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Resource Utilization of Agricultural and Forestry Organic Waste for the Preparation of Biochar Fertilizers and Harmless Disposal

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Abstract

Our country is a major agricultural nation, with an annual production of agricultural and forestry organic waste exceeding 4 billion tons, mainly including crop residues, livestock manure, edible fungus residue, fruit and vegetable residues, garden pruning waste, and agricultural product processing by-products. A large amount of waste is discarded randomly, incinerated outdoors, or stored in a simple manner, which not only causes resource waste but also leads to air pollution, water body eutrophication, soil heavy metal accumulation, pest and disease proliferation and spread, etc., becoming a prominent bottleneck restricting rural ecological revitalization and agricultural green development. At the same time, the demand for high-quality organic fertilizers, soil improvers, and functional carbon-based materials in agricultural production continues to rise. Excessive application of traditional fertilizers has led to soil compaction, acidification, decline in organic matter, and increased surface pollution, and the pressure of carbon sequestration and emission reduction in farmland is increasing day by day. It is urgently needed to have green, efficient, and low-cost resource utilization technologies as support. This article focuses on the major demands of national agricultural green development, rural revitalization, carbon peak and carbon neutrality, and agricultural non-point source pollution control, and focuses on the core issues of harmless disposal and high-value resource utilization of agricultural and forestry organic waste. It proposes to carry out research and development on the coupling technology of preparing biochar/biofertilizer and harmless disposal of agricultural and forestry organic waste, so as to break through the technical bottlenecks restricting the high-value utilization of agricultural and forestry waste and promote the development of regional agricultural circular economy.

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1. Introduction

1.1. Agricultural and forestry organic waste pre-treatment and harmlessization technology

1.1.1. Characterization and Pre-treatment of Waste Types

For the main types of agricultural and forestry organic wastes in Jingzhou City and its surrounding areas (rice straw, corn straw, rape straw, pig manure, cow manure, edible fungus residue, fruit and vegetable tail leaves, garden branches), the system measures indicators such as moisture content, organic matter, total carbon, total nitrogen, total phosphorus, total potassium, crude fiber, lignin, cellulose, hemicellulose, heavy metals (Cd, Cr, Pb, As, Hg), pathogenic bacteria (*Escherichia coli*, *Salmonella*, *Bacillus*), and weed seeds, and establishes a regional database of agricultural and forestry organic waste characteristics to provide a basis for precise optimization of process parameters^[1].

Based on the characteristics of the waste, a classification and grading pre-treatment process was developed: (1) for straw and branch types, the "crushing - screening - conditioning" process was adopted, with the crushing particle size controlled at 2-5 cm; (2) for livestock manure types, the "solid-liquid separation - dehydration - aging" process was used, with the moisture content controlled at 50%-60%; (3) for fruit and vegetable residues, fungus residue types, the "crushing - pressing - dehydration" process was used to remove free water; (4) for mixed waste, the carbon-nitrogen ratio was optimized at 25:1-30:1 to meet the dual x

1.2. Research on Core Technologies for Inactivation

For the four types of harmful factors (heavy metals, pathogenic bacteria, weed seeds, and organic pollutants), a collaborative inactivation technology was developed:

1. Heavy metal stabilization technology, selecting biochar-based, phosphate-based, and silicate-based stabilizers, optimizing the addition ratio and mixing method to stabilize heavy metals in the waste, reducing their bioavailability and preventing their entry into the food chain;
2. High-temperature inactivation technology, using the dual effects of pyrolysis at high temperature and fermentation at high temperature to inactivate pathogenic bacteria and weed seeds;
3. Organic pollutant degradation technology, through the synergistic effect of functional microorganisms' degradation and high-temperature oxidation, degrading pesticide residues, antibiotics, etc., organic pollutants. Through single-factor experiments and orthogonal experiments, the key process thresholds (temperature, time, stabilizer dosage, pH value) of the inactivation technology were determined, forming a low-cost, high-efficiency, and pollution-free inactivation technology solution.

The inactivation experiment was conducted with a "stabilizer type (4 levels) $\times$ addition ratio (3 levels) $\times$ reaction temperature (3 levels)" orthogonal experiment, using the reduction rate of heavy metal bioavailability and the inactivation rate of pathogenic bacteria as evaluation indicators, to determine the optimal combination; at the same time, a blank control was set up to verify the inactivation effect.

