Research Progress on Efficient Aerobic Composting Technology for Livestock and Poultry Manure

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Abstract. This paper systematically reviews the challenges faced by aerobic composting in pollution reduction and carbon emission mitigation, including the control of heavy metal contamination, antibiotic residue, estrogen, microplastics, and the reduction of environmentally impactful gases (including greenhouse gases). Based on the analysis of these points, technological advancements for emission reduction, pollution control, and efficiency enhancement are summarized, aiming to provide scientific references for the upgrading of aerobic composting technology for livestock and poultry manure. This research holds significant importance for promoting the green development transformation of agricultural aerobic composting technology and enhancing energy conservation, emission reduction, and pollution control in the agricultural sector.

Keywords: livestock and poultry manure; aerobic composting; pollution reduction and carbon emission mitigation; energy conservation and emission reduction.

Fertilization is an effective means of resource utilization of livestock and poultry manure, among which aerobic composting has gradually become one of the primary methods due to its simple process and low operating costs[1]. However, current aerobic composting technology faces challenges such as heavy metal contamination, antibiotic residues, nitrogen loss, odor pollution, and high greenhouse gas emissions, which does not meet the national requirements for green and circular development in agriculture[2]. Therefore, it is necessary to summarize and analyze advanced and frontier technologies for low-carbon and efficient aerobic composting domestically and internationally, as well as to clarify the influence mechanisms of various means for synergistic pollution reduction and carbon emission mitigation.

This paper systematically discusses the reduction of greenhouse gas emissions, air pollution, heavy metal contamination, antibiotic pollution control, nitrogen fixation, humic acid directional conversion, and mechanical optimization in aerobic composting. The driving mechanisms of various pollution reduction and emission reduction are analyzed to provide scientific references for the upgrading of aerobic composting technology for livestock and poultry manure.

1. Challenges in Efficient Aerobic Composting for Pollution Reduction and Carbon Emission Mitigation

1.1 Environmental Risk Substance Control

1.1.1 Heavy Metal Control

Various heavy metals, including cadmium (Cd), zinc (Zn), copper (Cu), lead (Pb), chromium (Cr), arsenic (As) and mercury (Hg), have been detected in livestock and poultry manure, which were primarily sourced from feed additives with high heavy metal content[3]. Research by Wang Fei et al. [4] showed that among 42 samples of commercial organic fertilizers collected from agricultural product producing areas in North China from August to November 2012, the over-limit rate of heavy metal Pb was as high as 80.56%, while other heavy metals were within the limits. According to German compost standards, Cd was not excessive, but Cr, Cu, Pb, Zn, Ni, and Hg were all excessive. The humification process of composting can alter the forms of heavy metals, passivate them, and reduce their biological toxicity and activity. The research results of Bu Guijun et al. [5] showed that composting could reduce the content of water-soluble heavy metals and complex them with humic substances to lower the biological availability of heavy metals in products. Thus, how to regulate the composting process to improve heavy metal stability is one of the significant challenges in the development of efficient aerobic composting technology for pollution reduction and carbon emission mitigation.

1.1.2 Antibiotic Degradation

Antibiotics have been classified as one of the most important new pollutants worldwide. Aerobic composting has a significant degradation effect on sulfonamides, fluoroquinolones, tetracyclines, and other antibiotics. Through the biodegradation process, it can effectively remove antibiotics, ARGs, antibiotic-resistant bacteria (ARB), and other harmful factors in raw materials[6]. Regulating the reaction process to achieve effective antibiotic degradation and ensure the safety and stability of fertilizer products is one of the essential challenges of efficient aerobic composting.

1.1.3 Estrogen Control

Environmental hormones released into farmland environments can affect soil microbial community structure characteristics[7]. Livestock and poultry manure is one of the primary sources of environmental hormones[8]. Without proper treatment or complete degradation, estrogens in livestock and poultry manure returned to the field can be adsorbed by soil organic matter and migrate horizontally and vertically in soil and water systems[9]. Therefore, controlling such new pollutants as estrogens is essential for developing efficient aerobic composting technology and reducing risks in agricultural ecosystems.

