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An Optimization Design for the Resource Utilization of Grape Branches Based on the Orthogonal Test and Gray Relational Analysis Method

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Abstract: Composting is an environment-friendly and sustainable way to transform grape branches (GBs) into a useful product. Different parameters can differently affect fertilizer quality. Here, the compost product nutrient content was evaluated using an L9 orthogonal array (parameters, nitrogen source: chicken manure, sheep manure, urea; stirring temperature: 50, 60, 70 °C; initial pH: 6, 7, 8; conditioning agent: calcium superphosphate, zeolite, and copper sulfate). Among the treatments, the T3 (chicken manure, 70 °C, pH = 8, copper sulfate), T2 (chicken manure, 60 °C, pH = 7, zeolite), and T9 (urea, 70 °C, pH = 7, calcium superphosphate) had high gray relational grades (0.7424, 0.7132, 0.7110, respectively). The nitrogen source type (R = 0.1140) had the greatest influence on the nutrient content of the final product, followed by the stirring temperature (R = 0.1104), the conditioning agent (R = 0.0522), and the initial pH (R = 0.0408). Finally, the best nitrogen source of the grape branch compost was chicken manure, the best stirring temperature was 70 °C, the best initial pH was 7, and the best conditioning agent was zeolite. An experimental verification showed that the weighted correlation degree of the optimal treatment predicted by the orthogonal experiment increased by 3.63%.

Keywords: compost factor; composting effect evaluation; grape branch; gray relational analysis; orthogonal test

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1. Introduction

Urban greening and agricultural activities produce a large amount of green waste every year, which will cause serious damage to the environment if it is not dealt with effectively [1,2]. Composting is a green waste disposal method and can convert organics into stabilized humus, which can be used widely in agriculture and industry to achieve a cleaner product and sustainability [3,4]. Grape branches (GBs) are a type of green waste that can be converted into organic products containing nutrients, and especially humic substances, by composting [5]. Recently, scholars have improved the composting efficiency of garden wastes by controlling the composting conditions [2,6]. Compared with fallen leaves and rank grass, GBs contain more lignin and cellulose, which is difficult to degrade, limiting their resource utilization. Therefore, optimizing composting conditions can promote the degradation of cellulose and lignin and improve the product quality [3].

The nitrogen source type, temperature, pH, and conditioning agents are important factors during composting [5,7–9]. Specific nitrogen sources have distinct nitrogen contents and morphology, which impact the utilization of microorganisms and final quality of the compost [10]. A suitable temperature and pH can improve the microbial activity and accelerate the degradation of crude fiber [11]. Stirring ensures adequate ventilation in the composting to ensure a proper oxygen concentration in the stack [12], while reducing the reactor temperature. Conditioning agents can effectively improve the physical and chemical conditions of the stack, react with the NH_4^+ in the stack to reduce nutrient loss, and speed up the composting process [5,9].

Although the factors that affect composting have been previously studied for the organic waste [7,13,14], they have not been studied in combination for the green waste. Meanwhile, there are many types of green waste (dry branches, fallen leaves, seeds, rank grass, etc.), with different degradation difficulties [5]. In addition, with the development of the grape and wine industry, a large amount of GBs are produced around the world every year [15]. Therefore, it is necessary to study the composting of GBs. To better achieve the goal of sustainable development of vineyards, our study focuses on the fertilizer properties of the compost product compared to previous studies. We establish corresponding evaluation criteria based on previous studies [16,17] and predict the optimal treatment, which will provide an effective theoretical and practical guidance for the return of GBs to the field.

2. Materials and Methods

2.1. Collection of Materials

GBs, collected in the Wenquan and Lashan Demonstration Base, Research Institute of Pomology, Chinese Academy of Agricultural Sciences (Liaoning Province, China), were dried and cut to lengths of 10–25 mm. The following substances are used as sources of nitrogen during GB composting: chicken manure, sheep manure, and urea [18]. Some selected physicochemical properties of the raw materials are shown in Table 1 (a). Potassium dihydrogen phosphate and calcium oxide are used to regulate the pH of compost. These two substances are common pH regulators and widely used in compost production [19,20]. The conditioning agents used were copper sulfate, calcium superphosphate, and zeolite, which can adjust the physical and chemical properties of the stack and reduce nutrient loss. These conditioning agents have the characteristics of optimizing compost conditions and improving the quality of the compost [9,21].

Table 1. Physicochemical properties of each material and the orthogonal experimental design.

(a) Selected Physicochemical Properties of Raw Materials.

	Sheep Manure	Urea	Grape Branch	Chicken Manure
Carbon content (g/kg)	76.18 (0.92) ^{c}	37.61 (3.12) ^{d}	423.09 (20.29) ^{a}	373.75 (13.43) ^{b}
Nitrogen content (g/kg)	8.94 (0.77) ^{c}	464.57 (11.35) ^{a}	10.18 (0.04) ^{c}	57.09 (2.96) ^{b}
C/N	8.52 (0.69) ^{b}	0.08 (0.01) ^{d}	41.55 (1.82) ^{a}	6.55 (0.58) ^{c}
Rate of water content	0.26 (0.01) ^{b}	——	0.09 (0.01) ^{c}	0.59 (0.02) ^{a}

(b) Process Parameters (Factors and Levels).

Process Parameters	Symbol	Level 1	Level 2	Level 3
Nitrogen source	A	Chicken manure	Sheep manure	Urea
Stirring temperature (°C)	B	50	60	70
Initial pH	C	6	7	8
Conditioning agent	D	Calcium superphosphate	Zeolite	Copper sulfate

(c) Test Treatment Arrangement and Amount of Raw Material Added.

Treatment	GB (kg)	Nitrogen Source (kg)			Stirring Temperature (°C)	Initial pH	Conditioning Agent (kg)		
		Chicken Manure	Sheep Manure	Urea			Calcium superphosphate	Zeolite	Copper Sulfate
T1	135	9			50	6	7		
T2	135	9			60	7		7	
T3	135	9			70	8			7
T4	86		59		50	7			7
T5	86		59		60	8	7		
T6	86		59		70	6		7	
T7	147			1	50	8		7	
T8	147			1	60	6			7
T9	147			1	70	7	7		

Note. Values are listed as the means with the standard deviation in parentheses. Lower case letters a, b, c, and d represent a significance in the differences between the nitrogen source at $p < 0.05$. The sample size was 3 in each instance.

Chicken manure was purchased from the Xingcheng broiler farm and sheep manure was purchased from Xilin Gol League, Inner Mongolia. Urea was purchased from Lianmeng Co., Ltd. (Shandong, China). Potassium dihydrogen phosphate was purchased from Yuda Co., Ltd. (Sichuan, China). Calcium superphosphate was purchased from Chuming Co., Ltd. (Hubei, China).

