Research on Village Waste Treatment and Low-Carbon Planning Technology Based on Carbon Emission Accounting

Linlin Wang*

shenyang urban construction university, Shenyang, Liaoning, 110167, China

*15840050358@163.com

Abstract. This study addresses the high carbon emissions and low resource utilization in agricultural waste treatment. An integrated low-carbon treatment system was designed and developed, incorporating intelligent pretreatment, aerobic composting, and anaerobic digestion processes. Through the optimization of system operating parameters and carbon emission reduction path analysis, a carbon emission prediction model was established to achieve precise control of the treatment process. The results indicate that the system significantly improves the resource utilization efficiency of waste and achieves substantial carbon emission reductions, demonstrating good technical and economic feasibility. This provides new insights into low-carbon treatment of agricultural waste.

Keywords: Village waste treatment; Carbon emission accounting; Low-carbon technology; Composting process

1 Introduction

Efficient treatment and resource utilization of agricultural waste are key to achieving green agricultural development. Traditional treatment methods generally suffer from high carbon emission intensity and low resource efficiency, necessitating the development of new low-carbon treatment technologies. Research both domestically and internationally has mainly focused on optimizing single treatment processes, with limited research on system integration and carbon emission reduction evaluation[1]. This paper explores the synergistic pathways for waste reduction and resource utilization by constructing an integrated treatment system, which has significant implications for promoting green and low-carbon agricultural development.

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2 Carbon Emission Characteristics and Modeling of Village Waste Treatment Processes

2.1 Village Waste Characteristics Analysis

This study conducted field surveys in 20 administrative villages in typical agricultural counties, collecting and analyzing samples of typical village waste. The survey showed that village waste mainly consists of agricultural production waste (52.3%), household garbage (31.5%), and livestock manure (16.2%). Elemental analysis revealed that agricultural waste has a high carbon content (42.5%) and a large amount of cellulose; household garbage has a high moisture content (over 65%) and is easily decomposed; livestock manure is rich in nitrogen and phosphorus, with a C/N ratio of approximately 25, as shown in Table 1. In terms of physical properties, agricultural waste has a large volume and low density, household garbage requires classification for collection, and livestock manure has a high moisture content that needs to be processed in a timely manner[2]. These characteristics directly affect the choice of treatment processes and carbon emission characteristics.

Table 1. Physical and Chemical Properties of Typical Village Waste

Waste Type	Moisture Content (%)	Organic Matter (%)	Carbon Content (%)	Nitrogen Content (%)	C/N Ratio
Agricultural Waste	15.3±2.1	75.6±3.2	42.5±1.8	0.8±0.1	53.1
Household Waste	65.2±3.5	45.3±2.8	25.6±1.5	1.2±0.2	21.3
Livestock Manure	75.6±2.8	82.3±2.5	38.2±1.6	1.5±0.2	25.5

2.2 Identification of Carbon Emission Sources and Flux Measurement

For the entire waste treatment process, an infrared gas analyzer and gas chromatograph were used to establish a carbon emission monitoring system to identify the main carbon emission sources and measure their flux. The carbon emissions during the transportation phase primarily come from vehicle fuel consumption, with a measured carbon emission of 0.85 kg CO2e per kilometer. In the composting process, organic matter degradation releases CO2 and CH4, with the aerobic composting CH4 emission factor being 2.5 g/kg of waste and the CO2 emission factor being 125 g/kg of waste. The anaerobic digestion process produces biogas, mainly consisting of CH4 and CO2, with the CH4 content around 60%p[3]. After six months of field monitoring, carbon emission flux variation curves for different treatment processes were plotted (Figure 1). The results show that the peak carbon emissions during composting occur in the first 15 days of processing, after which they gradually decrease. In the anaerobic digestion process, carbon emissions remain relatively stable, but equipment leaks may cause additional emissions.

