STUDY ON HIGH-TEMPERATURE AEROBIC FERMENTATION TECHNOLOGY OF KITCHEN WASTE
/
餐厨垃圾高温好氧发酵工艺的研究

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ABSTRACT

With the rapid urbanization in China, there has been a gradual increase in the production of kitchen waste, which poses significant environmental challenges. High-temperature aerobic fermentation is an effective method for recycling kitchen waste. This study focuses on utilizing kitchen waste, wood chips, and compound microbial agents as the main raw materials for fermentation. Various parameters such as temperature, moisture content, and amount of compound microbial agent were selected to conduct experiments on the high-temperature stage of the aerobic fermentation process for kitchen waste. Through response surface optimization experiments, it was determined that the optimal conditions for achieving fast high-temperature fermentation of kitchen waste are as follows: temperature at 60ºC, moisture content at 60%, and amount of compound microbial agent at 10%. The order of influence on the reduction rate of kitchen waste is found to be temperature followed by the amount of compound microbial agent and moisture content. These findings provide valuable insights into resource utilization strategies for managing kitchen waste.

摘要

随着我国城市化进程的加快,餐厨垃圾的产量也在逐渐增加,对环境产生了极大影响。将餐厨垃圾进行高温好氧发酵是其资源化利用的有效途径。本文主要发酵原料是餐厨垃圾、木屑和复合发酵菌剂,选取了发酵工艺的主要参数：温度、含水率和复合菌剂添加量进行试验,对餐厨垃圾高温好氧发酵工艺的高温阶段开展实验研究,通过响应曲面优化实验,得出餐厨垃圾高温快速发酵最优工艺条件为：温度60℃、含水率60%、菌剂添加量10%,各因素影对餐厨垃圾减量率的影响顺序为温度、菌剂添加量、含水率。为餐厨垃圾资源化利用提供了依据。

INTRODUCTION

Kitchen waste primarily refers to the waste generated during household, hotel, school canteen, and food processing activities *(Huang et al., 2016)*. According to statistics, the United States, Japan, India, and South Korea discard between 624 – 3500×10^4 t/year of food waste, while developing countries such as Thailand, Vietnam, and Malaysia generate about 440 – 712×104 t/year of food waste. China alone produces an enormous amount of approximately 19,500×10^4 t/year of food waste (*Hafid et al., 2017*). In 2017, the United States produced over 41 million US tons of total food waste, of which only 6% were composted (*Thiel et al., 2021*). According to EUROSTAT, the annual municipal solid waste production per capita in the European Union is 481 kg *(Vakalis et al., 2017)*. The inadequate timely treatment of substantial amounts of food and kitchen waste not only leads to resource wastage but also imposes significant environmental burdens while hindering the establishment of zero-waste cities *(Uçkun et al, 2014*; *Melikoglu, 2020)*. Therefore, high-temperature aerobic fermentation represents an efficacious approach to the safe and sustainable recycling of kitchen waste *(Padoan et al., 2023; Liu, 2021).* Consequently, it holds immense potential for broad application prospects. Both domestic and international researchers have turned their attention towards investigating the speed, quality, and in-situ reduction of kitchen waste. *Yu et al. (2009)* discovered that precise temperature control at approximately 50ºC can enhance the degradation of organic matter by microorganisms, thereby accelerating the fermentation process.

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Liu Minru et al.'s research demonstrated that collaborative fermentation of kitchen waste and other organic waste exhibits superior fermentation quality and efficiency compared to sole utilization of kitchen waste alone *(Liu et al., 2016)*. The addition of auxiliary materials (such as wood chips, straw, and bamboo charcoal) and the inoculation of microbial inoculants not only reduce the fermentation cycle but also enhance the fermentation quality *(Li et al., 2013; Khan et al., 2016).* Li Yun et al. investigated the impact of different auxiliary materials on kitchen waste fermentation and observed that their addition significantly reduced the fermentation cycle duration. Furthermore, sawdust incorporation effectively absorbed H_2S (*Li et al., 2017*). Ravindran et al. explored the effects of bamboo charcoal and biochar supplementation on aerobic kitchen waste fermentation, revealing that both additives extended the high-temperature phase, enhanced organic matter degradation rate, and improved overall fermentation efficiency *(Ravindran B. et al., 2022).* Wang Y et al. introduced mature fermentation products into kitchen waste to expedite degradation by leveraging their rich microbial content for rapid adaptation to the environment, thereby shortening the overall cycle *(Wang et al., 2022)*. Rosik et al.'s research demonstrated that adding 5–10% of compost biochar to kitchen waste significantly reduced the emissions in 70% of the detected volatile organic compounds *(Rosik et al., 2023)*.

