature feedback. They highly accurately predict ammonia peaks and total nitrogen loss. This provides quantitative theoretical bases for nitrogen conservation [91].

4.1.2. Mass–Heat Transfer and Three-Dimensional Multi-Physics Models

Heat and mass balance determines reaction rates. The macroscopic outcome depends on the dynamic interplay of microbial heat production, latent heat evaporation, and convective heat loss.

Early lumped-parameter models assumed uniform environments, ignoring spatial gradients. With the advancement of computational capabilities, computational fluid dynamics (CFD) has been introduced into solid-state fermentation modeling. CFD treats the pile as a non-uniform porous medium. By solving Navier–Stokes equations coupled with Darcy’s law, it rigorously describes fluid dynamics of forced aeration in complex matrices [33].

These multi-physics models precisely simulate three-dimensional temperature, oxygen, and moisture distribution. They accurately locate bottom “cold zones” and internal “anaerobic dead zones”. This provides reliable digital twin support for reactor design and precise aeration.

4.2. IoT and Multi-Parameter In Situ Online Monitoring

Traditional monitoring relies on manual offline sampling. It exhibits severe spatiotemporal lag. It fails to capture transient microbial metabolic shifts. The Internet of Things (IoT) builds multi-dimensional data sensing networks. It drives the leap from “empirical black boxes” to “data-driven digital precision regulation” [92].

4.2.1. Sensor Arrays and In Situ Data Sensing Mechanisms

IoT architectures center on distributed in situ sensor arrays.

Probes deployed at different depths continuously acquire high-frequency measurements of temperature, humidity, oxygen content, and volatile organic compounds (VOCs).

Mechanistically, electrochemical or zirconia-based oxygen sensors enable the accurate tracking of the dynamic oxygen uptake rate (OUR), which directly mirrors aerobic microbial metabolic activity. Metal–oxide–semiconductor (MOS) sensor arrays target and quantify NH_3 and VOC concentrations. These signals are transmitted to cloud servers through low-power wide-area networks (LPWANs), building a real-time data panorama of microecological succession [36].

4.2.2. Closed-Loop Synergistic Control of Smart Membrane-Assisted Aeration

Within advanced membrane-coupled solid-state fermentation systems, IoT platforms serve as both monitoring units and actuation drivers for closed-loop control. Smart membrane aeration perfectly couples sensor arrays with actuators.

When internal sensors detect oxygen dropping below thresholds or VOC spikes, edge computing units engage. They run fuzzy PID control algorithms. The system calculates optimal compensation air volumes. It precisely regulates the frequencies and duty cycles of variable-frequency drive (VFD) fans. Such “on-demand variable-frequency oxygen supply” prevents overcooling and drying caused by continuous aeration. It perfectly matches the internal micro-positive pressure with the ePTFE membrane’s physical interception [89]. It ensures efficient deep maturation. It aerodynamically suppresses the diffusion of VOCs and GHGs. It minimizes energy use while maximizing environmental benefits.

4.3. Decision Making in AI-Driven Processes

Traditional dynamic models struggle with highly heterogeneous, fluctuating multi-source waste. Parameter calibration is difficult. With enhanced edge computing and a large

number of IoT historical data, machine learning (ML) data-driven models are becoming crucial to precise decision making.

4.3.1. Machine Learning-Based Maturity Prediction

Accurate prediction of final maturity, represented by indicators such as the germination index (GI), guarantees the quality of fermented organic fertilizers. Since solid-state fermentation processes exhibit strong nonlinear characteristics, conventional linear regression approaches show poor performance. Artificial neural networks (ANNs) and random forest (RF) show massive advantages here [93].

ANNs build multi-layer hidden structures imitating neural synapses. They autonomously extract nonlinear mapping relationships and link easily measurable precursors (e.g., initial moisture, C/N, temperature curves, and pH) with final maturity. This achieves high-precision end-to-end prediction [94]. RF is a powerful ensemble learning algorithm. It builds hundreds of independent decision trees using voting mechanisms. It easily handles high-dimensional, noisy engineering data. It quantitatively outputs the importance contribution of each input feature toward fermentation maturity [95]. This provides critical guidance for optimal front-end raw material blending [96].