2.2. Experimental Design

2.2.1. Orthogonal Test

Orthogonal testing is an efficient, fast, and economical test design method and is widely used in many fields [22,23]. The orthogonal experimental design in this study included L9 orthogonal arrays to organize these process parameters at possible combinations of factors and their levels to get a robust design. Table 1 (b) shows factors and their levels of the process parameters.

We added GBs and the nitrogen source to adjust the carbon–nitrogen ratio (C/N) to 30. The dosage of the conditioning agent was 5% by weight of dry matter. We used calcium oxide and potassium dihydrogen phosphate to adjust the initial pH to 6, 7, and 8. The water content of the reactor was maintained at about 60%. In the process of fermentation, we added no bacterial agent. Native bacteria were used for natural fermentation. The experimental design of the current investigation is displayed in Table 1 (c).

Each compost stack was 1.5 m long, 1 m wide, and 0.8 m high. The temperature was measured once a day. Samples were collected every 10 days to measure the physical and chemical indexes.

Composting was performed for 112 days, from 11 July 2021 to 31 October 2021, at the Wenquan Base Grape Core Technology Demonstration Park, Research Institute of Pomology, Chinese Academy of Agricultural Sciences.

2.2.2. Gray Relational Analysis

The gray relational analysis method was proposed in the gray system theory. This theory is based on the comparison of a development trend and the degree of dissimilarity between the data columns of several factors in a system. The purpose of the method is to judge the degree of closeness of the correlation and the behavior of the examined factors [24].

The different treatments of GB composting were examined as a gray system:

$$u = u\ (i), \tag{1}$$

where u stands for treatment; i = integers from 0 to 9, and $i = 0$ is the ideal compost and each nutrient component is calculated according to the highest content between treatments: $i = 1$, u (1) is T1; $i = 2$, u (2) is T2; ... $i = 9$, u (9) is T9. The ideal compost sample sequence

$$\{x_0(k)\} = \{x_0(1), x_0(2), x_0(3), x_0(4), x_0(5), x_0(6), x_0(7)\}$$

was set as the reference sequence, and

$$\{x_i(k)\} = \{x_i(1), x_i(2), x_i(3), x_i(4), x_i(5), x_i(6), x_i(7)\}$$

was set as the compared sequence, where i is the composting treatment sequence number, x stands for nutrient category, and k is taken as integers 1–7.

The basic formula for a correlation analysis is the correlation coefficient (L_{0i}) formula, which can be expressed as follows in the evaluation process:

$$L_{0i}(k) = \frac{\frac{min}{i}\ \frac{min}{k}|x_0(k) - x_i(k)| + \frac{\rho max}{i}\ \frac{max}{k}|x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \frac{\rho max}{i}\ \frac{max}{k}|x_0(k) - x_i(k)|}. \tag{2}$$

where ρ is the resolution coefficient (approximately 0–1), and is generally taken as 0.5. The degree of correlation between the compared sequence $\{x_i(k)\}$ and the reference sequence $\{x_0(k)\}$ can be calculated using Equation (3):

$$r_{0i} = \frac{1}{7}\sum\nolimits_{k=1}^{7} L_{0i}(k). \tag{3}$$

According to the gray relational grade (r_{0i}), the similarity between different composting treatments and the ideal compost can be determined. The larger the r_{0i}, the closer the compost is under that treatment condition to the ideal compost.

2.3. Analytical Procedure

2.3.1. Physical Analyses

The stack temperature was measured using a mechanical thermometer and recorded daily. Particle-size distribution and Coarseness index (CI) were determined according to Gabhane et al., [9]. Air-dried compost samples were shaken on sieves with openings of 0.3, 1, 2, and 5 mm (3 min of shaking on each sieve size). The material retained on each sieve was weighed. The CI—i.e., a percentage (based on air-dried weight) of particles > 1 mm—was calculated [5]. The bulk density (BD), water-holding capacity (WHC), and porosity were determined as described by Yin et al. [5]. The void ratio (VR) was the ratio of the aerated porosity (AP) to water-filled porosity, and was determined as described by Yin et al. [5]. For the determination of these properties, the air-dried sample was first placed in a 100-cm^3 ring knife (M_0), which was weighted (M_1). The ring knife was then placed in distilled water and was then removed from the water after 24 h (M_2). The lid of the ring knife was removed, and the ring knife was sealed with water-permeable gauze. Then, the ring knife with the saturated compost was placed upside down on a screen until the water stopped dripping from the bottom for about 4 h. When the water had stopped dripping, the ring knife was weighed and recorded as M_3. Finally, the ring knife was oven-dried at 65 °C until the weight (M4) did not change. BD (g/cm^3) = ($M_4 - M0$)/100; WHC (%) = 100 ($M_3 - M_1$)/($M_1 - M_0$); total porosity (TPS) (%) = 100 ($M_2 - M_4$)/100; AP (%) = 100 ($M_2 - M_3$)/100; WFP (%) = TPS − AP; and VR = AP/WFP. The above physical properties are commonly used to evaluate composting efficiency and compost maturity [5,9].

2.3.2. Chemical Analyses

The pH was determined for a filtrate ($W_{compost}/V_{distilled}$ water = 1/10) using a Seven-Compact pH meter (METTLER TOLEDO, Swiss). The electrical conductivity (EC) value was determined for a filtrate ($W_{compost}/V_{distilled}$ water = 1/5) using a DDS-307 digital conductivity meter (DAPU, China). The organic matter content was determined using the high-temperature external heat potassium dichromate oxidation method. The total humic acid (THA) content was determined using the sodium pyrophosphate–sodium hydroxide extraction of potassium dichromate oxidation capacity method. Available phosphorus (AP) was extracted with 50 ml of 0.5 M $NaHCO_3$ (1:20 ratio for 0.5 h) and determined using a flow analyzer (Futura AMS Alliance, Paris, France). Available potassium (AK) was extracted with 50 ml of 1 M NH_4OAc (1:20 ratio for 0.5 h) and determined using flame photometry. NH_4^+-N and NO_3^--N (AN) were extracted using 50 mL of 2 M KCl (1:20 ratio for 1 h) and determined using a flow analyzer (Futura AMS Alliance, France). Available calcium (ACa) and magnesium (AMg) were extracted with 50 mL of 1 M NH_4OAc (1:20 ratio for 0.5 h), diluted with 30 g/L $SrCl_2{\cdot}6H_2O$, and determined using an atomic absorption spectrometer (ZEENIT 700P, Jena, Germany).

2.3.3. Seed Germination Test

First, a filter paper in a sterile Petri dish was wetted with a filtrate (1 g of compost with 10 mL of water). Distilled water (CK, the control) was used as the control. After 10 green stem cabbage (Hebei, China) seeds were spread on the filter paper in each dish, the dishes were incubated for 48 h at 25 °C in the dark. The seed germination rate

(SGR), root length (RL), and germination index (GI) were then calculated according to Yin et al. [5]: GI (%) = (mean number of germinated seeds in the treatment × mean RL in the treatment × 100)/(mean number of germinated seeds in the CK × mean RL in the CK).

