Research Advances in Fertilizer Production Technologies Utilizing Solid Waste Resources

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Abstract The conversion of waste resources into fertilizer represents a crucial strategy for optimizing waste utilization and attaining "carbon peak and neutrality" objectives. This approach not only effectively mitigates greenhouse gas emissions but also enhances the organic matter content in soil, thereby supporting the advancement of sustainable agriculture. Currently, the principal fertilizer production technologies utilizing solid waste resources encompass hydrothermal fertilizer production, aerobic fermentation, wrapping fertilizer production, micro-storage fertilizer production, and biochemical rapid decomposition. This paper examines the applicability and limitations of these technologies in practical contexts, and anticipates their developmental trends and future prospects. It aims to offer practical guidance and constructive support for the resource utilization of solid waste and the sustainable development of related industries.

Key words Solid waste utilization, Waste fertilizer production technology, Hydrothermal carbonization, Aerobic fermentation, Current application, Research advance

0 Introduction

With global economic development and the rapid pace of urbanization, the volume of solid waste generated has been increasing steadily, making its resource utilization a critical issue for sustainable development worldwide. According to relevant studies, improper management of solid waste not only leads to inefficient consumption of resources and energy but also contributes to significant ecological and environmental pollution problems[1]. China, as a major producer of solid waste, generates substantial amounts of both agricultural waste and municipal solid waste. Agricultural waste primarily comprises straw and livestock manure, while urban kitchen waste constitutes a significant portion of municipal solid waste[2-3].

If these wastes are disposed of using traditional landfill methods, they will generate large quantities of greenhouse gases, accelerating global warming, occupying land resources, and potentially causing land degradation[4]. Although conventional incineration can reduce waste volume, it carries the risk of emitting harmful gases such as dioxins, which may result in secondary environmental pollution.

In contrast, converting organic waste into organic fertilizers enriched with humus and essential nutrients (including nitrogen, phosphorus, and potassium) through resource-based fertilizer production technologies (*e.g.*, microbial or chemical transformation) offers substantial environmental and ecological advantages. This process effectively reduces greenhouse gas emissions, and the resulting organic fertilizer enhances soil organic matter content, thereby supporting the advancement of sustainable agriculture[2-3,5]. This article categorizes several primary types of waste-to-fertilizer production technologies and summarizes their applicability, advantages, and disadvantages. It aims to provide comprehensive references for understanding the application and promotion prospects of these technologies in agricultural production, thereby establishing a theoretical foundation for the coordinated development of solid waste resource utilization and sustainable agriculture.

1 Brief description of solid waste

Solid waste refers to solid and semi-solid materials generated during human production, daily life, and other activities. Its sources are diverse, covering sectors such as industrial production, agricultural activities, and daily living, and its composition is highly complex. The *Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution* explicitly defines solid waste as: solid, semi-solid, and gaseous materials contained in vessels generated during industrial, domestic, and other activities that have lost their original utility, or have been discarded or abandoned despite retaining utility. It also includes items and substances designated for solid waste management in accordance with relevant laws and administrative regulations.

Based on sources, solid waste is primarily categorized into industrial solid waste, agricultural solid waste, and municipal solid waste. Industrial solid waste arises from industrial production and processing activities, including mining waste rock, mineral processing tailings, smelting waste residues, chemical waste resi-

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dues, and coal gangue. Agricultural solid waste comprises by-products from agricultural production, livestock and poultry breeding, and related activities, such as crop straw, livestock and poultry manure, and discarded agricultural films. Municipal solid waste originates from urban residents' daily lives and related service activities, including domestic garbage, construction debris, and kitchen waste.

In terms of distribution characteristics, solid waste exhibits significant regional and industrial variations. Its generation volume is strongly positively correlated with population density and economic development level. Major sources include large cities, urban agglomerations, and industrial zones. Economically advanced and densely populated areas produce large quantities of solid waste due to high industrialization levels and frequent consumption activities, while economically underdeveloped and sparsely populated areas generate relatively less.