Addressing the prevailing issues in aerobic fermentation of kitchen waste, this study focused on utilizing kitchen waste as the primary substrate and supplemented it with wood chips and a composite microbial agent. The key influencing factors, namely temperature, moisture content, and compound microbial agent were carefully selected for comparative experiments to develop an optimized high-temperature aerobic fermentation process. This research holds significant implications for enhancing urban ecological environments, improving the utilization efficiency of kitchen waste resources, establishing zero-waste cities, and promoting sustainable ecological development.

MATERIALS AND METHODS

Experimental equipment

The experimental setup employs a self-designed vertical fermenter, as depicted in the figure below, comprising four main components: the fermenter tank, heating system, stirring system, and ventilation system. The effective fermentation volume of the fermenter is 40 litres (D=360 mm, H=540 mm). The stirring system incorporates a double-layer three-blade propulsion agitator *(Lane, 2017)*. The insulation layer is composed of perlite particles *(Qian et al., 2009)*. Due to the compact size of the fermenter in this study, direct ventilation is achieved using a fan *(Feng et al., 2019).*

The overall experimental platform design is illustrated in Figure 1. Oxygen is a crucial prerequisite for high-temperature aerobic fermentation. Insufficient oxygen supply leads to increased proliferation of anaerobic bacteria in the fermentation product, resulting in anaerobic fermentation and the generation of abundant malodorous gases such as hydrogen sulfide *(Cummins, 2022)*. To ensure sufficient oxygen content during high-temperature aerobic fermentation, the air intake is connected via a silicone hose, with the other end of the hose linked to a 74.4 W small blower. The ventilation mode employed is interstitial-type ventilation (30 minutes of ventilation followed by 30 minutes without), with a ventilation rate set at 0.1 m^3 of air per cubic meter of fermentation per minute, thereby meeting the oxygen requirements for fermentation *(Shen et al., 2011).* Additionally, to maintain the fermentation temperature within a narrow fluctuation range around a specific value, a PID temperature controller and five-chip sensors are utilized. These sensors are strategically placed at the bottom and sides of the fermentation device, and their average reading determines the fermentation temperature of the experiment. Given that heating power reaches up to 4 kW, a solid-state relay is chosen as well as an added heat sink beneath it to ensure experimental safety.

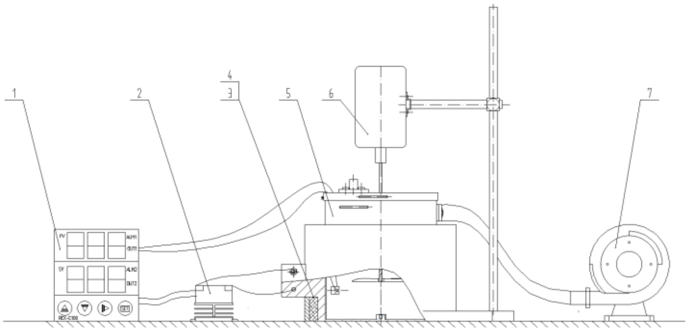

Fig. 1 - Fermentation platform diagram

1 - temperature controller; 2 - solid-state relay; 3 - heating ring; 4 - insulating layer;
5 - fermentation tank; 6 - motors and agitators; 7 - air blower

Experimental material

The primary experimental materials utilized in this study include kitchen waste, wood chips, and compound microbial agents *(Rong et al., 2021; Lanno et al., 2022)*. The kitchen waste was sourced from the school canteen and primarily consisted of vegetables, meat, and rice. Non-fermentable materials such as bone and plastic were meticulously removed and subsequently crushed into particles with a diameter of 5 mm. The wood chips employed were derived from pine wood with a water content below 9% and an approximate diameter ranging between 1-5 mm. For the experiment, a high temperature-resistant composite microbial agent comprising *Aspergillus usamii, Trichoderma longibrachiatum, Candida tropicalis, Aspergillus fumigatus, Chaetomium globosum, Paenibacillus curdlanolyticus, Bacillus thermoliquefaciens, Bacillus subtilis, Thermus thermophilus,* and *Alcaligenes faecalis* was used *(Zhu et al., 2018)*. These bacterial strains are known for their ability to withstand high temperatures up to 80℃ while maintaining excellent survival rates due to their remarkable thermal stability. Moreover, this microbial consortium effectively degrades organic matter present in kitchen waste under elevated temperatures. The fundamental physical and chemical properties of both kitchen waste and wood chips are summarized in Table 1.

