Key Technology and Process of Preparing Soil Fertilizer by Anaerobic Fermentation

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Abstract: This paper introduces the research progress of anaerobic fermentation for soil fertilizer preparation, the current research status and technical principles, and focuses on the process parameters of anaerobic fermentation for soil fertilizer preparation, which mainly include the selection of raw materials and pretreatment, the reasonable inoculum selection, the control of fermentation temperature, the control of PH value, the control of carbon and nitrogen ratios, the control of organic loading, the selection of mixing methods, post-treatment and product optimization. By analyzing the existing research results, summarizing the challenges and problems, and proposing future research directions and trends, we hope to provide a reference basis for researchers in the related fields and provide theoretical guidance for the optimization of the anaerobic fermentation process in actual production, to ultimately achieve the purpose of improving the efficiency of anaerobic fermentation and expanding the scope of its application in Agricultural production.

Keywords: Anaerobic Fermentation; Soil Fertilizer; Technical Principles; Process Parameters

1. Introduction

The preparation of soil fertilizer by anaerobic fermentation is of great significance in the improvement of functionally deficient soil. The massive use of traditional chemical fertilizers not only leads to the decline of soil fertility but also provokes environmental pollution and ecological damage. Studies have shown that these problems can be effectively solved by converting organic wastes into efficient and environmentally friendly soil fertilizers through anaerobic fermentation technology. The biogas produced during anaerobic fermentation can be utilized as a clean energy source to reduce dependence on fossil fuels, while the anaerobic digestion products are rich in a variety of nutrients, which can significantly improve the soil structure and increase crop yield and quality [1].

Agricultural wastes such as livestock manure and crop residues are important organic resources, but their direct discharge or improper treatment can cause serious pollution to the environment. Anaerobic fermentation technology provides a scientific and reasonable solution to eliminate potential sources of pollution as well as to recycle resources by bioconversion of these wastes. According to the literature, the residue after anaerobic fermentation has a high content of nitrogen, phosphorus, potassium, and other elements, and the microbial activity is enhanced, which helps to promote the growth of plant roots and enhance the resistance to pests and diseases. The metabolites during anaerobic fermentation, such as volatile fatty acids and amino acids, also have a positive impact on the structure of the soil microbial community, which is conducive to the construction of a healthy soil ecosystem.

Anaerobic fermentation for the preparation of soil fertilizers also offers significant advantages from an economic point of view. Compared with traditional chemical fertilizers, this green fertilizer is cheaper and easier to obtain. Anaerobic fermentation equipment and technology are relatively simple, easy to operate and maintain, and mixing with functionally deficient soil to prepare green soil can reduce the cost of purchasing green soil. In recent years, China's government attaches great importance to the prevention and control of agricultural surface pollution and has introduced a series of policy measures to support the development of the organic fertilizer industry, which provides a good opportunity for the application of anaerobic fermentation technology. Therefore, an in-depth study of the key technologies and processes of anaerobic fermentation for soil fertilizer preparation is of great practical significance for promoting the green development of agriculture and realizing the win-win situation of ecological environmental protection and economic benefits.

2. Research Progress and Current Research Status

2.1 Progress in Research

Research results on the preparation of soil fertilizers by anaerobic fermentation have shown remarkable progress in different periods. Early studies focused on basic theories and technical feasibility, e.g., J Wang [2] explored the impact of decentralized anaerobic digestion on-farm ecosystems, pointing out that this technology not only effectively treats organic waste but also produces high-quality biofertilizers. Battini et al. [3] analyzed the application of anaerobic digestion of manure in the process of dairy production using a case study, and the results showed that this technology can significantly reduce negative environmental impacts and increase resource utilization.

Möller and Müller [4] reviewed the effectiveness of nutrients and crop growth effects in digestate after anaerobic digestion and found that the waste treated by anaerobic fermentation not only improves the soil structure but also provides nutrients required by plants when used as a fertilizer; they also emphasized the importance of the control of parameters such as temperature and pH during anaerobic fermentation, which have a direct influence the quality and application effect of the final product.