2.4. Statistical Analysis

Data processing was performed with Microsoft Office 2016, and statistical analysis was completed using R-4.04. Analysis of variance (ANOVA) was used to determine whether the effects were significant. When ANOVA was significant ($p < 0.05$), the means were separated with an LSD test at $p < 0.05$.

3. Results and Discussion

3.1. Effect of Different Conditions on the Temperature during the Composting Process

Temperature can directly reflect the activity of microorganisms in a compost system [25]. In the early stage of composting, the microorganisms were active, and the temperature of each treatment increased rapidly. The temperature of each stack was maintained at 50–60 °C for more than 3 days to meet the requirements of disinfection in the compost [1]. Differences in the temperature changes among treatments occurred over time (Figure 1). T2 and T1 maintained a high temperature for the longest time, with the high temperature above 50 °C for 52 days and 46 days, respectively. Fresh chicken manure contains more active microorganisms which are more active under neutral-to-weakly acidic conditions [26]. Therefore, the duration of the elevated temperatures for T1 and T2 was longer than for other treatments and the temperature of the reactor was the highest, exceeding 70 °C. The duration of the elevated temperatures for T3, T4, and T8 were shorter than those for T1 and T2. This may be related to the addition of copper sulfate. When Cu^{2+} fixed nitrogen, it also destroyed the structure and function of enzymes and inhibited the normal life activities of microorganisms, resulting in a shorter duration of elevated temperatures than other treatments with the same nitrogen source [27].

3.2. Effect of Different Conditions on the pH and Electrical Conductivity of the Compost Product

The pH changes for the nine treatments differed (Figure 2a). Compared to the pH before composting, the pH significantly ($p < 0.05$) increased in 6 treatments (T1, 40.76%; T2, 20.74%; T4, 21.16%; T6, 21.76%; T8, 29.05%; and T9, 4.78%). T3 and T7 experienced no significant decreases in pH and there was only a minor change in pH in T5. During the composting process, the increase in pH may be related to the degradation of organic acids and the accumulation of NH_4^+ [28]. The NH_4^+-N contents were lower after T1, T2, T6, and T8 than that at the beginning of composting. The increase in pH for these treatments may have been primarily owing to the decomposition of organic acids in the process of composting. The NH_4^+-N content increased in T4 and T9 during composting. Proteins and urea can be broken down by microorganisms to produce NH_4^+, causing the pH to increase [7]. The main reason for the decrease in pH in T3, T5, and T7 was that the stack was a complex reactor and had a certain self-regulating ability. A higher pH will inhibit the life activities of microorganisms, so microorganisms work to reduce the pH value of the reactor in various ways, such as producing organic acids and CO_2, so that the conditions of the reactor change in the direction suitable for microbial survival [29]. However, this self-regulating ability is limited, so the decrease in pH may be indiscernible.

After composting, the EC values decreased to varying degrees in the nine treatments (Figure 2b). T2 demonstrated the greatest decrease at 48.63%. T7 experienced the least decrease at 16.83%. Chicken manure and sheep manure have higher EC values owing to their own complex nutrient content and total ions. In the process of fermentation, with the addition of water, some of the ions were lost, reducing the ion concentration in the stack [30]. Additionally, further evaporation of ammonia will reduce the EC value [11]. Related studies have shown that when the EC value is greater than 4 ms/cm, the composting product may have phytotoxicity, negatively impacting crop growth [14]. Each of the nine treatments met the requirements of farmland application after composting, despite

T1, T3, T4, and T6 having initial EC values exceeding 4 ms/cm. The EC value was reduced through composting to meet the requirements of farmland application. However, the excessive reduction of EC also indicates a serious loss of soluble mineral nutrients during the composting process. This has a negative impact on the quality of composted products [31]. The initial EC value in T2 was within a reasonable range, but dropped more than other treatments during composting, resulting in a loss of nutrients. The same problem was evident in T5, T7, T8, and T9. Volatilization of NH_3 and CO_2 [32], accumulation of soluble ions, and mineralization of composting materials [33] are the main reasons for the decrease in EC when composting livestock and poultry manure. In T5, although livestock manure was not added, the available potassium content decreased substantially after composting. The loss of soluble ions may be the main reason for this decrease of EC.