Improper management of solid waste can lead to numerous problems. In terms of land use, the continuous accumulation of industrial and construction waste has encroached on valuable land resources. Although Chinese cities have increased the treatment rate to 58% by building landfills, the treatment capacity remains insufficient to meet the needs of economic and social development[6]. For the atmospheric environment, malodorous gases from the decomposition of organic matter in open storage, dust and dioxins emitted during incineration, and methane and hydrogen sulfide released from landfills all cause impacts. Notably, after subsidies for waste incineration power generation were reduced, improper management can easily exacerbate pollution and affect project profitability[7]. The aquatic environment is vulnerable to pollution from the direct disposal of solid waste into water bodies. Leachate from such waste, carried by rainwater, may contaminate river systems and groundwater—for example, leachate pollution frequently occurs during the biological composting of kitchen waste. In the soil environment, solid waste and its leachate can damage soil physical and chemical properties, inhibit microbial activity, hinder crop growth, and even cause desertification. Additionally, improper processing of kitchen waste into fertilizer may lead to "salt damage". Meanwhile, harmful substances in solid waste can enter the human body through water, air, soil, and other pathways, and the mixing of hazardous wastes may cause explosions and toxic gas leaks[3].

Producing fertilizer from solid waste resources offers numerous advantages. In terms of resource recycling, the nutrient content of biogas residue from the anaerobic fermentation of municipal solid waste meets standards and can be used as fertilizer[8], enabling resource reuse. Mixing agricultural straw and pig manure at a 7 : 3 ratio to produce biogas fertilizer promotes resource recycling[9] and reduces reliance on natural fertilizers. From an environmental protection perspective, the production of agricultural biochemical fertilizers addresses the limitations of traditional composting[10]. Moreover, urban high-temperature wet decomposition fertilizer production, integrated with waste sorting, can absorb organic matter and reduce dioxin emissions[11], effectively reducing land occupation by solid waste and mitigating air, water, and soil pollution. In agricultural production, hydrothermal conversion fertilizers made from kitchen waste through nutrient regulation have improved quality[3]. Organic-inorganic compound fertilizers produced from municipal solid waste can promote flower growth[8], improve soil structure, and increase crop yields. From an industrial development perspective, small-scale automated biochemical fertilizer production equipment helps agricultural cooperatives achieve resource recycling and drive industrial upgrading[12].

2 Fertilizer production technology system and research advances

2.1 Hydrothermal fertilizer production technology In the field of organic waste resource utilization and harmless treatment, hydrothermal technology has shown great application potential due to its unique advantages. This technology creates a high-temperature (150 – 280 ℃) and high-pressure (2 – 10 MPa) aqueous environment in a sealed reaction vessel, facilitating a series of reactions such as hydrolysis, dehydration, and polycondensation of organic matter. These processes convert macromolecular cellulose and lignin into small-molecular humic acid, providing an effective approach for organic waste resource recovery. Meanwhile, hydrothermal treatment achieves efficient inactivation of pathogenic bacteria, with a kill rate exceeding 99.9%[13]. It has significant effects in harmless treatment, which is of great significance for reducing environmental pollution and ensuring ecological security.

In the field of co-processing agricultural and forestry waste, Li Chaosheng *et al.*[2] demonstrated that mixing corn cobs (C/N = 85) and pig manure (C/N = 15) at a 1 : 1 ratio and conducting hydrothermal co-treatment at 240 ℃ for 120 min significantly improves nitrogen recovery efficiency through carbon-nitrogen complementarity. The nitrogen recovery rate increased from 28.3% (when a single raw material was processed) to 47.61%, and the phosphorus recovery rate reached 86.41%, greatly promoting resource utilization and alleviating the shortage of nitrogen and phosphorus resources in agricultural production. Meanwhile, sulfide precipitates formed during the reaction reduced the leaching rate of heavy metals such as Pb and Cd by 30%, effectively lowering environmental risks and ensuring agricultural product safety and soil ecological protection.