In recent years, with the enhancement of environmental awareness and technological advances, anaerobic fermentation has made more breakthroughs in the resource utilization of agricultural wastes. For example, Karouach et al [5] used water hyacinth for anaerobic digestion to prepare biomethane and biofertilizer, and the study showed that this technology not only solved the problem of water hyacinth flooding but also provided high-quality organic fertilizers for agricultural production. Similarly, Song Guanlin et al [6] optimized the preparation process of bio-organic fertilizer fermentation bacterial agent, which improved the nutritive value and stability of the fertilizer and further promoted the application of anaerobic fermentation technology in agriculture.

Wang Chunrong et al [7], on the other hand, focused on the dry anaerobic fermentation of food waste organic matter, and successfully improved the gas production efficiency and digestate quality by adjusting the reaction conditions and adding auxiliary materials. Ji Jieli [8] conducted an in-depth study on the coupled process of solid biogas fermentation of swine manure mixed with rice straw and aerobic composting of digestate and proposed an optimization scheme to improve the stability and economic efficiency of the overall system.

Overall, the research on the preparation of soil fertilizers by anaerobic fermentation has been deepening and evolving from the early basic explorations to present-day technological innovations. The results of the various stages of research are interrelated and together they have contributed to the progress of this field. Future research should continue to focus on how to further enhance the performance of anaerobic fermentation systems, reduce operating costs, and ensure their feasibility and sustainability in practical applications.

2.2 Current Research Status and Review

The current research hotspots of anaerobic fermentation for soil fertilizer preparation mainly focus on optimizing process parameters, improving gas production efficiency, and improving product quality. In recent years, with the increasing awareness of environmental protection and the demand for sustainable development of agriculture, anaerobic fermentation technology has received extensive attention in the treatment of organic wastes and their conversion into efficient soil fertilizers. According to the literature review, the existing studies not only cover basic theoretical discussions but also go deep into practical application case studies, revealing the latest progress and challenges in this field.

Studies have shown that key factors such as temperature, pH, and carbon-to-nitrogen ratio during anaerobic fermentation have a significant impact on the quality and yield of the final product. For example, under suitable conditions (e.g., 35-55°C), microbial activity is maximized, thus increasing the rate and total amount of methane production. Rationalization of the feedstock ratios is also one of the most important tools to enhance the fermentation results. By mixing different types of organic wastes, the nutrients can be effectively balanced and the diversity of the microbial community can be promoted, thus improving the conversion efficiency.

Despite the many achievements, there are still some limitations in the existing research. On the one hand, most of the experiments are mostly focused on the laboratory scale, and there is a lack of validation data for large-scale industrialized production. This makes it difficult for many innovative results to be directly applied in actual production. On the other hand, the understanding of the structure of microbial communities and their functional mechanisms in complex environments is not deep enough, which limits the development of targeted regulatory measures. Some studies have focused too much on single indicators (e.g., gas yield) and neglected the comprehensive assessment of other important attributes (e.g., fertilizer nutrient content, heavy metal residues, etc.).

Future research should further strengthen interdisciplinary cooperation, combining knowledge from biology, chemistry, engineering, and other fields to explore more efficient anaerobic fermentation processes. In particular, more efforts are needed to optimize operating conditions, screen efficient strains, and develop novel pretreatment technologies. It is also necessary to focus on long-term monitoring and evaluation of the performance of anaerobic fermentation products in farmland ecosystems to ensure their safety and efficacy, and to provide solid technical support for the promotion of green transformation of agriculture.

3. Basic Principles of Anaerobic Fermentation

Anaerobic fermentation is a biochemical process in which organic wastes are converted into stabilized products by microbial action under anaerobic conditions. In soil fertilizer preparation, the basic theory of anaerobic fermentation involves microbial community structure, substrate degradation pathway, and product generation mechanism. The process usually includes pretreatment, adjustment of pH and C/N ratio, inoculation of anaerobic microorganisms, sealed fermentation, and post-treatment.

The basic principle of anaerobic fermentation for the preparation of soil fertilizers lies in the use of specific microorganisms to decompose organic matter in an anaerobic environment to produce nutrient-rich humus. In this process, microorganisms convert complex organic matter into simple inorganic matter and stabilize humus through hydrolysis, acidification, acetic acid production, and methanogenesis.