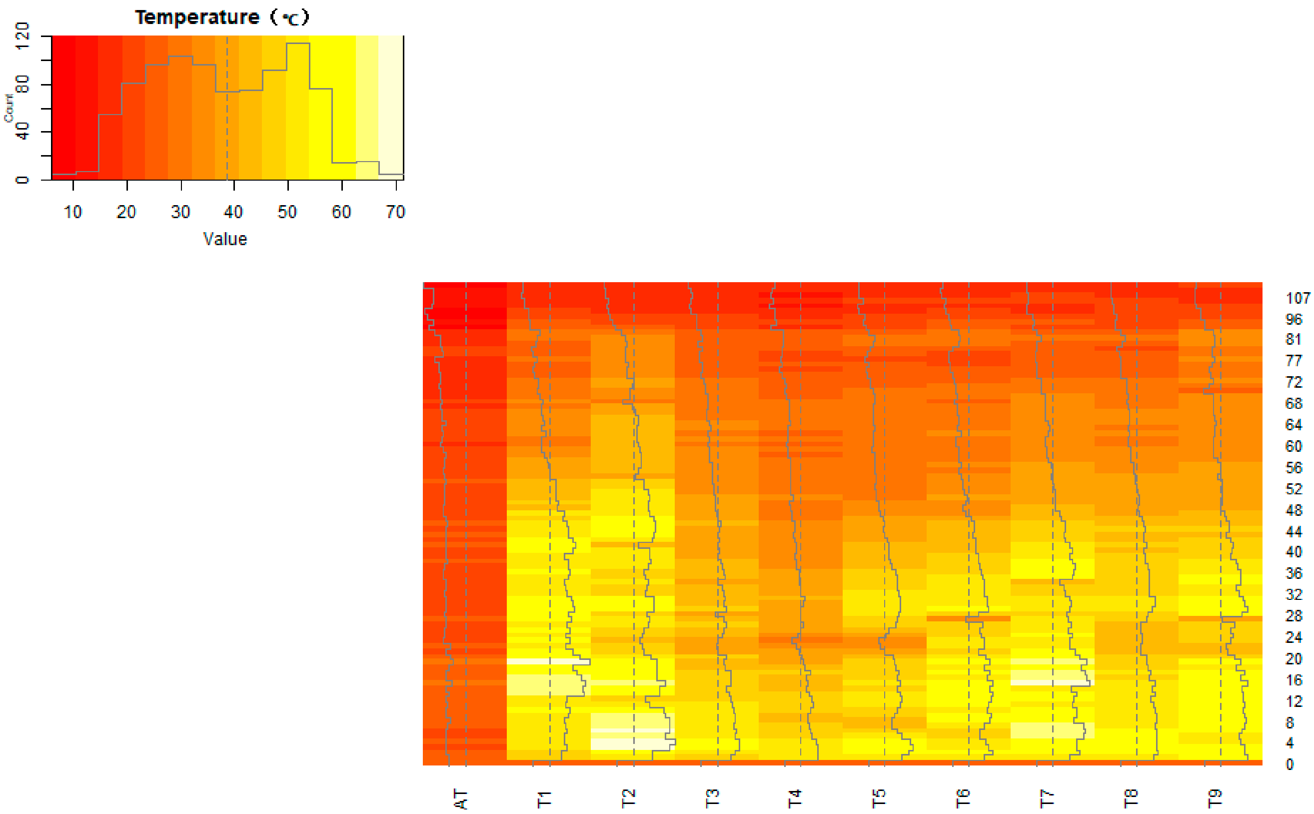
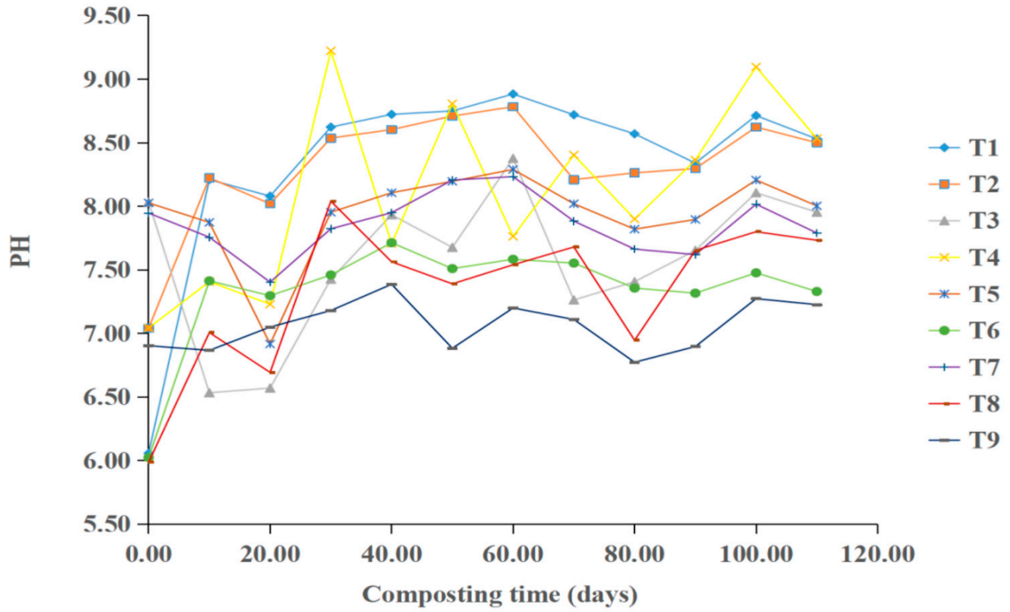
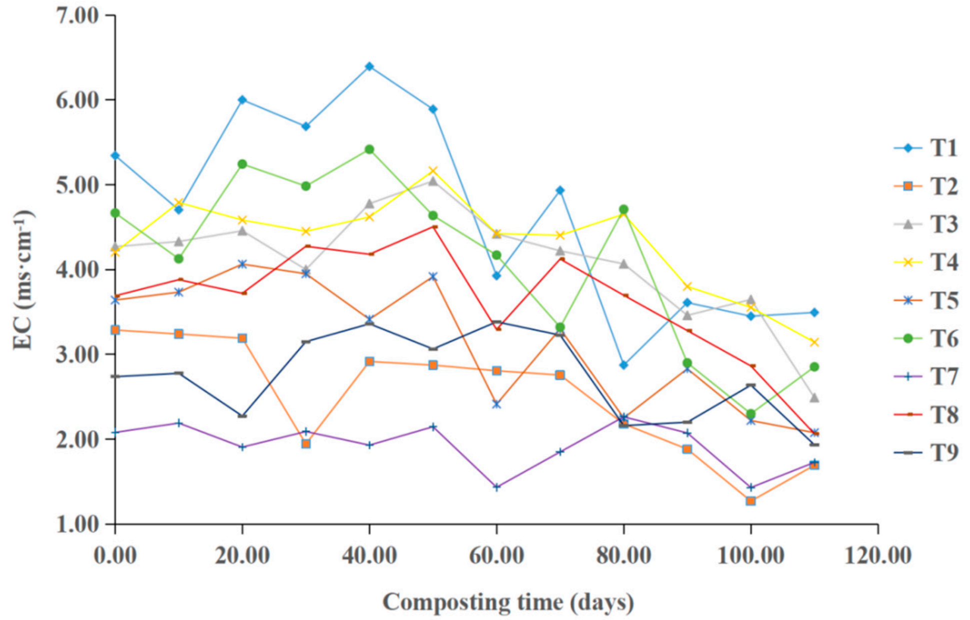


Figure 1. Temperature variations for treatments (AT, ambient temperature). Note. AT = ambient temperature; T1 = chicken manure, calcium superphosphate, initial pH of 6, and stirring temperature 50 °C; T2 = chicken manure, zeolite, initial pH of 7, and stirring temperature 60 °C; T3 = chicken manure, copper sulfate, initial pH of 8, and stirring temperature 70 °C; T4 = sheep manure, copper sulfate, initial pH of 7, and stirring temperature 50 °C; T5 = sheep manure, calcium superphosphate, initial pH of 8, and stirring temperature 60 °C; T6 = sheep manure, zeolite, initial pH of 6, and stirring temperature 70 °C; T7 = urea, zeolite, initial pH of 8, and stirring temperature 50 °C; T8 = urea, copper sulfate, initial pH of 6, and stirring temperature 60 °C; T9 = urea, calcium superphosphate, initial pH of 7, and stirring temperature 70 °C.



(**a**)



(**b**)

Figure 2. The pH and EC variations for the various treatments: the pH variations for the various treatments (**a**), and the electrical conductivity (EC) variations for the various treatments (**b**).

3.3. Effect of Different Conditions on Phytotoxicity of the Compost Product

The germination index can be used to evaluate the phytotoxicity of composting products [34]. The higher the GI, the weaker the phytotoxicity of composting products [6,35,36]. The process of composting can degrade, transform, and accumulate harmful substances to reduce phytotoxicity [37]. Of the 9 treatments, the GI in T7 was the greatest at 188%, followed by T4 and T9 at 175% and 162%, respectively (Table 2). The germination index is affected by the EC of compost products. The higher the EC value at the end of compost, the lower the GI. Elevated EC values will have a negative impact on the germination of seeds [3].

Table 2. Plant toxicity study of compost products based on a Chinese cabbage seed germination test.