2. Green Preparation Technology of Biochar

2.1. Optimization of Directed Pyrolysis for Char Production

By comparing the two processes of low-temperature slow pyrolysis (300-400°C) and medium-temperature rapid pyrolysis (450-600°C), the effects of pyrolysis temperature, heating rate, holding time, and oxygen supply conditions on the fixed carbon content, specific surface area, pore structure, and carbon sequestration capacity of biochar were systematically studied. Single-factor and orthogonal experiments were conducted using the fixed carbon content, specific surface area, and carbon yield as evaluation indicators to determine the optimal process range: pyrolysis temperature 450-550°C, heating rate 10-20°C/min, and holding time 60-90 min [2]. This achieved high yield, high performance, and low energy consumption of biochar.

2.2. Biocarbon Modification and Activation Technology

To enhance the adsorption performance, ion exchange capacity, and soil compatibility of biocarbon, physical, chemical, and biological modification research was carried out. Physical modification involved steam activation and CO₂ activation, which expanded the pores and increased the specific surface area by more than 30% compared to the unmodified state; chemical modification utilized low-concentration potassium hydroxide and phosphoric acid activation to increase the number of surface functional groups; biological modification involved the use of composite functional microorganisms to enhance the activity

and synergistic effect of biochar in the soil. The best modification agents and conditions were selected based on the evaluation indicators of specific surface area, pore size distribution, and functional group quantity.

2.3. Utilization of Pyrolysis By-products for Resource Recycling

The by-products generated during pyrolysis, such as pyrolysis gas, pyrolysis oil, and vinegar liquid, were fully resourceized. Pyrolysis gas was recovered for heating the pyrolysis furnace to achieve self-energy circulation; pyrolysis oil was purified and used as a bio-based fuel, anti-corrosion material; vinegar liquid was used as a biofertilizer additive, plant growth regulator, and soil bacteriostatic agent, and its organic acid composition and antibacterial activity were determined.

3. Preparation and Coupling Technology of Composite Bio-fertilizer

3.1. Optimization of Compound Biofertilizer Formula and Fermentation Process

Using harmless agricultural and forestry organic waste and modified biochar as the core raw materials, combined with functional microbial communities and inorganic nutrient elements, a multifunctional compound biofertilizer was developed. The substrate ratio was: 60%-70% of harmless waste, 10%-15% of modified biochar, 2%-5% of microbial agents, and 10%-15% of inorganic nutrients. The functional bacteria were screened for combinations of phosphorus-removing bacteria, nitrogen-fixing bacteria, silicate bacteria, decomposing bacteria, and *Bacillus subtilis*, etc. The aerobic high-temperature fermentation process was adopted, with a temperature range of 55-65°C and a fermentation period of 7-10 days, achieving rapid decomposition, odorlessness, and harmless treatment. The evaluation indicators were organic matter content, total nutrients, viable bacteria count, and maturity (seed germination index GI). Orthogonal optimization of the formula and process was carried out.

3.2. Research and Development of Biochar-Biofertilizer Coupling Technology

The core innovation of this project lies in the "biochar-biofertilizer" deep coupling. The residual heat from the pyrolysis process is recycled and used for heating the biofertilizer fermentation, shortening the fermentation period and reducing energy consumption; material circulation, with the pyrolysis residue and fermentation tailings flowing back to the pre-treatment system to achieve full utilization of the materials; functional synergy, biochar improves the pore structure of the fertilizer, enhances water retention and fertilizer retention, and prolongs the fertilizer effect; mechanism analysis, clarifying the protective effect of biochar on microorganisms, the nutrient release mechanism, and the synergistic mechanism of soil improvement.

In terms of engineering implementation, the coupling process is organically connected by optimizing the workshop layout and designing the heat and material pipelines. The residual heat from the pyrolysis unit is connected to the fermentation unit through a heat exchange device to achieve stepwise utilization of the residual heat. The pyrolysis residue and fermentation tailings are crushed and conditioned and then returned to the pre-treatment unit together to form a material loop. The intelligent control system uniformly schedules the temperature control, feeding, and discharging of both units to

ensure the continuous and stable operation of the coupling process, thereby ensuring the feasibility of the "biochar-biofertilizer" deep coupling at the engineering level.

4. Coupling Technology Integration and Equipment Development

4.1. Integrated Process Technology

Integrate the six unit technologies of pretreatment - harmless treatment - pyrolysis to charcoal - fermentation to fertilizer - waste heat recovery - exhaust gas treatment into a single integrated coupled process, achieving continuous material circulation without intermediate accumulation, minimum energy consumption for energy cascade utilization, centralized treatment of pollutants to meet discharge standards, and stable product output with controllable quality. The integrated process connects the entire chain of "harmless disposal - resource utilization - high value production", forming a replicable and promotable model for the resource utilization of agricultural and forestry organic waste in county areas.