4. Process Flow and Technical Parameters

In the preparation of soil fertilizer by anaerobic fermentation, reasonable control of the process and technical parameters is the key to ensuring the fermentation effect and product quality. The commonly used process includes raw material pretreatment, inoculation, fermentation process monitoring and control, and post-treatment. In these steps, technical parameters such as fermentation temperature, pH, carbon/nitrogen ratio (C/N), organic loading rate (OLR), and stirring method have a significant effect on the effect of anaerobic fermentation.

4.1 Selection and Pretreatment of Raw Materials

The annual production of livestock and poultry manure and agricultural straw in China is very huge, which can be used as a common anaerobic digestion substrate.

At the stage of raw material pretreatment, the homogeneity and degradability of raw materials can be effectively improved using crushing and mixing, thus promoting the metabolic activities of microorganisms. For example, in the study of solid biogas fermentation of swine manure mixed with rice straw, Ji Jieli [8] pointed out that appropriate pretreatment can significantly improve the gas production efficiency and the quality of digestate. Reasonable pretreatment can also reduce the inhibitory effect of harmful substances on the fermentation process and ensure that the subsequent fermentation proceeds smoothly.

4.2 Rational Selection of Inoculum

Inoculation is one of the important aspects of anaerobic fermentation, and the selection of appropriate strains or inoculums can accelerate the initiation and maintain a stable fermentation environment. Studies have shown that the use of screened and optimized high-efficiency anaerobic bacterial flora as inoculum can achieve higher methane production in a shorter period. For example, Chen Mingyuan [9] mentioned in his study on the preparation of microbial fertilizers from edible mushroom residues that specific strain combinations not only increased the fermentation rate but also enhanced the nutrient content and bioactivity of the fertilizers.

4.3 Fermentation Temperature Control

Temperature control during fermentation is critical, and in general, mesophilic fermentation (35-40°C) and hyperthermic fermentation (50-60°C) are the two common modes of operation. Medium-temperature conditions result in higher microbial activity and lower maintenance costs, while high-temperature fermentation helps to kill pathogens and stray bacteria, but it is important to note that high temperatures may inactivate some functional bacteria. Therefore, it is necessary to choose the appropriate temperature range according to the specific application scenario.

4.4 PH Control

pH is also one of the key factors affecting the success of anaerobic fermentation. The ideal pH range is usually between 6.8 and 7.2, with either too high or too low inhibiting the growth of microorganisms, which in turn affects the fermentation process. To maintain this balance, pH can be adjusted by adding buffers or adjusting the composition of the feed. Literature has shown that by precisely controlling the pH, not only can gas production be increased, but also the quality of the final product can be improved.

4.5 Control of Carbon to Nitrogen Ratio

The carbon to nitrogen (C/N) ratio directly affects the energy source and nutrient supply of microorganisms in the fermentation system. Theoretically, the C/N ratio should be maintained between 20:1 and 30:1 for optimal fermentation. When the C/N ratio is too high, the system may lack sufficient nitrogen source leading to fermentation stagnation; on the contrary, if the C/N ratio is too low, it is easy to produce ammonia and nitrogen accumulation, which will inhibit methane production. Therefore, it is necessary to flexibly adjust the C/N ratio according to the characteristics of the raw materials to ensure a stable and efficient fermentation process.

4.6 Control of Organic Loading Rate

The organic loading rate (OLR) determines the total amount of organic matter entering the reactor per unit time, which is closely related to the fermentation rate. An appropriate increase of OLR can accelerate the fermentation rate, but too high OLR may lead to substrate excess and trigger an acidification phenomenon. Based on this, researchers generally recommend a gradual increase strategy to determine the optimal OLR and dynamic adjustment with real-time monitoring data to ensure the smooth operation of the fermentation system.

4.7 Selection of Stirring Method

The choice of stirring mode is important for improving mass transfer conditions and preventing localized accumulation. Effective stirring not only promotes gas release but also enhances the contact area between materials, which is conducive to full contact between microorganisms and substrates. In his study on the optimization of the stirring scheme for the anaerobic fermentation system of corn stover, Liu Yuyingnan [10] suggested that the fermentation efficiency could be significantly improved by optimizing the frequency and intensity of stirring while reducing energy consumption.