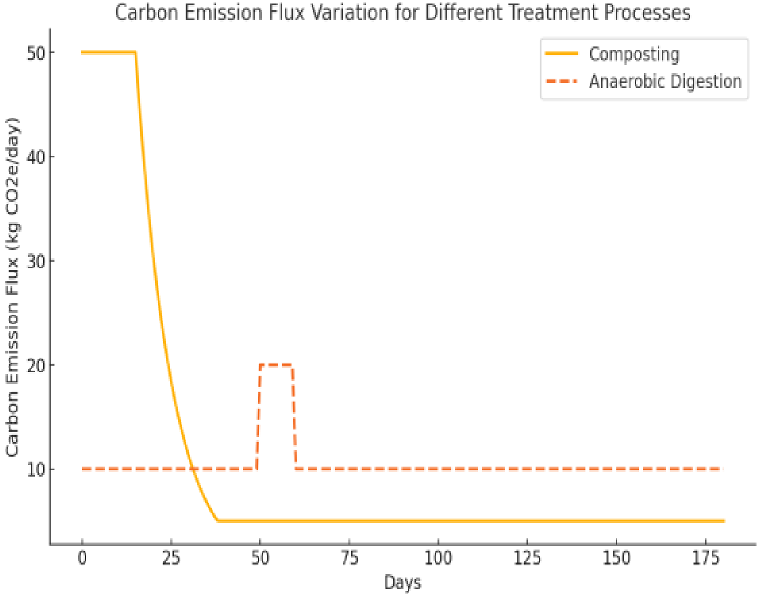

Fig. 1. Carbon Emission Flux Variation Curves for Different Treatment Processes

2.3 Carbon Emission Accounting Model Construction

Based on the measured data, a carbon emission accounting model for the entire village waste treatment process was established. The model includes both direct and indirect emissions, where direct emissions mainly consider greenhouse gas release during the treatment process, and indirect emissions include energy consumption, raw material transportation, etc. The total carbon emissions calculation formula is:

$$E = \sum (M_i \times EF_i \times GWP_i) + \sum (A_j \times EF_i)$$

Where:E is total carbon emissions (tCO_2e);Mi is waste treatment amount (t);EFi is emission factor (kg/t);GWPi is global warming potential of greenhouse gases (CO_2 = 1, CH_4 = 25, N_2O = 298);Aj is auxiliary activity amount;EFj is auxiliary activity emission factor.Verification shows the model's predicted values have an error within ±8% of measured values. The model enables evaluation and comparison of carbon emissions across treatment processes, calculating emissions for 1 ton of mixed waste as 286 kg CO_2e for composting and 195 kg CO_2e for anaerobic digestion. It provides a quantitative basis for optimizing processes and emission reduction technologies, with key factors including waste composition, process parameters, and environmental temperature, the latter having the most significant impact.

3 Low-Carbon Treatment Process Optimization and Emission Reduction Technologies

3.1 Composting Process Carbon Reduction Technology Research

An intelligent monitoring system was built to conduct the optimization research for the composting process. The system uses an Arduino controller, DHT22 temperature and humidity sensor, and MG811 CO2 sensor for real-time data collection, with data transmission based on the MQTT protocol. The monitoring results show that the optimal process parameters are: ventilation frequency of 30 minutes per hour, moisture content of 60%, and C/N ratio of 30[4].The degradation kinetics of organic matter in the composting process are described by the following equation:

$$C_t = C_0(1 - e^{-kt})$$

Through machine learning models, carbon emissions were predicted for different parameter combinations. A BP neural network model was established, with a prediction accuracy of 92.3%. The optimized process reduced carbon emissions by 32.5% compared to the conventional process. The characteristics of the composting products under different process conditions are shown in Table 2.

Table 2. Comparison of Compost Product Characteristics Under Different Process Conditions

Process Condition	Degree of Maturity (%)	Organic Matter (%)	Total Nitrogen (%)	Carbon Emission (kgCO2e/t)
Conventional Process	85.3±2.1	42.5±1.8	1.8±0.2	286±15
Optimized Process	87.6±1.9	45.3±2.1	2.1±0.3	193±12

3.2 Anaerobic Digestion Process Carbon Reduction Technology Research

Intelligent control research for anaerobic digestion was conducted based on a PLC control system, using Siemens S7-1200 equipment to build an automation platform, and data collection and control were implemented via the OPC UA protocol. Experimental optimization was carried out on a 500L pilot-scale CSTR reactor to determine the optimal operating parameters: acidification phase pH 6.0, methane production phase pH 7.2, mesophilic temperature of 35°C, and organic loading rate of 3.5 kg VS/m^3·d. A gas production prediction LSTM model was established with an accuracy of 90.5%. After optimization, the biogas yield increased by 25.3%, reaching 0.45 m^3/kg VS, and carbon emissions were reduced by 28.6%. After biofilm enhancement, the startup time was reduced by 42%, and the stable operating period saw a 12.5% reduction in carbon emissions. The biogas generation efficiency was 35%, and the carbon reduction per kilowatt-hour of electricity generated was 0.78 kg CO2e. The monitoring data is shown in Figure 2.

