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Rabbit Manure Compost for Seedling Nursery Blocks: Suitability and Optimization of the Manufacturing Production Process

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Abstract: Using rabbit manure to prepare growing media is an effective method to solve environmental pollution and realize resource utilization. The solution to rabbit manure management is the composting process which could produce compost suitable for seedling nursery blocks, which could improve transplanting efficiency and seedlings' survival rate. Seedling nursery blocks were obtained by mixing rabbit manure compost, vermiculite, rice straw, and peat. The effect of cold pressing parameters, including moisture content (25–45%), binder content (1–5%), molding compression ratio (2.5–4.5:1), and strain maintenance time (0–120 s), were investigated on blocks quality (i.e., ventilatory porosity, relaxation density, compressive resistance, and specific energy consumption) through a general rotation combined experiment. These results showed there were significant interaction effects between molding compression ratio and moisture content, moisture and binder content, binder content and strain maintenance time, and molding compression ratio and binder content on block quality. The optimal parameters for manufacturing blocks were that the molding compression ratio, moisture content, binder content, and strain maintenance time were 4:1, 33.5%, 3.1%, and 60 s, and the relaxation density, ventilation porosity, and specific energy consumption were 363.31 kg/m^3, 18.72%, and 0.44 J/g, which could achieve emergence performance.

Keywords: waste management; sustainability; growing media; compression molding; peat substitute

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1. Introduction

China has a long history of rabbit breeding and is the largest rabbit meat producer, consumer, and exporter in the world [1]. Rabbit breeding has become one of the pillar industries for targeted poverty alleviation in some areas due to its low input cost and considerable economic benefits [2,3]. With the continuous improvement of the large-scale and intensive breeding industry, the amount of rabbit manure is increasing. China's annual output of rabbit manure is about 18.1 million tons. Rabbit manure could represent an environmental issue due to the presence of antibiotics and high levels of nitrogen; the manure would release ammonia and nitrogen oxides into the atmosphere and cause other issues during the accumulation. Thereby, its valorization treatment has become a top priority because it is an organic waste and may be a cost for farmers who have not had to spread the manure (in landless intensive systems) [4–7].

Rabbit manure commonly has a good granule structure and low water content. This means rabbit manure is easier to collect than some livestock and poultry manure, which may be conducive to its resource utilization. Besides, it was shown in existing studies that rabbit manure contains nutrient content (N > 1.6%, P > 6.5%, and K > 1.2% of the dry matter) and minimal risk of potentially toxic elements [8]. Therefore, rabbit manure can be used as a high-quality organic fertilizer for flowers, fruits, and vegetables [9–11]. It has been proven that the growing media prepared by agricultural and forestry wastes, such as livestock and poultry manure and crop straw, have sound seedling effects. This can also partially or entirely replace non-renewable peat and rock wool to meet the increasing demand for growing media for facility agriculture and conform to the concept of green agricultural development [12,13]. In previous studies, the breeding feasibility of rabbit manure compound growing media for salt-tolerant calendula and salt-intolerant cucumber had been preliminarily verified [14]. Preparing rabbit manure for growing media may realize its high-value utilization nearby.

The seedling nursery block can replace the seedling tray, which has the advantage of improving the survival rate of seedlings and facilitating mechanized transplanting [15]. Therefore, pressing the granular growing media into the seedling nursery block has become the direction of developing high-grade growing media [16,17]. Rabbit manure contains more hemicellulose than other manure types. In contrast, as a viscoelastic composition, hemicellulose helps form the "solid bridge," reduces the energy consumption of the molding, and may promote the water absorption and ventilatory porosity of the manufactured seedling nursery blocks. That is, rabbit manure has good growing media-forming characteristics [18–20].