4.8 Post-Processing and Product Optimization

The products of anaerobic fermentation include biogas sludge and biogas liquid. After the reaction is completed, the fermented material will be separated into solid-liquid, the solid part will be used as base fertilizer, and the liquid part (biogas liquid) can be diluted and used as liquid fertilizer.

To improve the degree of decomposition of fertilizers, secondary composting can be carried out, i.e., short-term aerobic composting (7-10 days) of the fermentation products to promote humus formation; or adding functional substances, such as a mixture of humic acid, phosphorus powder or microbial fungicides, to enhance the effectiveness of fertilizers.

The preparation of soil fertilizer by anaerobic fermentation involves some complex technical parameters and processes, each of which needs to be carefully designed and strictly controlled.

Through scientific management of key elements such as fermentation temperature, pH, C/N ratio, OLR, and stirring mode, an efficient and stable anaerobic fermentation process can be realized, providing high-quality soil fertilizer products for sustainable agricultural development.

5. Challenges and Future Directions

5.1 Challenges and Problems

The preparation of soil fertilizers by anaerobic fermentation does face many challenges in practical application. At the technical level, an efficient and stable anaerobic fermentation process requires a very high balance of temperature, pH, and nutrients, and a slight deviation may lead to inefficient fermentation or the production of undesirable by-products, e.g., excessive accumulation of ammonia and nitrogen will inhibit microbial activity. The cost of pre-treatment of raw materials is also a major challenge, especially for agricultural wastes with high lignin content, which are expensive to crush and degrade.

From an economic point of view, the initial investment in anaerobic fermentation equipment is large, and the operation and maintenance costs are expensive, which is difficult for small-scale farmers to afford. Currently, the selling price of anaerobic fermentation fertilizers in the market has no obvious advantage over traditional fertilizers, which affects its market competitiveness.

In terms of environmental adaptability, the anaerobic fermentation process is susceptible to external environmental influences, such as extreme weather conditions that may lead to instability in the fermentation system, affecting the quality of fertilizers. The lack of professional technical support and personnel training in some regions limits the promotion and application of anaerobic fermentation technology. Although the preparation of soil fertilizers by anaerobic fermentation is promising, it still needs to overcome many challenges in terms of technology optimization, cost control, and environmental adaptability.

5.2 Future Research Directions and Trends

Future research directions in anaerobic fermentation for soil fertilizer preparation will focus on improving fermentation efficiency and product quality. With the continuous progress of biotechnology, researchers may explore more efficient microbial communities to accelerate the degradation process of organic wastes and at the same time increase the nutrient content in fertilizers. The introduction of intelligent control systems, such as Internet of Things (IoT) technology and big data analysis, is expected to achieve precise regulation of the fermentation process, optimize fermentation temperature, pH, and other key parameters, and further improve product quality. The environmental friendliness of anaerobic fermentation technology will become a research priority in the context of the increasing emphasis on environmental protection. Future research will focus on the reduction of greenhouse gas emissions, e.g. through the capture and utilization of methane gas, as well as the development of low-energy, high-efficiency fermentation processes. The development of customized fertilizers for specific crop needs will also become a trend to meet the demand for precision fertilization in modern agriculture.

The large-scale application and commercialization of anaerobic fermentation technology will be an important direction for future development. Reducing production costs and improving economic benefits through policy guidance and technological innovation will promote the wide application of anaerobic fermentation soil fertilizer in agricultural production.

6. Conclusion

The conversion of organic solid waste into efficient soil fertilizer through anaerobic fermentation technology can not only improve soil fertility but also reduce environmental pollution and ecological damage caused by the arbitrary disposal of solid waste. In the process of preparing soil fertilizer, the reasonable control of technical parameters is the key to ensure the fermentation effect and soil fertilizer, and the synergistic effect between each technical parameter should be further optimized. With the advancement of technology, future research may address the current challenges of anaerobic fermentation for soil fertilizer preparation in practical applications by exploring efficient microbial communities and introducing intelligent systems. Reducing production costs and improving economic benefits through policy guidance and technological innovation will promote the widespread application of anaerobic fermentation soil fertilizers in agricultural production.

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