Treatment	Seed Germination Rate (%)	Average Root Length (mm)	GI (%)
T1	93 (12) ^{a}	14 (5) ^{a}	143 (64) ^{abc}
T2	87 (6) ^{ab}	15 (3) ^{a}	137 (29) ^{abc}
T3	40 (10) ^{d}	16 (5) ^{a}	70 (32) ^{c}
T4	77 (23) ^{ab}	23 (9) ^{a}	175 (12) ^{ab}
T5	50 (10) ^{cd}	23 (5) ^{a}	122 (23) ^{abc}
T6	83 (6) ^{ab}	15 (2) ^{a}	131 (9) ^{abc}
T7	77 (6) ^{ab}	22 (6) ^{a}	188 (61) ^{a}
T8	73 (15) ^{ab}	15 (5) ^{a}	119 (55) ^{abc}
T9	80 (10) ^{ab}	19 (6) ^{a}	162 (58) ^{ab}
CK	67 (6) ^{bc}	14 (7) ^{a}	100 (53) ^{bc}

Note. T1 = chicken manure, calcium superphosphate, initial pH of 6, and stirring temperature 50 °C; T2 = chicken manure, zeolite, initial pH of 7, and stirring temperature 60 °C; T3 = chicken manure, copper sulfate, initial pH of 8, and stirring temperature 70 °C; T4 = sheep manure, copper sulfate, initial pH of 7, and stirring temperature 50 °C; T5 = sheep manure, calcium superphosphate, initial pH of 8, and stirring temperature 60 °C; T6 = sheep manure, zeolite, initial pH of 6, and stirring temperature 70 °C; T7 = urea, zeolite, initial pH of 8, and stirring temperature 50 °C; T8 = urea, copper sulfate, initial pH of 6, and stirring temperature 60 °C; T9 = urea, calcium superphosphate, initial pH of 7, and stirring temperature 70 °C; CK = without additives. GI = germination index. Values are listed as the means with the standard deviation in parentheses. The sample size was 3 in each instance. Lower case letters a, b, c, and d represent a significance in the differences between treatments at $p < 0.05$.

Substances produced in compost that are phytotoxic, such as low molecular weight organic acids and inorganic nitrogen, can inhibit seed germination [13]. Because of the elevated temperatures, the maintenance time in T3 was substantially shorter than that in the other two treatments with added chicken manure (T1, T2). The pH value was the lowest in T3 among the three treatments with chicken manure as a nitrogen source. The higher organic acid content and other substances may have reduced the GI [38]. Concurrently, NH_4^+ and Cu_2^+ in high concentrations also resulted in a low seed germination rate.

3.4. Effect of Different Conditions on Organic Matter and Total Humic Acid of the Compost Product

The variation of organic matter in the composting process reflects the decomposition of GB by microorganisms. The organic matter degradation rates of the 9 treatments were 28.72%, 20.75%, 4.37%, 8.44%, 13.33%, 9.64%, 2.37%, 6.17%, and 6.02%, respectively (Table 3). In general, the organic matter degradation rate of urea as a nitrogen source was significantly lower than that of chicken manure as a nitrogen source ($p < 0.05$). As the types and contents of microorganisms in urea were lower than those in the chicken manure treatment, the degradation rate of organic matter was lower than that in the chicken manure treatment [26]. Stirring the stack can reduce the temperature of a reactor and avoid elevated stack temperatures, which inhibit the life activities of microorganisms. At the same time, stirring can improve porosity and oxygen concentration, promote microbial respiration, and accelerate GB decomposition. For GB compost fermentation, the degradation rate of organic matter is the highest at 60 °C. Under conditions close to 60 °C, the enzyme activity is higher, thus promoting the decomposition of cellulose and other macromolecular substances [39].

Humic acid is a kind of polymer complex organic colloid which can improve the activity of polyphenol oxidase in plants, thus accelerating the metabolism and dry matter accumulation of crops. Organic matter can be transformed into humus after mineralization and saponification [40]. The species and activity of microorganisms are closely related to the transformation of organic matter and the formation of humic acid. NH_4^+ is a precursor to humic acid formation. T2, T3, and T9 treatments had higher NH_4^+ and humic acid contents [41].

Table 3. Selected physicochemical properties of the feedstock mixture and the final compost product.