Table 1

Basic physicochemical parameters of materials

Material	Moisture content/%	pH	Volatile solid/%	C/N
Kitchen waste	72.4	5.81	17.45	8.86
Wood chip	8.35	5.72	91.05	130.61

Single factor experiment

The effects of temperature, water content, and compound microbial agent on the substrate decrement rate were investigated through a single-factor experiment using a self-designed experimental fermenter.

- **Temperature**

The moisture content was adjusted to 60%, the amount of compound microbial agent was set at 10% of the fermentation substrate, and the fermenter temperature was controlled at 50ºC, 55 ºC, 60 ºC, 65 ºC, and 70 ºC, respectively. The electric stirring speed was maintained at a constant rate of 15 r/min (stirring every half hour for 4~6 minutes), while intermittent ventilation was achieved using a small blower. Aerobic fermentation experiments were conducted at different temperatures for 24 hours *(Zhang et al., 2021).*

- **Moisture content**

The temperature was set at 60℃, with a composite microbial agent addition rate of 10%. The water content was adjusted to 45%, 50%, 55%, 60%, and 65% respectively while maintaining a rotational speed of 15 r/min (stirring every half hour for 4~6 minutes). Intermittent ventilation was implemented using small blowers, and the fermentation substrate underwent 24-hour aerobic fermentation under varying water contents.

- **Compound microbial agent**

The temperature was set at 60ºC, while the moisture content was adjusted to 60%. The amount of compound microbial agent varied as follows: 5%, 10%, 15%, and 20% respectively *(Zhou et al., 2020)*. Electric stirring was conducted at a speed of 15 r/min, intermittent ventilation was achieved using a small blower, and the fermentation substrate underwent aerobic fermentation for 24 hours under different moisture contents *(Liu et al., 2022).*

Response optimization experimental design

The response surface method effectively analyses the interaction between multiple factors, addressing the limitations of single-factor experiments. It enhances and optimizes statistical and mathematical techniques, ultimately achieving the optimal response value through the establishment of a functional model. Following the principles of the BBD method in Design-Expert software, a three-factor, three-level response surface experiment was designed to investigate its impact on temperature, moisture content, compound microbial agent, and the 24-hour decrement rate of food waste aerobic fermentation as the response variable. The level values and codes for each factor are presented in Table 2.

Table 2

BBD experimental factors and levels

Level	Influencing factor		
	Fermentation temperature / ℃	**Moisture content / %**	**compound microbial agent / %**
-1	55	55	5
0	60	60	10
1	65	65	15

Detection method

- **Temperature detection**

The temperature is determined using a thermometer. By precisely measuring the positions of the material both near and far from the centre within the tank, the depth at each position is recorded once, resulting in four averaged temperature measurements for accurate determination of the material temperature. Additionally, ambient room temperature is also documented.

- **Moisture content detection**

The moisture content was determined using the drying method by standard CJ/T 313-2009. Firstly, the ceramic crucible was thoroughly cleaned and placed in an electric blast drying oven for 30 minutes to ensure complete dryness before being weighed. Subsequently, 5 g samples were carefully transferred into the prepared crucible and subjected to drying at a temperature of 110 ºC for 6 hours. After cooling for half an hour, the samples were weighed again and underwent additional cycles of drying (1 hour) followed by cooling and weighing until the weight difference between consecutive measurements was less than 1% of the sample volume. The moisture content of each sample was then calculated using the following formula:

$$W=\frac{M_2-M_1}{M_1-M}\times 100\% \qquad (1)$$

where:

W is the moisture content of the sample, (%); M is the mass of the ceramic crucible, (g);

M_1 is the mass of the sample crucible after drying, (g);

M_2 is the mass of the crucible with the sample, (g).