Hydrothermal technology also contributes to the high-value utilization of kitchen waste. Wang Lixian *et al.*[3] showed that heating a mixture of 10% starch, 15% protein, and water significantly promotes the Maillard reaction, producing humic acid at concentrations up to 32 g/kg—approximately five times higher than that from single-component treatments. As a valuable component of organic fertilizer, humic acid effectively improves soil structure and fertility, playing a crucial role in the sustainable development of agriculture.

In the field of energy self-sufficiency optimization, innovative advancements in hydrothermal technology have created opportunities for reducing processing costs and facilitating energy recycling. The " hydrothermal-biogas" combined model developed by Xu Fengzhi *et al.* [14] has considerable practical application potential. This model generates electricity by burning waste gas (containing 12% CH_4) produced during hydrothermal treatment at 280 ℃. The electricity generated can meet 35% of the system's energy demand, significantly reducing reliance on external energy sources and promoting low-carbon development in organic waste treatment. Additionally, the calorific value of the produced hydrothermal carbon reached 24.67 MJ/kg, a 35.22% increase compared to raw materials. This hydrothermal carbon shows promise as a slow-release fertilizer carrier, expanding the application scope of hydrothermal products and enhancing the economic efficiency and resource utilization of the entire treatment process.

Currently, several challenges hinder the widespread adoption of hydrothermal technology, and addressing these is crucial for its development and dissemination. In terms of energy consumption costs, the energy required per unit of processing ranges from 0.8 to 1.2 kWh/kg, accounting for approximately 55% to 60% of total operating expenses. Notably, energy consumption during the heating phase accounts for up to 70% of total energy use[14], significantly increasing processing costs. Therefore, reducing energy consumption and improving energy utilization efficiency are imperative for the advancement of this technology, as they are directly linked to its economic feasibility and market competitiveness.

Product safety risks also restrict its application scope. First, chloride ions ($Cl-$) tend to accumulate in the solid phase, with concentrations ranging from 1.2% to 3.5%. When applied to saline-alkali soils, this accumulation can reduce crop yields by 15% – 20% [3], hindering the improvement of saline-alkali land and agricultural productivity. Second, the concentration effect of the hydrothermal process increases the content of heavy metals such as Cu and Zn in the solid phase by 1.5 – 2.0 times compared to raw materials, occasionally exceeding the limits specified in the GB/T 38400 – 2019 organic fertilizer standard[2]. This limits the agricultural application of these products. Therefore, addressing product safety issues is essential to ensure the compliant application of hydrothermal technology in agriculture and to realize the value of technological resource transformation.

2.2 Aerobic fermentation technology Aerobic composting technology is a key method for organic waste treatment. It uses aerobic microorganisms (*e. g.*, *Bacillus* and *Streptomyces*) to decompose organic matter in an oxygen-rich environment, undergoing three distinct stages: heating, high temperature, and cooling. The resulting compost has a stable pH range of 7.0 – 8.5, and the germination index (GI) exceeds 80% [5]. This technology effectively reduces organic waste volume and converts it into high-quality organic fertilizers, which significantly contribute to improving soil quality, enhancing cultivated land productivity, mitigating environmental pollution, and promoting the development of a circular agricultural economy.

Technological innovations have significantly improved the efficiency and quality of aerobic composting. In terms of precise parameter control, Wang Tiejun *et al.* [5] used the response surface method to optimize the fermentation parameters of straw and cow dung. They identified the optimal conditions as a fertilizer source material ratio of 23%, moisture content of 60%, and compression ratio of 39.50%. These conditions effectively extended the high-temperature phase of the compost pile (>55 ℃), resulting in a GI of 96.52%—a significant improvement over traditional parameters. This optimization enhances compost maturity and safety, providing a scientific basis for efficient composting of various materials and promoting the standardized application of this technology.