Treatment	Before Composting						
	ACa (mg/g)	**AK (mg/g)**	**AMg (mg/g)**	**AP (mg/g)**	**NO_3^{-}-N (mg/kg)**	**NH_4^{+}-N (mg/kg)**	**OM (g/kg)**
T1	12.88 (0.42) ^{b}	18.71 (0.57) ^{b}	1.66 (0.08) ^{c}	1.61 (0.12) ^{b}	95.12 (3) ^{c}	199.76 (1.29) ^{a}	692.96 (0.45) ^{b}
T2	10.91 (0.36) ^{c}	11.38 (0.20) ^{c}	1.89 (0.02) ^{a}	1.33 (0.11) ^{c}	61.31 (3.91) ^{f}	186.43 (7.12) ^{b}	689.17 (1.42) ^{c}
T3	15.45 (1.15) ^{a}	9.43 (0.25) e	1.86 (0.05) ^{ab}	0.48 (0.02) ^{f}	74.27 (2.25) ^{e}	181.11 (4.91) ^{b}	693.49 (1.04) ^{b}
T4	12.42 (0.74) ^{bc}	10.35 (1.28) ^{d}	1.87 (0.02) ^{ab}	0.70 (0.18) ^{e}	242.54 (3.67) ^{a}	106.31 (7.17) ^{d}	481.79 (0.40) ^{e}
T5	10.6 (1.22) ^{c}	10.46 (0.28) ^{d}	1.84 (0.06) ^{ab}	1.26 (0.06) ^{c}	86.37 (1.52) ^{d}	102.66 (5.89) ^{d}	480.23 (1.18) ^{e}
T6	6.3 (0.38) ^{d}	21.90 (0.29) ^{a}	1.44 (0.06) ^{d}	6.89 (0.05) ^{a}	182.29 (3.04) ^{b}	172.61 (3.43) ^{c}	483.75 (1.80) ^{d}
T7	7.59 (0.78) ^{d}	8.73 (0.09) ^{e}	1.68 (0.08) ^{c}	0.94 (0.05) ^{d}	63.48 (2.51) ^{f}	203.24 (0.33) ^{a}	700.41 (0.99) ^{a}
T8	10.97 (1.39) ^{c}	7.33 (0.17) ^{f}	1.80 (0.04) ^{ab}	0.49 (0.08) ^{f}	61.64 (4.8) ^{f}	205.81 (0.17) ^{a}	699.1 (0.45) ^{a}
T9	10.84 (1.68) ^{bc}	7.59 (0.17) ^{f}	1.76 (0.10) ^{bc}	1.04 (0.07) ^{d}	76.95 (11.62) ^{e}	205.39 (0.93) ^{a}	700.54 (0) ^{a}
	THA (g/kg)	BD (g/cm^3)	WHC (%)	VR	Bacteria ($\times 10^{10}$CFU/g)	Actinomycetes ($\times 10^{7}$CFU/g)	Fungi ($\times 10^{5}$CFU/g)
T1	-	-	-	-	-	-	-
T2	-	-	-	-	-	-	-
T3	-	-	-	-	-	-	-
T4	-	-	-	-	-	-	-
T5	-	-	-	-	-	-	-
T6	-	-	-	-	-	-	-
T7	-	-	-	-	-	-	-
T8	-	-	-	-	-	-	-
T9	-	-	-	-	-	-	-
Treatment	**After composting**						
	ACa (mg/g)	**AK (mg/g)**	**AMg (mg/g)**	**AP (mg/g)**	**NO_3^{-}-N (mg/kg)**	**NH_4^{+}-N (mg/kg)**	**OM(g/kg)**
T1	14.45 (0.85) cd, δ	18.72 (1.18) b, β	2.02 (0.06) cd, α β	2.19 (0.33) b, α	126.66 (4.41) a, α	90.61 (8.09) g, γ	493.95 (12.85) c, α
T2	15.96 (1.73) bc, α β	13.00 (0.44) c, α	2.26 (0.01) a, α β	1.38 (0.07) c, β γ	92.84 (0.56) b, α	108.77 (5.00) ef, δ	582.80 (68.83) b, β
T3	18.55 (0.52) a, β γ δ	8.08 (0.06) e, γ	2.18 (0.02) ab, α β	0.85 (0.03) d, α β	58.64 (4.53) cd, γ	153.87 (12.04) c, γ	663.17 (2.27) a, ε
T4	16.55 (0.92) b, α β γ	7.25 (0.12) ef, δ	2.00 (0.03) d, γ	0.43 (0.10) e, γ	54.39 (0.99) de, ζ	120.58 (1.98) de, α	441.15 (1.37) d, δ ε
T5	13.2 (0.46) d, γ δ	7.21 (0.27) ef, δ	2.07 (0.07) bcd, β γ	1.30 (0.02) c, β γ	56.48 (0.27) cd, δ	117.70 (5.09) de, α	416.20 (6.44) d, γ
T6	8.88 (1.41) e, γ δ	21.83 (0.65) a, β	1.85 (0.12) e, α	5.83 (0.40) a, δ	59.47 (3.49) c, ε	97.67 (6.39) fg, α	437.10 (5.88) d, δ
T7	13.37 (0.56) d, α	10.87 (0.17) d, α	2.06 (0.06) cd, α β	0.93 (0.15) d, β γ	51.17 (1.29) e, γ	128.44 (8.51) d, γ	683.81 (0.60) a, ζ
T8	17.21 (1.13) ab, α	6.72 (0.16) f, β γ	2.11 (0.05) bc, α β	0.59 (0.12) de, β γ	59.06 (2.31) cd, β	175.00 (1.64) b, β	655.98 (1.13) a, δ ε
T9	12.79 (0.54) d, γ δ	6.99 (0.07) f, β γ	2.08 (0.02) bcd, α β	0.85 (0.04) d, γ	49.74 (1.16) f, δ	217.02 (5.38) a, β	658.33 (1.20) a, δ ε
	THA (g/kg)	BD (g/cm^3)	WHC (%)	VR	Bacteria ($\times 10^{10}$CFU/g)	Actinomycetes ($\times 10^{7}$CFU/g)	Fungi ($\times 10^{5}$CFU/g)
T1	18.21 (0.63) ^{d}	0.28 (0.02) ^{b}	215 (8) ^{d}	2.78 (0.24) ^{f}	9.23 (0.35) ^{a}	5.17 (0.57) ^{ab}	6.13 (0.71) ^{a}
T2	26.48 (0.45) ^{a}	0.27 (0.01) ^{b}	228 (13) ^{d}	9.83 (0.82) ^{de}	8.47 (0.31) ^{b}	5.27 (0.25) ^{a}	4.83 (0.15) ^{b}
T3	26.38 (0.62) ^{a}	0.14 (0.03) ^{e}	218 (18) ^{d}	56.79 (6.53) ^{a}	5.2 (0.46) ^{c}	2.83 (0.32) ^{d}	1.83 (0.35) ^{d}
T4	21.76 (1.86) ^{c}	0.23 (0.01) ^{c}	151 (9) ^{f}	27.80 (3.65) ^{b}	4.43 (0.45) ^{d}	3.67 (0.32) ^{c}	2.63 (0.31) ^{cd}
T5	17.17 (0.18) ^{d}	0.32 (0.02) ^{a}	165 (19) ^{ef}	11.99 (1.39) ^{d}	3.33 (0.42) ^{e}	3.17 (0.45) ^{cd}	2.33 (0.42) ^{cd}
T6	18.59 (1.66) ^{d}	0.32 (0.01) ^{a}	187 (4.5) ^{e}	7.26 (1.26) ^{def}	3.87 (0.35) ^{de}	3.17 (0.47) ^{cd}	2.93 (0.31) ^{c}
T7	23.86 (1.76) ^{b}	0.23 (0.01) ^{c}	276 (21) ^{c}	8.31 (1.37) ^{de}	5.23 (0.38) ^{c}	5.23 (0.32) ^{a}	5.7 (0.36) ^{a}
T8	23.48 (0.31) ^{bc}	0.14 (0.02) ^{e}	303 (18) ^{b}	19.95 (2.33) ^{c}	3.5 (0.35) ^{e}	4.5 (0.36) ^{b}	3.13 (0.57) ^{c}
T9	26.45 (1.11) ^{a}	0.17 (0.01) ^{d}	330 (15) ^{a}	5.37 (0.81) ^{ef}	4.5 (0.36) ^{d}	5.4 (0.46) ^{a}	4.73 (0.76) ^{b}

Note. T1 = chicken manure, calcium superphosphate, initial pH of 6, and stirring temperature 50 °C; T2 = chicken manure, zeolite, initial pH of 7, and stirring temperature 60 °C; T3 = chicken manure, copper sulfate, initial pH of 8, and stirring temperature 70 °C; T4 = sheep manure, copper sulfate, initial pH of 7, and stirring temperature 50 °C; T5 = sheep manure, calcium superphosphate, initial pH of 8, and stirring temperature 60 °C; T6 = sheep manure, zeolite, initial pH of 6, and stirring temperature 70 °C; T7 = urea, zeolite, initial pH of 8, and stirring temperature 50 °C; T8 = urea, copper sulfate, initial pH of 6, and stirring temperature 60 °C; T9 = urea, calcium superphosphate, initial pH of 7, and stirring temperature 70 °C. Values are listed as the means with the standard deviation in parentheses. The sample size was 3 in each instance. Lower case letters a, b, c, d, e, and f represent a significance in the differences between treatments at a specific time at $p < 0.05$. Greek letters α, β, γ, δ, ε, and ζ represent a significance in the differences in the amount of change between treatments at $p < 0.05$.