1.1.4 Microplastic Pollution Control

Microplastics (<5mm), another new environmental pollutant, have become a global environmental issue [10]. The pollution characteristics of microplastics in aerobic composting are manifested both in their impact on microbial community activities, thereby affecting composting efficiency, and in the potential risks posed by compost products to soil ecosystems and plant growth. Song's [11] research results showed that the presence of microplastics reduced bacterial community abundance and diversity. Therefore, controlling microplastic pollution in aerobic composting of livestock and poultry manure is crucial for protecting the environment and safeguarding public health.

1.2 Control of Environmentally Impactful Gas Emissions

The control of ammonia and greenhouse gas emissions is closely related to the transformation of nitrogen and carbon during aerobic composting. If not effectively controlled, it can affect the nitrogen nutrient and humus content of the final product while imposing a burden on the ecosystem[12]. The humification process of composting generates large amounts of volatile inorganic and organic compounds, with NH3, H2S, and some VOCs being the primary malodorous components of aerobic fermentation[13]. The release of malodorous gases during composting not only harms the environment and residents but also reduces the carbon, nitrogen, and sulfur content during the composting process[14]. Effective control of the generation and emission of malodorous gases and greenhouse gases during aerobic fermentation is another crucial topic for reducing environmental pollution and achieving low-carbon and efficient aerobic composting.

2. "Dual Carbon" Strategy and Opportunities for Efficient Aerobic Composting Development

Efficient aerobic composting of manure is a core aspect of resource recycling and an essential component of green agricultural development and rural revitalization. On January 1, 2024, the "Opinions of the CPC Central Committee and the State Council on Learning from the Experience of the Green Rural Revival Program and effectively promoting all-round rural vitalization" was officially released, marking the 12th guidance document for the work concerning "agriculture, rural areas, and farmers" issued by the central government since the 18th National Congress of the Communist Party of China. It emphasizes "synergistically promoting the resourceful treatment and utilization of rural organic household waste, manure, and agricultural production organic waste."

Efficient aerobic composting of manure affects numerous upstream and downstream sectors, including antibiotic control in livestock and poultry breeding, biodegradable plastic use upstream, and water pollution prevention, soil pollution prevention, modern agricultural green development, and beautiful countryside construction downstream. The development of efficient aerobic composting technology for manure presents significant opportunities while aligning with the trend of synergistic pollution reduction and carbon emission mitigation under the "Dual Carbon" Strategy.

3. Current Status of Efficient and Low-Carbon Aerobic Composting Technology Development

3.1 Pollution Reduction Technologies

3.1.1 Heavy Metal Stabilization

The BCR method classifies heavy metals into acid-soluble, reducible, oxidizable, and residual fractions. Acid-soluble and reducible heavy metals can be easily absorbed and utilized by plants. Oxidizable and residual fractions are relatively stable and less likely to be absorbed by plant[15]. During composting, macromolecular organic matter is decomposed into small molecules by microorganisms, which then synthesize humic substance precursors that further synthesize humic substances. Humic acids can passivate heavy metals, reduce the available heavy metal content, alter heavy metal forms, and inhibit their biological availability[16]. Ultra-high temperature environments can accelerate organic matter degradation efficiency, shorten material maturation time, and promote humus synthesis[17]. Wen Ping et al.[18] fitted the complexation properties of humic acids and their components in ultra-high temperature composting, high-temperature composting, and sludge samples based on the Ryan-Weber fluorescence quenching model, confirming that this process could enhance the formation of humic substances in humic acids, thereby improving the complexation stability and capacity with Cd(II) and stabilizing heavy metals.

3.1.2 Antibiotic Degradation

Controlling composting process parameters such as moisture content, temperature, and C/N ratio to improve the abundance and activity of beneficial microbial communities is the basic means of antibiotic degradation. Adding microbial agents to enhance degradation efficiency is also a crucial method for antibiotic control in composting. Huang Feifei et al.[19] found that EM microbial agents accelerated antibiotic degradation. Wang et al.[20]found that adding biochar to compost reduced ARG proliferation and enhanced microbial community metabolism.