Song Lianghong *et al.* [15] addressed the efficient conversion of garden waste by combining the properties of grass chips (nitrogen-rich) and branches (carbon-rich). They proposed a composting ratio of soybean residue (as a nitrogen source) : sheep manure (as a microbial carrier) : garden waste = 1 : 1 : 8. This formulation shortened the composting cycle and increased humic acid content. This advancement effectively resolves the problems of long treatment duration and low efficiency in garden waste processing, accelerating resource utilization. It has significant practical implications for the reduction and resource recovery of urban green waste.

Intelligent upgrading of equipment has greatly advanced aerobic composting technology. The double-drive trough-type turner developed by Yao Aiping *et al.* [16] has a turning depth of 0.8 – 1.5 m and an average turning efficiency of 100 – 200 m^3/h. Through optimizing turning operations and implementing automatic control, this technology has effectively reduced nitrogen loss and harmful gas emissions. The integration of intelligent equipment has improved composting efficiency, balancing economic and environmental benefits, and providing strong support for large-scale processing.

Despite its advantages, aerobic composting technology is still restricted by several limitations in widespread adoption, including long processing cycles and large space requirements. Conventional composting typically takes 20 – 60 d, with each ton of material requiring approximately 0.8 – 1.2 m^2 of space, limiting the feasibility of large-scale operations. These constraints are particularly prominent in regions with limited land. Furthermore, significant nitrogen loss during composting adversely affects the nutrient content of the final product[15], reducing its fertilizer efficacy. Additionally, lignin is resistant to degradation, and the degradation rate of lignin in straw is relatively low. Although adding functional bacterial agents can enhance lignin breakdown, this prolongs the processing cycle[12], affecting overall efficiency. Addressing these issues is essential to improve the technological competitiveness of aerobic composting and facilitate its broader implementation.

2.3 Wrapping fertilizer production technology Anaerobic wrapping technology, a key processing step after aerobic composting, has distinct technical principles and significant application value. This method involves placing materials (with moisture content below 60% after aerobic fermentation) into polyethylene film bags, mechanically compacting them to remove air, and thus establishing an anaerobic or microaerobic environment. Residual microorganisms then facilitate secondary decomposition for 30 – 60 d, enabling the process to serve dual functions of storage and decomposition[17]. This process not only further enhances the degree of material decomposition but also facilitates convenient storage, reducing nutrient loss during storage. It is of great significance for improving the continuity and efficiency of organic waste resource utilization.

Significant advancements have been made in equipment integration in the field of technological innovation. Zhang Chongliang *et al.*[16] developed a fertilizer wrapping production system for straw and livestock manure fermentation, which combines a high-temperature biological aerobic fermentation unit with an organic fertilizer baling and wrapping machine. This integration enables a continuous operational process including "crushing, mixing, fermentation, and wrapping". The associated solid-liquid separation equipment has a processing capacity of at least 10 m^3/h[16]. Furthermore, the implementation of efficient sealing technology has significantly reduced leachate generation, providing more effective control of secondary pollution compared to traditional composting methods. This integrated equipment not only improves processing efficiency but also reduces subsequent processing costs and environmental pollution risks, establishing a solid equipment foundation for the large-scale application of this technology. Deng Yanfang *et al.*[18] reported that this process can increase material maturity by 30% – 40% while keeping nutrient loss rates below 5%, which is significantly better than traditional composting methods. Liu Yan *et al.*[19] demonstrated that when the dry matter content of silage raw materials was maintained at 38% ± 2%, optimal fermentation results were achieved through the combined use of rapid microwave oven measurement and mechanical compaction.

From the perspective of farmland application, this technology shows considerable practical potential. Applying organic fertilizer produced by this method in agricultural settings (*e.g.*, orchards) can effectively increase soil organic matter content, improve soil fertility, and promote crop growth[15]. For example, using such organic fertilizers in fruit tree cultivation has been shown to significantly enhance fruit quality. These findings indicate that wrapped fertilizer substantially improves soil fertility and crop quality, which is of great practical significance for advancing sustainable agriculture and increasing the competitiveness of agricultural products.