3.5. Effect of Different Conditions on the Particle-Size Distribution and Coarseness Index of the Compost Product

The particle-size distribution is relevant to compost maturity because it indicates the extent of the degradation of complex substances [5]. Due to the large particle size, it is difficult for GB to decompose, and the CI of all final compost products is generally higher than the requirements of general compost [9]. The CI in T1 was the lowest at 59.94%, compared to above 70% in other treatments, with T3, T5, T6, T7, and T8 over 80% (Table 4). In this study, treatment with chicken manure as the nitrogen source effectively reduced the CI value of compost products. Meanwhile, pH influenced the CI value of compost products. The treatments with an initial pH of 8 had a larger CI value. Under the condition of a higher pH, the growth of microorganisms was inhibited and the decomposition effect of microorganisms on GB was reduced [42]. At the beginning of the treatment with chicken manure, the content of available mineral nutrients was higher, which provided nutrients required for the growth of microorganisms, thus improving the particle size distribution of compost [3].

Table 4. Initial value transformation of each index in compost treatments.

Treatment	>5.00 (mm)	2.00–5.00	1.00–2.00	1.00–0.30	<0.30	CI (>1.00)
T1	8.37	10.28	11.32	16.77	3.26	59.94 (0.29) ^{g}
T2	10.40	22.63	6.27	7.97	2.73	78.60 (0.24) ^{e}
T3	16.07	22.57	5.31	2.44	3.61	87.91 (0.78) ^{b}
T4	9.50	22.00	7.39	8.84	2.27	77.77 (1.11) ^{e}
T5	15.09	18.82	6.87	7.66	1.56	81.56 (0.66) ^{d}
T6	8.57	25.52	7.30	5.50	3.11	82.79 (0.58) ^{c}
T7	13.39	26.77	4.37	4.39	1.08	89.06 (0.36) ^{a}
T8	7.47	27.56	6.76	7.02	1.19	83.58 (0.22) ^{c}
T9	8.29	22.77	4.64	9.26	5.05	71.38 (0.27) ^{f}

Note. T1 = chicken manure, calcium superphosphate, initial pH of 6, and stirring temperature 50 °C; T2 = chicken manure, zeolite, initial pH of 7, and stirring temperature 60 °C; T3 = chicken manure, copper sulfate, initial pH of 8, and stirring temperature 70 °C; T4 = sheep manure, copper sulfate, initial pH of 7, and stirring temperature 50 °C; T5 = sheep manure, calcium superphosphate, initial pH of 8, and stirring temperature 60 °C; T6 = sheep manure, zeolite, initial pH of 6, and stirring temperature 70 °C; T7 = urea, zeolite, initial pH of 8, and stirring temperature 50 °C; T8 = urea, copper sulfate, initial pH of 6, and stirring temperature 60 °C; T9 = urea, calcium superphosphate, initial pH of 7, and stirring temperature 70 °C. Lower case letters a, b, c, d, e, f, and g represent a significance in the differences between treatments at a specific time at $p < 0.05$.

3.6. Effect of Different Conditions on the Mineral Nutrient of the Compost Product

GB can break down and release mineral nutrients, such as N, P, K, Ca, and Mg, for the direct absorption and utilization by plants, which are essential for plant growth [43]. In this study, the amount of available calcium was substantially increased in all nine compost treatments (Table 3). Among them, T7 had the greatest increase in available calcium content, which was up to 76.11%. The increase of available calcium content cannot be separated from the activity of microorganisms, which can convert calcium oxalate, pectate calcium, and other storage calcium in organic materials into active calcium [44], thus improving the calcium utilization rate.

After composting, the available potassium content in T2 and T7 increased, while that in T1 remained stable. T2 and T7 included zeolite as the conditioning agent. The loose and porous nature of zeolite and its large surface area can adsorb more potassium elements, thus reducing the loss of elemental potassium introduced by water runoff [45].

The type of conditioning agent had a pronounced effect on the change in the available magnesium. Zeolite can effectively promote the increase of available magnesium content in the composting process. T6 increased the available magnesium content by 28.28%, while the available magnesium increase in T4 was minimal at only 6.96%. Under alkaline conditions, the content of magnesium ions is reduced, while a lower pH value favors magnesium in the form of ions [46] to increase the available magnesium content in the compost.

Specific nitrogen sources produce distinct changes in available phosphorus content. The nitrogen source for T1, T2, and T3 was chicken manure, and the available phosphorus content of the 3 treatments was increased after composting by 36.02%, 3.76%, and 77.09%, respectively. The effect of chicken manure in improving the available phosphorus content was remarkably better than that of sheep manure and urea. A lower initial pH promotes an increase in available phosphorus content during composting [47]. The available phosphorus contents in T1 and T8 increased by 0.58 and 0.10 mg/g, respectively. A higher available phosphorus content tends to inhibit phosphorus release during composting and may even lead to the loss of available phosphorus [48].

In the 9 composting treatments, compared to conditions before composting, NO_3^--N content increased only in treatments T1 and T2 (33.15% and 51.42%, respectively), and decreased in the other treatments. T4 and T6 showed the largest decreases, decreasing by 77.57% and 67.38%, respectively. The NH_4^+-N contents of treatments T4, T5, and T9 increased by 13.42%, 14.66%, and 5.66%, respectively, after composting. However, the NH_4^+-N contents in other treatments decreased, among which the decreases in T1, T2, T6, and T7 treatments were significant (36.80–54.64%). These four treatments were maintained at elevated temperatures for extended times, causing the NH_4^+ to be altered into NH_3 and escape into the atmosphere [10]. Furthermore, the higher pH value of the stack led to NH_4^+ loss [49].

3.7. Analysis of GB Composting Effects

3.7.1. Gray Relational Analysis of GB Composting

The mean values of each index of 10 composting treatments (including the ideal treatment) were nondimensionalized by the initial value method. Then, 9 treatments were compared with the ideal treatment and the correlation coefficients of each index between the nine treatments and the ideal treatment were obtained. Finally, according to Winarso [16], Zheng [17], and the weighting factors (the weight of each indicator was successively: 2:2:2:2:2:3:1), we calculated the degree of correlation between the 9 treatments and the ideal treatment (Table 5).

Table 5. Initial value transformation of each index in compost treatments.