- **Decrement rate**

According to the single-factor experiment, specific parameters including temperature, moisture content, and the quantity of compound microbial agent added were carefully controlled. The reduction rate of the fermentation substrate was determined by weighing at 2-hour intervals *(Li et al., 2013)*. Each experimental condition was replicated twice to ensure accuracy, and the average value was calculated accordingly. The reduction rate of fermentation substrate is expressed as the ratio between the decrease in material weight after fermentation and its initial weight.

The weight reduction rate is computed using the following formula:

$$Decrement\ rate=\frac{A+B-C}{B}\times 100\% \qquad (2)$$

where:

A is the additive amount of compound microbial agent, (g); B is the mass of the fermentation substrate, (g); C is the mass of the material after fermentation, (g).

The experimental results and analysis

Single factor experimental results and analysis

- **Temperature**

Controlling temperature is a crucial factor in enhancing the efficiency of high-temperature and rapid fermentation of kitchen waste. To determine the optimal temperature for the aerobic fermentation process of kitchen waste, a 24-hour fermentation treatment was conducted. The change curve depicting the reduction rate of kitchen waste at different temperatures is illustrated in Figure 2.

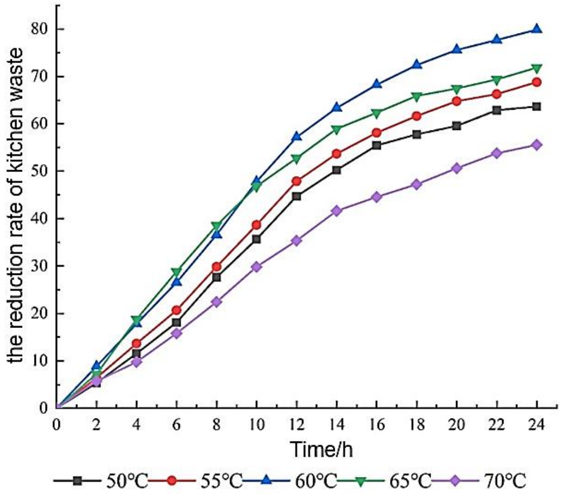

Fig. 2 - Reduction rate profiles of kitchen waste fermentation at varying temperatures

As depicted in the figure, the reduction rate of kitchen waste exhibited an upward trend after 24 hours of fermentation treatment, with the highest reduction rate recorded at 79.86% when maintained at a temperature of 60ºC. Within the range of 50ºC to 60ºC, an increase in temperature resulted in an elevated reduction rate for kitchen waste. However, as the temperature continued to rise beyond this range, during the initial ten hours, there was a higher decrement rate below 65℃ compared to that observed at 60℃; however, during later stages, it became lower than that observed at 60ºC. Even under conditions where a temperature as high as 70ºC was applied, only a minimal reduction rate (55.56%) for kitchen waste was achieved due to potential adverse effects on microbial activity caused by exceeding their optimum operating range. Considering both reduction effectiveness and compound microbial agent activity levels, it was ultimately determined that maintaining a temperature of 60℃ would be most suitable for achieving optimal results in high-temperature aerobic fermentation processes.

- **Moisture content**

Moisture content plays two crucial roles in the fermentation process: it provides an optimal environment for microbial reproduction and metabolism and facilitates temperature regulation through water evaporation. To determine the optimal moisture content for high-temperature aerobic fermentation of kitchen waste, a 24-hour fermentation treatment was conducted. The reduction rate of kitchen waste under different moisture contents is depicted in Figure 3. As shown in the figure, a water content of 65% resulted in the lowest reduction rate (60.89%) among all treatments. This could be attributed to excessive water content occupying material gaps, creating anaerobic conditions that hinder aerobic bacteria activity and causing temperature loss, thereby affecting waste reduction efficiency. Reduction rates increased with increasing water content between 45% and 60%, reaching a maximum of 79.67% at a water content of 60%. Considering both reduction effectiveness and compound microbial agent activity, a final optimal moisture content of 60% was selected for the high-temperature aerobic fermentation process.