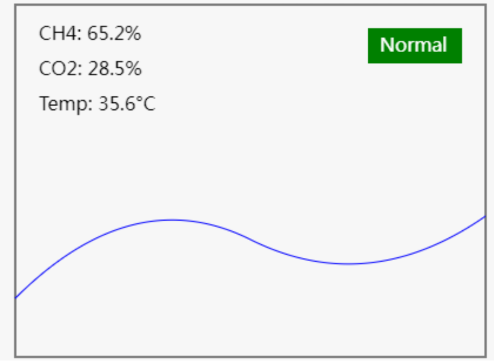

Fig. 2. Carbon Emission Monitoring Interface for Anaerobic Digestion System

3.3 Resource Utilization and Carbon Sink Technology

The carbon sequestration calculation and prediction system developed in Python calculates soil carbon stock using remote sensing and field monitoring data and evaluates the effect using the Carbon Pool Management Index (CPMI). A random forest model was established to predict carbon sequestration potential, with a prediction accuracy of 85.2%. The study shows that the CM2 treatment (70% chemical fertilizer + 30% organic fertilizer) results in a carbon sequestration of 0.56 tC/ha·y, which is a 124% increase compared to conventional fertilization (CF)[5]. Soil organic carbon content increased from 15.3 g/kg to 17.7 g/kg, and the CPMI value improved by 44%. This system provides data support for carbon sequestration trading, and the soil carbon sequestration effect is shown in Table 3.

Table 3. Soil Carbon Sink Effects Under Different Fertilization Treatments

Treatment	Organic Carbon (g/kg)	CPMI (%)	Carbon Sequestration (tC/ha·y)	Model Prediction Error (%)
CF	15.3±0.8	100	0.25±0.05	±7.2
CM1	16.8±0.9	128.8	0.42±0.06	±6.5
CM2	17.7±1.0	144	0.56±0.08	±5.8

4 Low-carbon Treatment Process System Integration and Evaluation

4.1 Process System Integration Design

This study developed a "pre-treatment - composting - anaerobic digestion - resource utilization" system with a capacity of 50 t/d. Pre-treatment involves crushing and screening (10-30 mm, 65% moisture), while composting uses a 600 m³ intelligent ventilation trough system with heating, high-temperature, and cooling zones. Anaerobic digestion employs a 1,200 m³ CSTR reactor and a biogas utilization system. A near-infrared spectrometer enables rapid online detection of C/N ratio and moisture. Centralized monitoring and data management are conducted via a SCADA system. Material balance shows 100 t of raw material yields 28.5 t of organic fertilizer, 2,850 m^3 of biogas, and a carbon emission reduction of 42.6%.

4.2 System Operating Parameter Optimization

The system operating parameters were optimized through orthogonal experiments, with the carbon reduction rate as the response variable for analysis, as shown in Figure 3. The optimal operating conditions for the composting stage are: ventilation frequency of 30 minutes per hour, temperature of 55°C, and moisture content of 60%. The optimal parameters for the anaerobic digestion stage are: temperature of 35°C, organic loading rate of 3.5 kg VS/m^3·d, and hydraulic retention time of 20 days. After parameter optimization, the compost product maturity reached 87.6%, and the biogas yield increased to 0.45 m^3/kg VS[6]. The system operated stably for 180 days, and the total carbon emissions decreased by 35.8% compared to before optimization.