Treatment	Initial Value Transformation							
	ACa	AK	AMg	AP	AN	THA	OM	
Ideal treatment	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
T1	0.78	0.86	0.89	0.38	0.81	0.69	0.72	
T2	0.86	0.60	1.00	0.24	0.76	1.00	0.85	
T3	1.00	0.37	0.96	0.15	0.80	1.00	0.97	
T4	0.89	0.33	0.88	0.07	0.66	0.82	0.65	
T5	0.71	0.33	0.92	0.22	0.65	0.65	0.61	
T6	0.48	1.00	0.82	1.00	0.59	0.70	0.64	
T7	0.72	0.50	0.91	0.16	0.67	0.90	1.00	
T8	0.93	0.31	0.93	0.10	0.88	0.89	0.96	
T9	0.69	0.32	0.92	0.15	1.00	1.00	0.96	
Treatment	**Correlation Coefficients**							**Gray Relational Grade**
	ACa	**AK**	**AMg**	**AP**	**AN**	**THA**	**OM**	
T1	0.6106	0.7113	0.7582	0.4286	0.6449	0.5267	0.5520	0.6028
T2	0.7113	0.4631	1.0000	0.3796	0.5897	1.0000	0.6970	0.7132
T3	1.0000	0.3538	0.8961	0.3536	0.6330	1.0000	0.9200	0.7424
T4	0.7582	0.3399	0.7419	0.3333	0.5036	0.6571	0.4964	0.5587
T5	0.5433	0.3399	0.8118	0.3735	0.4964	0.4964	0.4694	0.5063
T6	0.3988	1.0000	0.6571	1.0000	0.4570	0.5349	0.4894	0.6514
T7	0.5520	0.4083	0.7931	0.3563	0.5111	0.7753	1.0000	0.6120
T8	0.8313	0.3333	0.8313	0.3407	0.7419	0.7582	0.8961	0.6663
T9	0.5267	0.3366	0.8118	0.3536	1.0000	1.0000	0.8961	0.7110

Note. T1 = chicken manure, calcium superphosphate, initial pH of 6, and stirring temperature 50 °C; T2 = chicken manure, zeolite, initial pH of 7, and stirring temperature 60 °C; T3 = chicken manure, copper sulfate, initial pH of 8, and stirring temperature 70 °C; T4 = sheep manure, copper sulfate, initial pH of 7, and stirring temperature 50 °C; T5 = sheep manure, calcium superphosphate, initial pH of 8, and stirring temperature 60 °C; T6 = sheep manure, zeolite, initial pH of 6, and stirring temperature 70 °C; T7 = urea, zeolite, initial pH of 8, and stirring temperature 50 °C; T8 = urea, copper sulfate, initial pH of 6, and stirring temperature 60 °C; T9 = urea, calcium superphosphate, initial pH of 7, and stirring temperature 70 °C.

The optimization of a single gray relation grade (GRG) can be transformed into the optimization of multi-performance characteristics. The better the multiple performance attributes, the greater the GRG. Table 5 shows that in the experiment sequence T3, the process parameter configuration has the greatest GRG. Therefore, the third experiment provided the best multiple performance features out of the nine gray relational analysis experiments. In terms of the parameters' nitrogen source type (a), the stirring temperature (b), the initial pH (c), and the conditioning agents (d), the combination of a1 (chicken manure), b3 (70 °C), c3 (pH = 8), and d3 (copper sulfate) exhibited a more significant GRG for each and was therefore the ideal parameter combination for multi-performance characteristics.

3.7.2. Prediction of Optimal Conditions for GB Composting

The degree of the equal weight correlation between each treatment and the ideal treatment was set as the evaluation index. An orthogonal test analysis was conducted using R-4.04 (Table 6).

Table 6. Analysis results of the GB composting orthogonal experiment.

Treatment	a	b	c	d	Weighted Correlation Degree
T1	1	1	1	1	0.6028
T2	1	2	2	2	0.7132
T3	1	3	3	3	0.7424
T4	2	1	2	3	0.5587
T5	2	2	3	1	0.5063
T6	2	3	1	2	0.6514
T7	3	1	3	2	0.6120
T8	3	2	1	3	0.6663
T9	3	3	2	1	0.7110
$\overline{K1}$	0.6861	0.5912	0.6402	0.6067	
$\overline{K2}$	0.5721	0.6286	0.6610	0.6589	
$\overline{K3}$	0.6631	0.7016	0.6202	0.6558	
R	0.1140	0.1104	0.0408	0.0522	

Note. Column a indicates the nitrogen source: 1 chicken manure, 2 sheep manure, and 3 urea. Column b indicates the stirring temperature: 1 50 °C, 2 60 °C, and 3 70 °C. Column c indicates the initial pH value: 1 6, 2 7, and 3 8. Column d indicates the type of conditioning agent: 1 calcium superphosphate, 2 zeolite, and 3 copper sulfate. T1 = chicken manure, calcium superphosphate, initial pH of 6, and stirring temperature 50 °C; T2 = chicken manure, zeolite, initial pH of 7, and stirring temperature 60 °C; T3 = chicken manure, copper sulfate, initial pH of 8, and stirring temperature 70 °C; T4 = sheep manure, copper sulfate, initial pH of 7, and stirring temperature 50 °C; T5 = sheep manure, calcium superphosphate, initial pH of 8, and stirring temperature 60 °C; T6 = sheep manure, zeolite, initial pH of 6, and stirring temperature 70 °C; T7 = urea, zeolite, initial pH of 8, and stirring temperature 50 °C; T8 = urea, copper sulfate, initial pH of 6, and stirring temperature 60 °C; T9 = urea, calcium superphosphate, initial pH of 7, and stirring temperature 70 °C. K_{Jm} was named as the mean of the corresponding experiments of the m level of the J factor. The number could determine the quality of the level of J factor. R_J was the range of the column J factor, which responded the fluctuation of each level. That is to say, $R_J = K_{Jmax} - K_{Jmin}$.

According to the R value, the order of importance of the four factors was: nitrogen source > stirring temperature > conditioning agent > initial pH value. The orthogonal test method predicted that the optimal fermentation condition was a1b3c2d2, meaning that the optimal nitrogen source was chicken manure as a nitrogen source, a stirring temperature of 70 °C, initial pH of 7, and zeolite as conditioning agent. Under this condition, the contents of available calcium, potassium, magnesium, phosphorus, nitrogen, THA, and OM were 17.99 mg/g, 14.00 mg/g, 3.89 mg/g, 1.24 mg/g, 184.63 mg/kg, 25.59 g/kg, and 398.05 g/kg, respectively. After adding the optimal treatment, the correlation degree of T3 was 0.6771, and that of the optimal treatment was 0.7017, which increased by 3.63%.

4. Conclusions

We employed an orthogonal test design centered on gray relational analysis for optimizing composting. The highest gray relational grade was obtained when the nitrogen source was chicken manure, the stirring temperature was 70 °C, the initial pH was 8, and the conditioning agent was copper sulfate. Among the many factors of GB compost, the nitrogen source type (R = 0.1140) had the greatest influence on the nutrient content of the final product, followed by the turning temperature (R = 0.1104), conditioning agent (R = 0.0522), and initial pH (R = 0.0408). The optimal nitrogen source type was chicken manure, the optimal stirring temperature was 70 °C, the optimal conditioning agent was zeolite, and the optimal initial pH was 7. After optimization, the weighted correlation degree increased by 3.63% compared with the T3 treatment.

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