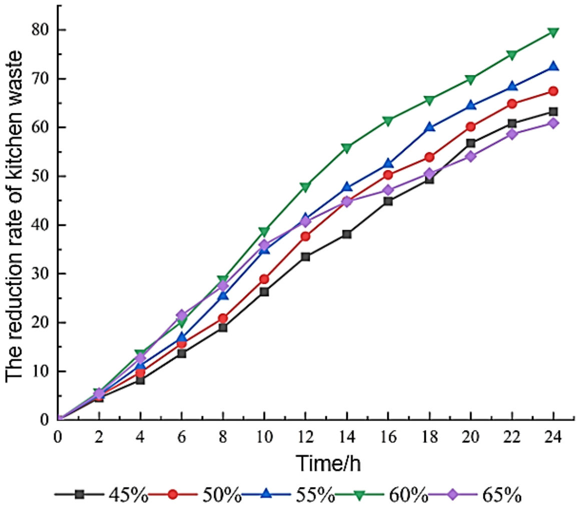

Fig. 3 - Reduction rate profiles of kitchen waste fermentation at varying moisture contents

- **Compound microbial agent**

The addition of a compound microbial agent during high-temperature rapid fermentation of kitchen waste can enhance its reduction efficiency. To determine the optimal dosage of bactericide in the high-temperature aerobic fermentation process, a 24-hour fermentation treatment was conducted on kitchen waste. The change curve depicting the reduction rate of kitchen waste under different dosages of compound microbial agents is presented in Figure 4. As observed from the figure, the reduction rate initially increased and then stabilized for each group. When using a 5% dosage of the compound microbial agent, the reduction rate was found to be minimal at only 62.29%. This could be attributed to insufficient microorganism population resulting in poor reduction efficiency. With an increase in compound microbial agent dosage from 10% to 20%, there was a gradual decrease in the reduction rate after 24 hours, with values recorded as follows: 79.34%, 77.84%, and 74.86% respectively. Considering both cost-effectiveness and reduction efficiency, an optimal inoculant addition amount of 10% was selected for the fermentation process.

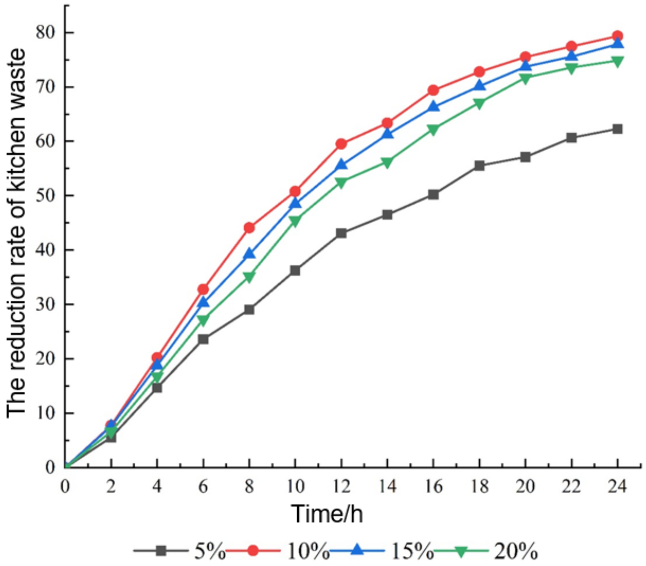

Fig. 4 - Reduction rate profiles of kitchen waste fermentation at varying compound microbial agent

RESULTS

Experimental results and analysis of response surface optimization

The three-factor and three-level experimental scheme was designed using Design-Expert 13 software based on the results of the single-factor experiments, and a mathematical regression model was constructed. The experimental design and results are presented in Table 3.

- **Regression model, equation, and analysis**

The regression analysis of the data presented in Table 3 was performed using Design-Expert 13 software, resulting in the derivation of a quadratic polynomial regression equation with the objective function being the reduction rate of kitchen waste after 24 hours of fermentation:

$$Y = 79.91 + 1.56A - 1.47B - 2.11C + 0.8675AB + 1.08AC - 0.1925BC - 8.73A^2 - 5.79B^2 - 7.56C^2 \tag{3}$$

where: Y is the reduction rate of kitchen waste, (%); A is the variable of temperature, (°C); B is the variable of moisture content, (%); C is the amount of compound microbial agent, (%).

The model underwent error statistical analysis and variance analysis, with the corresponding results presented in Table 4 and Table 5.