4.2. Research and Development of Miniaturized and Intelligent Equipment

For the needs of small-scale agricultural business entities, cooperatives, and family farms, develop a set of miniaturized, modular, and intelligent coupled equipment consisting of pretreatment unit, pyrolysis to charcoal unit, fermentation unit, waste heat recovery unit, and intelligent control system; adopt touch screen operation, achieving automatic temperature control, automatic feeding, automatic discharging, and fault alarm. It has the characteristics of small footprint, low investment, easy mobility, and easy maintenance, suitable for decentralized disposal in county areas^[3]. The equipment has been verified through the entire process of design, processing, trial production, and debugging, achieving continuous and automated stable operation.

5. Discussion

To clarify the synergistic principle of the "carbon production-fertilizer production" coupling process, the mechanism was analyzed from three aspects: material structure, microbial community, and nutrient release. Scanning electron microscopy and pore structure analysis showed that the modified biochar had a larger specific surface area and more pores, providing a favorable attachment and colonization carrier for functional microorganisms, protecting and enriching them, and prolonging their survival period and activity in the soil. This is the structural basis for biochar to enhance the efficacy of biological fertilizer agents.

The adsorption effect of biochar delays the release rate of fertilizer nutrients, and the total nutrient release period is approximately 20%-30% longer than that of conventional organic fertilizers, reducing nutrient loss and improving fertilizer utilization. At the same time, biochar improves the soil aggregate structure and water-holding and fertilizer-retaining performance, and forms a synergistic effect with the nutrient supply and promoting functions of biological fertilizers. Combined with the results of high-throughput sequencing of soil microorganisms, after applying the coupled product, the abundance of beneficial microorganisms in the soil significantly increased, while the abundance of pathogenic microorganisms decreased, and the structure of the soil microbial community tended to be

healthy. These mechanisms collectively constitute the scientific basis for the synergistic effect of biochar-biological fertilizer, quality improvement, and carbon sequestration and emission reduction.

The utilization rate of agricultural and forestry organic waste resources has actually reached 96.5%, higher than the contract requirement of $\geq 95\%$. Through the integrated process of "harmless treatment - carbon production - fertilizer production - waste heat recovery - tail material reflux", waste such as straw, manure, microbial residue, fruit and vegetable residues, and garden branches are converted into biochar, biological fertilizer, and wood vinegar liquid products. The material utilization rate is high, and the waste is basically fully utilized; the heavy metal passivation rate is 97.2% (Cd) and 96.5% (Pb), and the inactivation rate of pathogenic bacteria and weed seeds is over 99.9%. All meet or exceed the contract indicators, and the pollutant emissions throughout the production process comply with national and local environmental protection standards, without secondary pollution.

Under the optimal process conditions of 500° C for thermal decomposition, a 15° C/min heating rate, 75 minutes of holding time, and water vapor activation modification, the fixed carbon content of biochar is 73.6%, the specific surface area is 368 m²/g, the pH value is 9.2, and the ash content is 16.8%. Both the fixed carbon and specific surface area exceed the contract indicators; the content of heavy metals such as Cd, Cr, and Pb is 0.12, 8.6, and 2.4 mg/kg, respectively, meeting or exceeding the limit requirements of "Biochar Soil Improvement Agent" (NY/T 3616-2020). The product is suitable for soil improvement and carbon sequestration in farmland.

The organic matter content of the composite biological fertilizer is 42.5%, the total nutrient content is 17.8%, and the effective functional bacteria count is 1.2 billion/g, all exceeding the contract indicators; the moisture content, death rate of *Ascaris* eggs, and *E. coli* content meet the requirements of "Organic-Inorganic Compound Fertilizer" (GB/T 18877-2020) and hygiene standards, and the product is safe and qualified, with significant fertilizer efficacy.

The thermal decomposition energy consumption is 21.3% lower than that of traditional processes, exceeding the contract requirement of $\geq 15\%$; the utilization rate of waste heat recovery is 68%, exceeding the contract requirement of $\geq 60\%$; a set of miniaturized and intelligent coupled equipment has been developed, enabling continuous and automated operation, with simple operation, low maintenance costs, and suitable for small and medium-sized agricultural business entities.

6. Conclusion

Through the above research, the transformation of agricultural and forestry organic waste from an "environmental burden" to a "resource treasure trove" has been achieved. A county-level model for the resource utilization of agricultural and forestry organic waste integrating technology, equipment, standards and demonstrations has been established. This plays a significant supporting role in improving the regional agricultural ecological environment, enhancing agricultural comprehensive benefits, and promoting the green and high-quality development of agriculture.

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