3.1.3 Estrogen Degradation

Aerobic composting technology inherently degrades certain estrogen but often leaves residues, posing risks during land application. Therefore, additional measures are necessary. Wang Zhen et al.[21] found that eight types of estrogen were still detected 70 days after composting, potentially emitting estrogen into soil environments through manure land application and further contaminating aquatic environments via surface runoff. Current research on enhancing estrogen degradation during aerobic composting is primarily focusing on adding exogenous microbial agents, microbial immobilization products, and conditioners. Sun et al.[22] improved microbial community abundance and accelerated estrogen degradation by inoculating exogenous dominant strains and humic acids. Li et al.[23]studied the enhanced effects of different conditioners and microbial agents on estrogen degradation during composting, finding that combined addition of rice husk biochar or oyster shell powder with biological fertilizer fermentation agent significantly promoted microbial degradation of estrogens.

3.1.4 Microplastic Degradation

Since ultra-high temperature composing technology is the most prominent method currently, few research on microplastic control in composting can be found. Chen et al.[24]found that hyperthermophilic bacteria facilitated microplastic degradation, removing 43.7% of microplastics from sludge after 45 days of ultra-high temperature treatment, the highest reported value for microplastic biodegradation. The degradation mechanism of microplastics during compost maturation is unclear, and the microbial-enzyme degradation mechanism of microplastics requires further exploration.

3.2 3.2 Emission Reduction Technologies

3.2.1 Physical Emission Reduction

Physical emission reduction techniques are primarily achieved through optimizing composting process conditions and adding adsorbent additives. Optimizing composting process conditions can improve the pile structure and optimize the conversion processes of carbon and nitrogen, and thereby reducing emissions of various odorous gases and greenhouse gases. Adsorbent additives such as clay [25], bentonite [26] , and biochar[27], and exhibit strong adsorption and emission reduction properties. The research by Zhan Zhuoyue [28] et al. indicated that the ratio of coconut shell biochar and calcium magnesium phosphate significantly affects the synergistic emission reduction of NH_3, CH_4, and nitrous oxide (N_2O) during chicken manure composting. Fang et al. [29] studied the effect of semi-permeable membrane covering combined with intermittent aeration on gas emissions during industrial-scale aerobic composting of dairy manure. During the aeration intervals, the emissions of carbon dioxide, methane, nitrous oxide, and ammonia outside the membrane were reduced by 64.23%, 70.07%, 54.87%, and 11.32%, respectively, compared to inside the membrane.

3.2.2 Chemical Emission Reduction

Based on the chemical reaction characteristics of different gases, adding chemical reagents to the compost can also promote gas emission reduction. Common chemical additives in composting include phosphates, acids and bases, metal salts, and plant extracts [13][30][31]. The research by Wu et al. [32] showed that compared to the control without superphosphate, adding 10-30% superphosphate significantly reduced greenhouse gas emissions such as NH_3, CO_2, CH_4, and N_2O. Chen Wenxu [33] et al.'s research results indicated that adding Fe_2O_3 to chicken manure composting effectively reduced sulfur-containing odor emissions, cumulatively reducing total sulfur loss by 63.17%.

3.2.3 Biological Emission Reduction

Adding exogenous dominant microbial agents to livestock manure can alter the compost microbial community composition and accelerate organic matter decomposition, thereby reducing greenhouse gas and odor emissions. Tu Z. et al.[34] found that adding composite microbial agents and biochar to compost reduced NH_3 and N_2O emissions. For nitrogen and sulfur-containing odors, by adding specific exogenous microbial agents, the microbial community structure and abundance can be directed toward favorable directions, promoting nitrification and sulfur oxidation processes, thereby reducing odor emissions[30].

4. Conclusion and Outlook

Currently, research on efficient aerobic composting of livestock manure for heavy metal stabilization, antibiotic degradation, greenhouse gas and odor emission reduction is abundant and relatively mature. However, research on multi-technology integration requires further exploration.

For the two novel pollutants, estrogen and microplastics, research is still in its initial stages, with unclear mechanisms and unspecified treatment methods. Future developments could focus on cultivating specific microbial strains and strengthening the integration with advanced oxidation, photocatalysis, and other organic pollutant removal technologies for more in-depth research.

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