Table 3

Experimental scheme and results

Number No.	A / °C	B / %	C / %	Y / %
1	-1	-1	0	65.28
2	1	-1	0	68.29
3	-1	1	0	60.76
4	0	0	0	79.34
5	1	1	0	67.24

Number No.	A / °C	B / %	C / %	Y / %
6	-1	0	0	65.54
7	1	0	0	64.87
8	0	0	-1	79.67
9	-1	0	-1	60.23
10	1	0	0	63.86
11	0	-1	1	70.56
12	0	0	1	81.91
13	0	1	-1	67.84
14	0	-1	0	65.67
15	0	0	-1	78.98
16	0	1	1	62.18
17	0	0	1	79.67

Table 4

Error statistical analysis table

Statistical item	C.V.	R^2	Adjusted R^2	Predicted R^2	Adeq Precision
Value	1.95	0.9852	0.9663	0.8513	20.1796

Table 5

Regression model analysis of variance

Parameter	Sum of squares	Degree of freedom	Mean square	F	P	Significance (<0.05)
model	862.39	9	95.82	51.90	<0.0001	*
A	35.57	1	35.57	19.27	0.0032	*
B	17.35	1	17.35	9.40	0.0182	*
C	19.38	1	19.38	10.50	0.0143	*
AB	5.52	1	5.52	7.45	0.2423	
AC	4.62	1	4.62	2.50	0.1576	
BC	0.15	1	0.1482	0.08	0.7851	
A^2	320.86	1	320.86	173.80	<0.0001	*
B^2	141.25	1	141.25	76.51	<0.0001	*
C^2	260.61	1	240.61	130.34	<0.0001	*
Residual	12.92	7	1.85			
Lack of Fit	7.62	3	2.54	1.91	0.2687	
Pure Error	5.30	4	1.33			
Cor Total	875.31	16				

According to **F** of each factor in the variance analysis table, it can be seen that the order of the influence of each factor on the reduction rate of kitchen garbage is temperature, compound microbial agent, and moisture content.

- **Regression model, equation, and analysis**

The software generates contour maps and three-dimensional response surfaces based on the analysis data, vividly illustrating the pairwise interaction of various factors on the response value. Moreover, it identifies extreme value points in the model and determines corresponding optimal process parameters.

The contours and three-dimensional response surfaces of the interaction between temperature and moisture content on the reduction rate of kitchen waste are depicted in Figure 5. As illustrated in the figure, the interaction between temperature and moisture content exhibits an initial increase followed by a subsequent decrease in kitchen waste reduction. Under constant moisture content, the reduction rate of kitchen waste initially rises with increasing temperature but then declines due to potential deactivation or reduced activity of microbial agents at excessive temperatures, leading to diminished reduction efficacy. Similarly, at a fixed temperature, the influence of moisture content on kitchen waste reduction also follows a pattern of initial increase followed by eventual decrease. Based on the peak position shown in the figure, when keeping compound microbial agents, optimal conditions for achieving maximum reduction rate of kitchen waste are observed at 60 °C temperature and 60% water content.

The contours and three-dimensional response surfaces of the temperature-compound microbial agents' interaction on the reduction rate of kitchen waste are depicted in Figure 6. It is evident from the figure that the interaction between temperature and microbial agents exhibits an initial increase followed by a subsequent decrease in kitchen waste reduction. At constant temperature, the addition of microbial agents leads to an enhanced reduction rate of kitchen waste; however, when the amount of microbial agents exceeds 11%, a gradual decline in reduction rate is observed, possibly due to excessive bactericide concentration inhibiting growth and impeding kitchen waste reduction efficacy. Under identical amounts of microbial agents, the reduction effect initially increases with rising temperatures but eventually diminishes. Based on pole position analysis, at equivalent moisture content levels, optimal reductions in kitchen waste occur at 60℃ with the compound microbial agent of 10%.