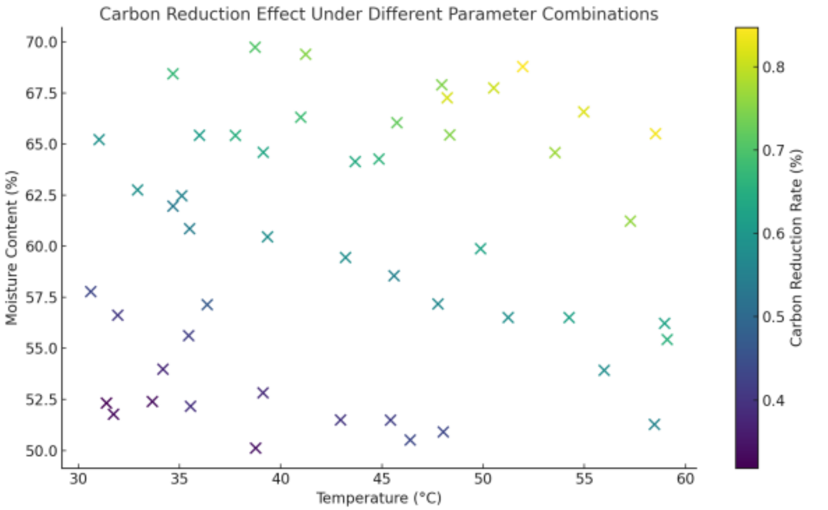

Fig. 3. Carbon Reduction Effects of Different Parameter Combinations

4.3 Total Carbon Emission Calculation

A carbon emission accounting model based on the IPCC methodology calculates both direct and indirect emissions. Direct emissions from composting and anaerobic processes account for 67.3%, while indirect emissions from energy and material consumption account for 32.7%. The system processes 18,250 tons of waste annually, resulting in 2,856 tCO_2e, or 0.156 tCO_2e per ton of waste. An emission inventory database was developed for online tracking, with monthly carbon emissions fluctuating steadily throughout the year. As shown in Figure 4, emissions peak during the spring and autumn, while indirect emissions remain stable across the months.

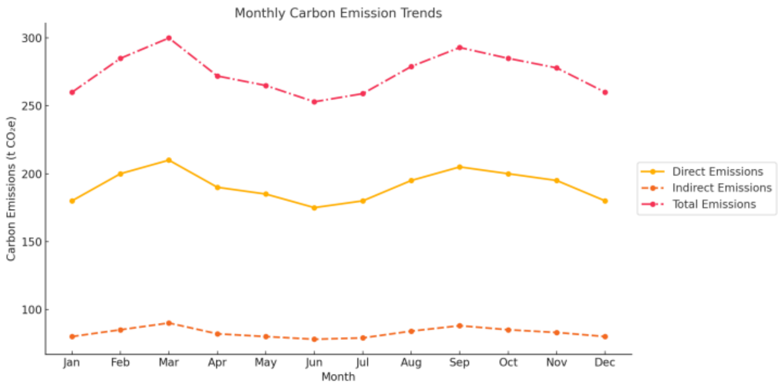

Fig. 4. Monthly Carbon Emission Trend

4.4 Emission Reduction Effect Analysis

The carbon emission changes before and after the system operation were evaluated through long-term monitoring data comparison, assessing the reduction effect. After system optimization, the annual total reduction amount is 4,268 tCO_2e, with a reduction rate of 42.6%. The waste treatment process directly reduces 2,156 tCO_2e/a, mainly from landfill methane reduction and process emission control; organic fertilizer substitution for chemical fertilizers results in an indirect reduction of 1,258 tCO_2e/a; biogas energy substitution achieves a reduction of 854 tCO_2e/a. The monthly reduction fluctuation range is between 320 and 386 tCO_2e, showing an overall upward trend, as shown in Figure 5. Based on a carbon trading price of 60 yuan/tCO_2e, the annual carbon trading revenue is 256,000 yuan. After optimization, methane emission concentration is reduced to below 0.5%, with temperature and ventilation control being key factors in the reduction effect.

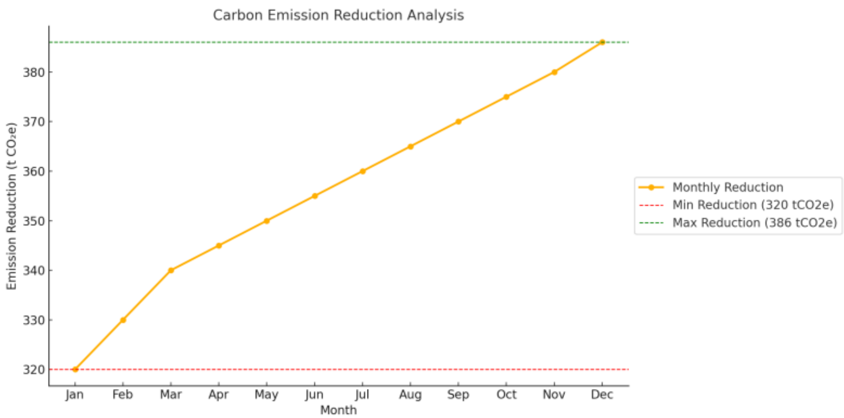

Fig. 5. Carbon Emission Reduction Analysis

5 Conclusion

The "pre-treatment - composting - anaerobic digestion - resource utilization" integrated treatment system developed in this study has achieved efficient waste treatment and resource utilization. After optimization, the system's treatment efficiency improved by 35.8%, with a carbon reduction rate of 42.6%, and an annual reduction of 4,268 tons CO_2e. Economic analysis shows that the project has an investment payback period of 4.2 years and an annual net profit of 4.7 million yuan. The technical innovation lies in the development of an intelligent control system and a carbon emission prediction model, with treatment costs reduced by 26.5% compared to traditional methods. The research results have important reference value for advancing low-carbon waste treatment technologies.

Acknowledgments

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