However, anaerobic wrapping technology still faces several challenges in its promotion. Poor economic performance is a major constraint on its development. The investment cost for necessary fertilizer production equipment is relatively high, posing a significant financial burden for small and medium-sized agricultural enterprises[16–17]. Calculated based on annual processing volume, the unit cost remains relatively high, and the payback period is long, leading many enterprises to hesitate in adopting the technology. Meanwhile, the risk of secondary pollution requires careful consideration. Polyethylene film, commonly used in traditional wrapping, degrades slowly in natural environments. Improper disposal or residual presence in agricultural fields can impair soil aeration and harm ecological protection. Addressing these issues is crucial for improving market acceptance and expanding the application scope of anaerobic wrapping technology.

2.4 Micro-storage fertilizer production technology Straw micro-storage technology plays a crucial role in the efficient utilization of crop straw resources. This technology uses crop straw as the main raw material, adds microbial agents, maintains a moisture content of 45% – 60%, undergoes specific compression treatment, and then is sealed for storage. Decomposition occurs through microbial activity, and under optimal conditions, the process can last more than 24 d[5]. This method effectively converts large quantities of crop straw into valuable resources, mitigates environmental pollution caused by straw burning, and simultaneously provides high-quality organic materials for agricultural production. Consequently, it is of great significance for advancing the circular development of agriculture.

Significant advancements have been made in the optimization of process parameters in the field of technological innovation. Wang Tiejun *et al.*[5] identified the optimal range of key process parameters through experimental research. Under optimized conditions—specifically, a microbial dosage of 1.5‰, composting duration of 32 d, material moisture content of 60%, compression ratio of 39.50%, and fertilizer source material ratio of 23%—the GI of the micro-storage fertilizer reached 96.52%. These conditions facilitated the efficient decomposition and utilization of straw and manure. Inner Mongolia Agricultural University isolated the dominant bacterial flora from more than 100 cellulose-degrading bacterial strains, optimized the culture conditions using the response surface method, and then developed a composite bacterial agent, which increased the GI of corn stalk fermentation products to 96.52%[20]. Additionally, the *Technical Regulations for Corn Stalk Expansion and Micro – Storage* of Jilin Province standardizes parameters such as expansion temperature and chopping length. Expansion pretreatment increases the porosity of stalks by 40%, thereby enhancing the penetration efficiency of microbial agents[21].

From the perspective of rural applicability, this technology has significant potential for widespread adoption. The corn slurry and corn stalk mixed micro-storage technology developed in Heilongjiang Province uses a box-type fermentation device. The investment cost for a single set of equipment is less than 50 000 yuan, and it can process straw and livestock manure on-site[22]. Guangxi has established 36 demonstration farms for elephant grass micro-storage using a "cooperative + farmer" model, training 820 farmers. The cost of producing each ton of micro-storage feed is maintained at 80 – 120 yuan[23–24]. The *Operating Procedures for Micro – Storage Technology* in Qinghai Province specifies the method for strain activation (immersing in 35 ℃ warm water for 2 h) and a layer-by-layer compaction process, facilitating production by farmers and herdsmen in traditional cellars[25].

However, straw micro-storage technology has certain limitations. The moisture content of materials has a significant impact on the germination index, accounting for 42% of the variation. When the moisture content deviates from the optimal range of 60% ±5%, the coefficient of variation in maturity can reach 15.7%[20,26]. Additionally, the total content of nitrogen, phosphorus, and potassium in micro-storage products made from single straw typically remains below 3.5%, requiring mixing with manure at a 1 : 0.3 ratio during storage to meet crop nutrient requirements[27]. Addressing these issues is crucial for improving the reliability and expanding the applicability of straw micro-storage technology.