4.3.2. Decision Making in Deep Learning-Enabled Multi-Objective Optimization of Aeration

For the core optimization of aeration strategies, artificial intelligence enables a paradigm shift from empirical response-oriented control toward feedforward predictive optimization. State-of-the-art intelligent systems couple deep time-series models (e.g., long short-term memory (LSTM)) with heuristic algorithms (Genetic Algorithms (Gas); Particle Swarm Optimization (PSO)) [97]. The decision mechanism works as follows: AI models use historical data to precisely predict future temperature trends, moisture loss, and fan energy use under different variable-frequency curves. Optimization algorithms then efficiently explore this high-dimensional prediction space to identify dynamic optimal solutions balancing three competing objectives: ensuring sufficient oxygen transfer, mitigating ammonia stripping, and minimizing fan power consumption. This AI-driven dynamic optimization frees systems from rigid timer/thermostat logic. It truly achieves energy-saving, low-carbon operation throughout the life cycle [98].

5. Challenges and Future Perspectives

Aerobic solid-state fermentation has achieved substantial breakthroughs in multi-physics coupling, intelligent process regulation, and targeted bioaugmentation. Nevertheless, considerable obstacles remain for translating theoretical findings into full-scale industrial deployment. Future research should overcome scale-up bottlenecks, decipher underlying biological mechanisms, and develop innovative product-oriented applications.

5.1. Current Research Limitations

5.1.1. Disconnect Between Laboratory-Scale Tests and Engineering Scale-Up

Numerous mechanistic investigations of novel processes (e.g., additives and microbial consortia) are performed in laboratory-scale reactors smaller than 100 L, where mixing and mass-heat transfer conditions are nearly ideal. Nevertheless, scale-up to hundred-ton-level systems generates pronounced spatial heterogeneity. Compaction causes anaerobic dead zones. Edge heat loss creates “cold zone” effects. Parameters optimized under laboratory conditions often perform poorly in practical engineering scenarios. This discrepancy is particularly prominent for microbial-coupled fuel cell-based solid-state fermentation/bioelectrochemical fermentation (MCFT/BFC). Micro-electric fields show excellent heating and degradation in the lab. In scale-up scenarios, low solid-matrix conductivity and increased electrode spacing raise internal resistance. Complex materials form insu-

lating layers on electrodes. The electron transfer network collapses. Electrogenic heating completely fails in large piles.

5.1.2. Inadequate Ecological Risk Assessment of Emerging Additives

Researchers have extensively leveraged nanomaterials (nano-zero-valent iron and graphene oxide) and modified hydrochar to maximize nitrogen retention or catalysis. Existing studies overemphasize the favorable catalytic effects observed during the fermentation stage while neglecting potential toxic risks after fermented products are applied to soils. Unreacted nanomaterials may agglomerate in soil pores or oxidize, releasing toxic ions. They disrupt indigenous soil microecology. They risk root absorption and food chain accumulation. The lack of cross-chain “fermentation–soil–plant” ecological risk assessments is a massive bottleneck for applying emerging conditioners.

5.2. Future Technological Evolution and Trends

5.2.1. Multi-Omics Mining of Microbial “Dark Matter”

Conventional isolation-based techniques can cultivate fewer than 5% of microbial taxa present during solid-state fermentation, and the remaining 95% are regarded as microbial dark matter. Breaking this blind spot relies on crossing multi-omics technologies (metagenomics, metatranscriptomics, and metabolomics). Using Metagenome-Assembled Genomes (MAGs), researchers can directly reconstruct complete genetic information of unknown extremophiles or lignin degraders from DNA without cultivation [99]. Combined with the metabolomics-enabled precise profiling of metabolic intermediates, this strategy allows for the reconstruction of the core metabolite interaction network over the whole fermentation life cycle. Such efforts facilitate the discovery of novel thermostable degrading enzymes and supply well-defined genetic-part libraries for next-generation synthetic artificial microbial consortia [100,101].

5.2.2. Life Cycle Assessment-Driven, Carbon-Negative, Green Solid-State Fermentation Processes

Against the background of carbon-neutrality targets, process-optimization objectives will shift from basic harmless treatment toward carbon-negative performance, which necessitates life cycle assessment (LCA). It demands rigorous carbon footprint accounting across all stages: waste collection, fermentation energy use, GHG diffusion, and final soil carbon sinks [102,103]. Future innovations will focus on two areas: first, utilizing intelligent membrane covers and chemical blocking to drop methane and N₂O emissions to near zero; second, coupling CO₂ mineralization reactions via alkaline minerals (silicates and fly ash) to fix CO₂ in situ within the compost. This ultimately converts solid waste into highly stable carbon sink carriers. It achieves net-negative carbon emissions over the processing life cycle [104,105].