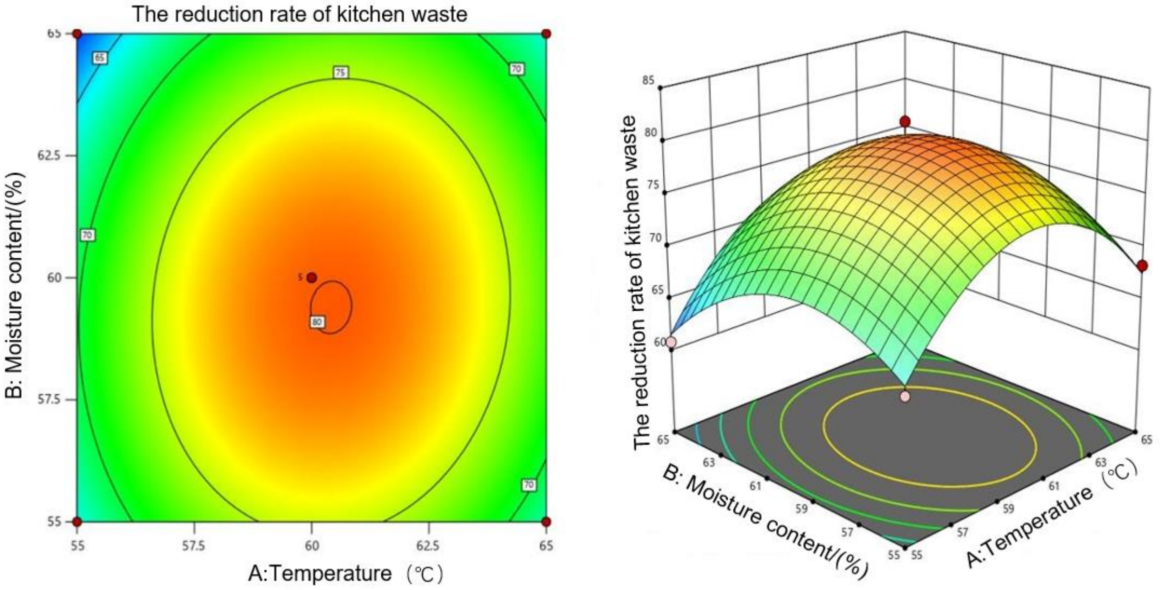

Fig. 5 -The contour and 3D response surface of the temperature-moisture content interaction

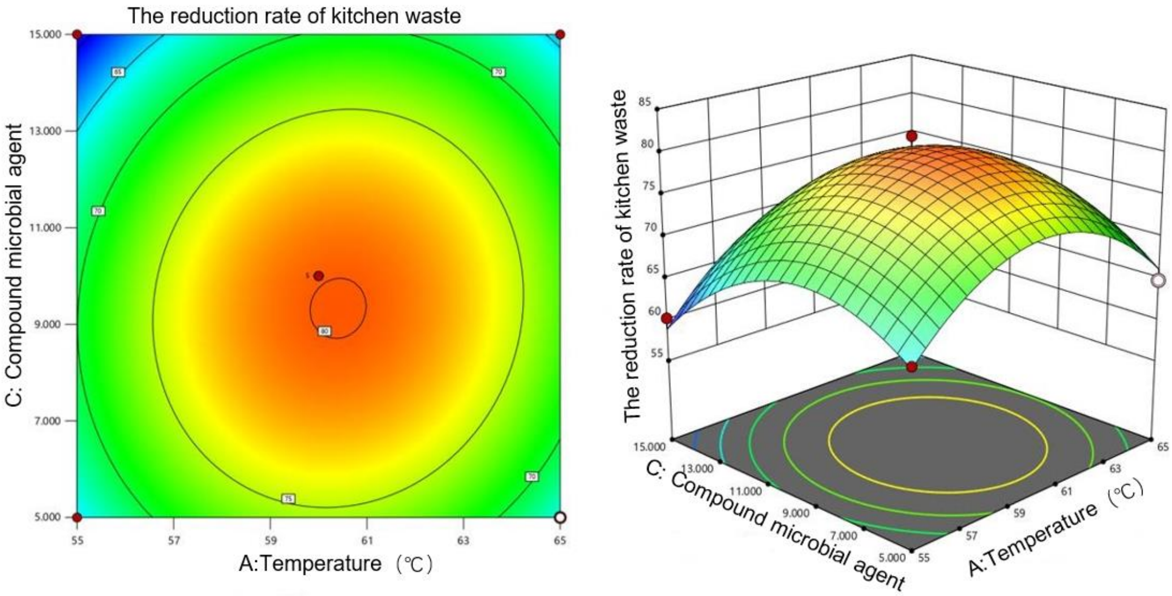

Fig. 6 -The contour and 3D response surface of the temperature-microbial agent interaction

The contours and three-dimensional response surfaces illustrating the interaction between moisture content and bactericide addition on the reduction rate of kitchen waste are depicted in Figure 7. It is evident from the figure that the reduction of kitchen waste initially increases and then decreases with the interaction between moisture content and the amount of bactericide added. When the temperature remains constant, under a fixed dosage of bactericide, the reduction rate of kitchen waste exhibits an initial increase followed by a decrease as material moisture content increases.