2.5 Biochemical rapid decomposition technology Biochemical rapid decomposition technology offers an efficient method for treating perishable waste. Using a composite bacterial agent as the core component, this technology achieves harmless treatment and primary decomposition in a closed system (*e. g.*, ZF-5.5 type) maintained at 55 – 65 ℃ for 24 – 72 h. The process involves sequential steps of "crushing, sterilization, inoculation, and fermentation", which effectively eliminate pathogenic bacteria while preserving nutrient content. It is applicable to various types of waste, including garden branches and kitchen refuse[10,28–29]. This technology has significant potential for waste reduction and resource recovery, addressing the inefficiencies and severe pollution associated with conventional treatment methods.

Significant advancements have been made in the development of biochemical rapid decomposition technology. Wang Jie *et al.*[10] developed a high-temperature rapid fermentation tank equipped with double helix stirring blades, using heat transfer oil to raise the temperature with a control accuracy of ±2 ℃. This design ensures a bacterial agent survival rate exceeding 90% and reduces the maturation cycle by 30% compared to traditional methods. Additionally, the ZF-5.5 agricultural waste biochemical treatment and fertilizer production equipment[28] features an integrated design with one-button operation. Combined with the characteristics of related biochemical fertilizer production systems[16], it achieves a daily processing capacity of 0.8 t, eliminates pathogenic bacteria within 6 h, and produces organic fertilizer with a GI greater than 60% within 24 h.

Significant improvements have been observed in the efficiency of microbial agent applications. Yang Fan *et al.*[30] used closed high-temperature aerobic biological fermentation technology for urban kitchen waste and straw, utilizing high-temperature-resistant microbial agents. This approach increased the organic matter conversion rate of kitchen waste by 40%, with the total nutrient content reaching 6.3%, surpassing the standard of *Organic Fertilizer* (NY 525-2021). Furthermore, pilot verification in the Chongqing tobacco system[31] demonstrated that treating plant residues using this technology achieved a heavy metal passivation rate exceeding 80%, and the resulting products complied with relevant organic fertilizer standards.

The application of this technology has shown positive outcomes. In Zhejiang, the promotion of small-scale biochemical fertilizer production equipment has covered over 66.67 ha of orchard farmland, reduced chemical fertilizer usage by 35%, and increased soil organic matter by 0.8% annually[10,16]. Additionally, a pilot project in a Nanjing community indicates that the technology reduces kitchen waste by 65%, and the produced fertilizer is used for landscaping maintenance, lowering treatment costs by 42% compared to landfill disposal[29].

However, this technology has considerable limitations. The initial equipment purchase cost is relatively high (exceeding 200 000 yuan), and the cost of bacterial agents ranges from approximately 80 – 120 yuan/t. The investment payback period exceeds 5 years, and the daily processing capacity of a single device is generally limited to 5 t or less[12,16,29], posing challenges for meeting the demands of large-scale centralized processing. Additionally, hard branches and other waste materials require pre-crushing to particle sizes within 2 cm[10], resulting in a 30% increase in energy consumption. Furthermore, the use of domestic gasoline engines in pulverizers, combined with noise generated during cutting operations, causes operational noise levels to exceed 85 dB[16]. Moreover, rapid biochemical fertilizer production equipment lacks real-time monitoring technology to accurately determine the completion of fermentation[10,16], relying primarily on sensory and empirical assessments. This leads to significant variability in the degree of maturity, with GI values ranging from 30% to 85%.

2.6 Comparative analysis of fertilizer production technologies utilizing solid waste resources The applicability, limitations, and potential application scenarios of currently used solid waste resource-based fertilizer production technologies are systematically compared and analyzed, as detailed in Table 1.