5.2.3. Development of Customized Functional Solid-State Fermentation Products

Traditional compost products act as low-value general base fertilizers. They struggle to solve specific agricultural issues. Future products will evolve into targeted soil-conditioning agents. For heavy-metal-polluted mining soils (e.g., Cd- and Pb-contaminated sites), complex-functionalized fermented products can be tailored for application. Fermentation specifically enhances active functional groups (e.g., carboxyl and sulfhydryl) in humus, making them act as long-acting metal passivators. For saline–alkali soils, salt-tolerant, plant growth-promoting rhizobacteria (PGPR) can be directionally inoculated. This yields stress-tolerant, growth-promoting microecological inoculant preparations [97]. This closed-loop “soil diagnosis–reverse customized composting process” R&D model will unlock immense commercial and ecological potential for organic solid waste.

6. Conclusions

Most current published reviews only discuss isolated single technologies, such as separate aeration regulation, biochar amendment and intelligent monitoring. They ignore the internal mutual restriction and synergistic coupling relationships of parameter control, material enhancement, microbial engineering, cross-field electrothermal coupling and intelligent control in actual industrial solid-state fermentation. Fragmented single-technology summaries cannot provide systematic whole-chain low-carbon guidance for practical organic waste treatment engineering.

The present paper systematically summarizes the technical pathways and research advances of aerobic solid-state fermentation in its transition from empirical operation to high-efficiency, low-carbon, intelligent, and environmentally safe performance.

First, we clarify the optimal ranges and multi-dimensional control indices for core parameters. The ideal initial C/N ratio is 25–30:1. Moisture should be 50–65%. For aeration, OUR-based dynamic intermittent aeration (IA) maintains exhaust oxygen at 10–15%. This eliminates anaerobic zones while minimizing energy use and gas losses. In situ regulation using superphosphate or magnesium salts locks system pH between 7.0 and 8.0. This precise microenvironment regulation ensures that the pile enters and maintains the thermophilic phase (>55 °C). It completely inactivates pathogens and accelerates recalcitrant pollutant cleavage. Second, we summarize multi-dimensional state-of-the-art process-enhancement strategies. The dynamic fed-batch feeding of fresh organic substrates alleviates late-stage substrate starvation and overcooling induced by false maturation. In biomaterial enhancement, multi-omics-designed synthetic consortia use cross-feeding to relieve inhibition. They synergistically secrete extracellular polymeric substances (EPSs) to build dense biofilms, overcoming single-strain colonization failures. Bioelectrochemical solid-state fermentation combined with hydrochar recycling realizes cross-field coupling among physical, electrochemical, and microecological processes, triggering Direct Inter-Species Electron Transfer (DIET). Such coupling reduces the activation energy for lignocellulose decomposition and substantially elevates humic acid content and humification indices. Furthermore, HTC series processes use physical encapsulation and chemical chelation to convert highly toxic heavy metals into stable residues, eliminating application risks. Finally, goal-oriented innovations effectively mitigate emerging contaminants and block GHGs. For solid-phase risks, thermophilic heat stress damages host membranes and thermally degrades DNA to block the horizontal gene transfer of antibiotic-resistance genes (ARGs). Specific fungi and actinobacteria secrete powerful extracellular enzymes to target non-crystalline microplastic surfaces. This catalyzes bond cleavage for surface depolymerization. For gas-phase blocking, smart semi-permeable membranes utilize a “gas–liquid phase-transition reflux” mechanism to intercept and dissolve ammonia in situ. The synergistic internal pre-mixing of nitrification inhibitors or functional biochar creates an “internal biochemical inhibition, external physical blocking” network. This conquers small-molecule GHG diffusion.

In summary, through deep integration of state-of-the-art materials, synthetic microbial reprogramming, cross-domain process coupling, and artificial intelligence-driven decision-making algorithms, aerobic solid-state fermentation realizes precise digital parameter regulation and full-life cycle energy conservation. It fulfills macroscopic environmental objectives: efficient emerging-contaminant (EC) mitigation, high-efficiency nitrogen retention, and near-zero greenhouse gas emissions.

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administration, J.C. (Jie Cao) and J.C. (Jinling Cai) All authors have read and agreed to the published version of the manuscript.

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