Similarly, for a given moisture content, altering the amount of bactericide also follows an initial increase, followed by a decrease in its impact on the decrement rate. Based on analysis from Figure 7, it can be concluded that under identical temperature conditions, optimal conditions for achieving maximum reduction rate of kitchen waste are observed at 10% moisture content and 10% microbial agent addition.

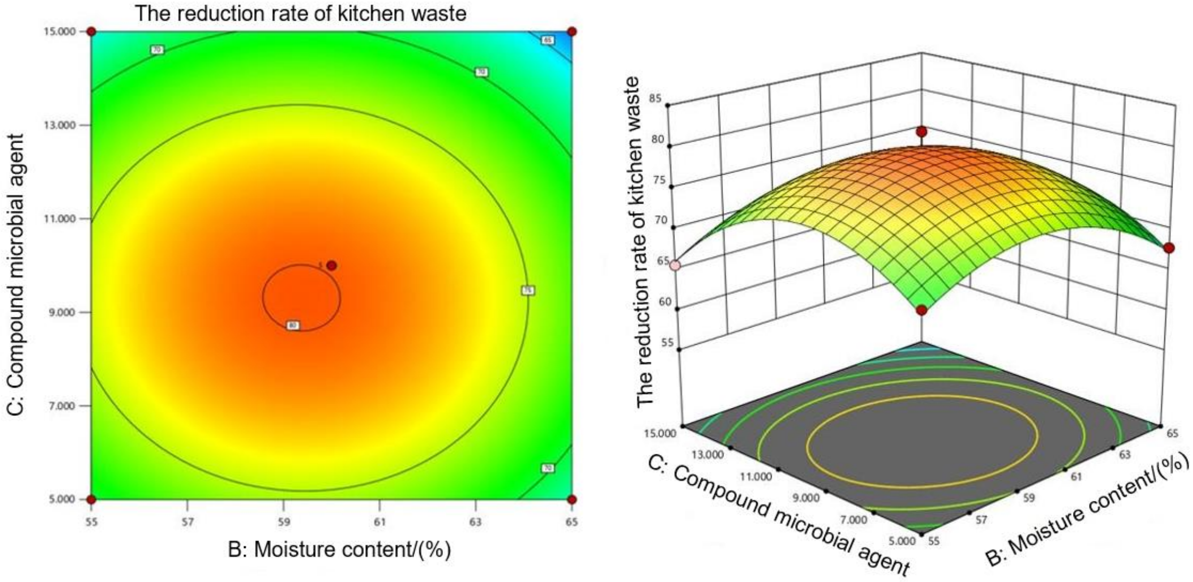

Fig. 7 -The contour and 3D response surface of the microbial agent-moisture content interaction

- **Optimal combination of optimization and verification testing**

According to the Design-Expert software, a combination optimization approach was employed to determine the range of influencing factors and select the maximum reduction rate of kitchen waste as the response value. Consequently, optimal process conditions for high-temperature rapid fermentation of kitchen waste were obtained. The main parameters included a temperature of 60.38℃, material moisture content of 59.40%, and microbial agent amount of 9.83%. The predicted reduction rate of kitchen waste after 24 hours of high-temperature rapid fermentation was found to be 80.20%. Considering practical constraints and limitations in process parameters, the optimal conditions for high-temperature rapid fermentation were determined as follows: a temperature of 60℃, moisture content at 60%, and compound microbial agent addition amount at 10%. To validate the reliability and validity of the response surface model, three experiments were conducted based on these process conditions. The observed decrement rates in these experiments were respectively found to be 79.98%, 80.12%, and 80.08%, with an average value close to that predicted by the model (80.06%). This indicates that the model can effectively predict kitchen waste reduction after high-temperature rapid fermentation and confirms that reliable process conditions have been obtained.

CONCLUSIONS

The present study investigates the impact of temperature, moisture content, and bacterial quantity on the reduction of kitchen waste, followed by the optimization of a high-temperature rapid fermentation process for kitchen waste. The following conclusions can be drawn from this research:

The optimal process conditions and their influencing sequence are as follows, based on the experimental results: a temperature of 60 ^{o}C, an additional amount of compound microbial agent at 10%, and a water content of 60%.

Verification experiment results demonstrate that the actual reduction rate of kitchen waste after 24-hour rapid fermentation at high temperatures is consistent with the predicted value obtained through response surface analysis. This indicates that the process conditions optimized using response surface methodology are accurate and reliable.

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