Table 1 Comparison of fertilizer production technologies utilizing solid waste resources

Technology type	Core principle	Advantage	Limitation	Typical application scenarios
Hydrothermal fertilizer production	In a sealed reaction vessel maintained at 150 – 280 ℃ and 2 – 10 MPa in an aqueous environment, organic matter undergoes hydrolysis, dehydration, and condensation polymerization to transform into humic acid, with a pathogen inactivation rate exceeding 99.9%.	① The technology exhibits a high resource recovery rate, ensuring the effective retention of nutrients such as nitrogen and phosphorus. ② It accomplishes comprehensive harmless treatment, thereby minimizing risks associated with pathogenic bacteria and heavy metal contamination. ③ It is capable of achieving energy self-sufficiency, thus reducing dependence on external energy sources.	①The energy consumption cost is substantial, with a unit processing energy consumption ranging from 0.8 to 1.2 kWh/kg, constituting 55% – 60% of the total operating costs, while energy consumption during the heating phase accounts for 70%. ②Product safety risks include the solid-phase enrichment of Cl – at concentrations ranging from 1.2% to 3.5%, which results in a 15% to 20% decrease in crop yields on saline-alkali soils, and the levels of heavy metals such as Cu and Zn are elevated by 1.5 – 2.0 times compared to those in the raw materials, with some concentrations exceeding the limits established by the GB/T 38400 – 2019 standard.	Co-processing of agricultural and forestry residues (corn cobs, straw) with livestock and poultry manure, and high-value conversion of kitchen waste
Aerobic fermentation	Aerobic microorganisms, such as *Bacillus* and *Streptomyces*, decompose organic matter in an oxygen-rich environment. Following three stages of decomposition: "heating, high temperature, and cooling", the resulting product exhibits a pH ranging from 7.0 to 8.5 and a germination index (GI) exceeding 80%.	① The technology is mature, featuring a high degree of product decomposition, an excellent GI value, and consistent fertilizer efficacy. ② The equipment has been intelligently upgraded to enable automatic control of turning, thereby reducing nitrogen loss and the emission of harmful gases. ③ The system is compatible with various organic wastes, allowing for a wide range of applications.	① The process involves a prolonged cycle duration of 20 – 60 d and requires substantial land area, approximately 0.8 – 1.2 m^2/t, which limits the feasibility of large-scale production. ② Significant nitrogen loss occurs, adversely impacting the nutrient content of the final product. ③ Due to the recalcitrant nature of lignin degradation in straw, the addition of functional bacterial agents is necessary, and the treatment period must be extended accordingly.	Mixed treatment of urban domestic residues (kitchen waste), agricultural straw and livestock manure, and resource utilization of garden waste
Wrapping fertilizer production	Following aerobic fermentation, the materials (moisture content below 60%) are packed into polyethylene film bags, compacted, and air is expelled. They then undergo secondary decomposition in an anaerobic or micro-aerobic environment for 30 – 60 d, a process that facilitates both storage and further decomposition.	① Secondary decomposition enhances material quality and effectively preserves nutrients. ② Sealed storage minimizes secondary pollution, thereby facilitating transportation and long-term preservation. ③ When applied to agricultural land, this method can substantially increase soil organic matter and improve crop quality.	① The process exhibits poor economic performance, characterized by substantial equipment investment, significant initial financial burden for small and medium-sized enterprises, high unit costs, and an extended payback period. ② Polyethylene film degrades at a slow rate, and if not managed appropriately, it may persist in the field, thereby adversely affecting soil aeration.	Subsequent treatment and storage of materials after aerobic fermentation, as well as the preparation of organic fertilizers for agricultural scenarios such as orchards
Micro-storage fertilizer production	Straw serves as the raw material, to which microbial agents and moisture (45% – 60%) are added. The mixture is then compressed, sealed for storage, and subsequently decomposed through microbial activity (≥ 24 d).	① This technology demonstrates significant applicability in rural areas. The investment required for a single set of box-type equipment is less than 50 000 yuan, and processing can be conducted on-site. ② The "cooperative + farmers" model facilitates easy promotion, with costs ranging from 80 to 120 yuan/t. ③ The operation is straightforward, allowing farmers and herdsmen to utilize traditional cellars for production.	① The moisture content of the material is highly sensitive; when it deviates from 60% ± 5%, the coefficient of variation in maturity reaches 15.7%. ② The nitrogen, phosphorus, and potassium content in a single straw product is less than 3.5%, necessitating mixing with manure at a ratio of 1 : 0.3 during storage to comply with established standards.	Resource utilization of crop straw in rural areas and the production of fertilizer by mixing straw with livestock and poultry manure
Biochemical rapid decomposition	The compound bacterial agent serves as the core component, and the harmless treatment along with primary maturation are conducted within a closed device maintained at 55 – 65 ℃ for 24 – 72 h. This process follows the sequence of "crushing, sterilization, inoculation, and fermentation".	① The process demonstrates high processing efficiency, a short cycle duration of 24 – 72 h, and a substantial reduction rate of 65% for kitchen waste. ② Pathogenic bacteria are effectively eliminated, the passivation rate of heavy metals exceeds 80%, and the resulting products comply with established standards. ③ When applied in community or agricultural settings, this process can reduce the use of chemical fertilizers by 35% and increase soil organic matter by 0.8% annually.	① The cost of equipment and microbial agents is substantial, with equipment priced above 200 000 yuan and microbial agents costing between 80 and 120 yuan/t. The payback period exceeds 5 years, and the daily processing capacity is limited to 5 t or less. ② Hard branches must be crushed to particles smaller than 2 cm, resulting in a 30% increase in energy consumption and noise levels exceeding 85 dB. ③ The absence of real-time monitoring causes significant fluctuations in maturity, with the GI ranging from 30% to 85%.	Rapid treatment of perishable waste such as community kitchen waste, garden branches, and plant residues (tobacco)

3 Conclusions

Solid waste resource utilization for fertilizer production serves as a critical link between "waste management" and "sustainable agricultural development". It represents a vital technological approach to addressing the dual challenges of "waste accumulation" and "soil degradation". Moreover, it offers an effective strategy for achieving agricultural carbon neutrality, ensuring food security, and maintaining ecological sustainability. Based on the principles of ecological priority and circular development, the academic community has established a diversified technological framework including hydrothermal fertilizer production, aerobic fermentation, and wrapping fertilizer production. Compared to conventional disposal methods such as landfilling and incineration, these technologies have advantages including higher resource utilization efficiency and lower environmental impact. Nonetheless, challenges remain regarding product stability, pollution control, and economic feasibility during industrialization. Consequently, solid waste resource-based fertilizer production has significant potential for advancing the green transformation of agriculture but must address several critical obstacles.

China has a vast territory with diverse waste types (*e. g.*, kitchen waste, straw, livestock manure). Regional disparities in economic development lead to distinct treatment requirements and technological adaptability. For example, high-moisture waste such as kitchen waste is more suitable for hydrothermal fertilizer production technology, while dispersed agricultural waste such as straw is better suited for aerobic fermentation. Therefore, solid waste resource utilization should involve selecting appropriate technological models and combination strategies based on the resource endowments, industrial structures, and technological foundations of different regions. It is essential to promote the development of individual technologies toward a diversified, multidimensional, and sustainable direction characterized by "process integration, intelligent regulation, and model innovation". Furthermore, the development and iteration of emerging technologies (*e. g.*, low-carbon pretreatment, efficient detoxification, and intelligent equipment R&D) along with the improvement of policy frameworks will further overcome industrialization bottlenecks. This progress is of great practical significance for improving resource utilization efficiency and mitigating environmental risks.

In the future, through technological innovation to shorten the processing cycle and enhance product stability, and model innovation to reduce costs and expand application scenarios, it will be possible to ultimately establish a carbon-neutral closed loop encompassing "waste, fertilizer, and farmland". This approach can offer a Chinese solution to the sustainable development of global agriculture.

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