In the existing reports on the formation of seedling nursery blocks, the growing media materials, such as cow manure, vermicompost, straw, and peat, are pressed mainly by hydraulic pressure or pneumatic pressure through high pressure (4.5–247 kN) or elevated temperature (80–120 °C) [21–24]. However, their promotion and application are relatively limited due to increased equipment investment and large operating energy consumption. Rabbit manure with good forming characteristics may be pressed and formed at low pressure and normal temperature to achieve low energy consumption and high efficiency. However, it has not yet been systematically reported.

According to transportation and storage requirements, some parameters (e.g., relaxation density, dimensional stability, and compressive properties) may be used in the research of the seedling nursery block-forming process [25]. According to the requirements for seedling root growth, the block should have good ventilation porosity after water absorption [8]. Therefore, ventilation porosity should also be used to evaluate the block-forming effect. This has been relatively ignored in previous molding process studies or replaced only with an expansion ratio [25]. These indicators are affected by some internal factors (including types and additions of binders, moisture content of raw materials, length and additions of straws, and types of regulators) and external factors (e.g., molding pressure/load, molding temperature, compression ratio, and compression speed) [21–23]. There are also interactions among distinct factors. Therefore, exploring the influence of these parameters helps guide the research on the organic waste cold-pressing process. Seeking the optimal compression parameter combination to meet multiple objectives (e.g., transportation and seedling cultivation) will be conducive to the exploration and development of the seedling nursery block industry.

In this content, granular growing media were prepared with rabbit manure, rice straw, vermiculite, and peat. The forming characteristics under low pressure and normal temperature were explored, including the influence and interaction of moisture content, binder content, molding compression ratio, and strain maintenance time on the ventilatory porosity, relaxation density, compressive resistance, and specific energy consumption of the blocks. Then, regression equations of parameters and indexes were constructed, and multi-objective optimization was conducted to obtain a suitable combination of parameters for forming rabbit manure compost seedling nursery blocks. Finally, the seedling experiment was conducted to verify its feasibility. Theoretical support for the high-value utilization of rabbit manure and the optimization and development of the molding process of the seedling nursery block is provided by this study.

2. Materials and Methods

2.1. Growing Media Materials

The growing media materials mainly included decomposed rabbit manure compost, vermiculite, rice straw, and peat. The moisture and lignocellulose contents of growing media materials are shown in Table 1. Among them, rabbit manure was collected from a large-scale rabbit breeding herd in Henan Province, China, and the other materials were obtained from a local market. The materials were naturally air-dried, crushed, and passed through a 4.75 mm sieve. Since the ratio of length to width of rice straw is large and the ratio of width to height is small, it is challenging to obtain uniform rice straw directly. Therefore, a sieving instrument was used for screening. The selected sizes were 3.35 mm, 2.36 mm, 1.18 mm, 600 µm, 425 µm, and 150 µm. Finally, 50 µm–1.18 mm rice straw was selected for subsequent experiments. Additionally, a food-grade binder (sodium carboxymethyl cellulose) was used to improve the formation effect of the nursery block.

Table 1. Moisture and lignocellulose contents of main growing media materials.

	Moisture Content (%)	Cellulose (% Dry Matter)	Hemicellulose (% Dry Matter)	Lignin (% Dry Matter)
Rabbit manure compost	20.3	25.27	29.95	21.39
Rice straw	6.56	41.13	24.80	9.72
Vermiculite	2.4	/	/	/
Peat	37.5	36.87	22.17	18.26

2.2. Experimental Methods

2.2.1. Instruments and Procedures

The test system for cold compression molding is shown in Figure 1. It was mainly composed of a universal material testing machine (Instron-3367, Instron, Norwood, MA, USA), a punch-pin, a cavity mold, a die cushion, a stripper, and a control and display system. The pin diameter was 50 mm, and the protrusions were provided to form seeding troughs for substrate blocks while reducing surface runoff of moisture during seedling raising. The diameter of the cavity was 50 mm, the height was 90 mm, and the inner wall was polished to reduce the energy consumption of the molding. The system can control the compression procedures (by adjusting parameters such as compression force, displacement, time, speed, etc.) and simultaneously record the compression force and displacement of the growing media surface in real-time.

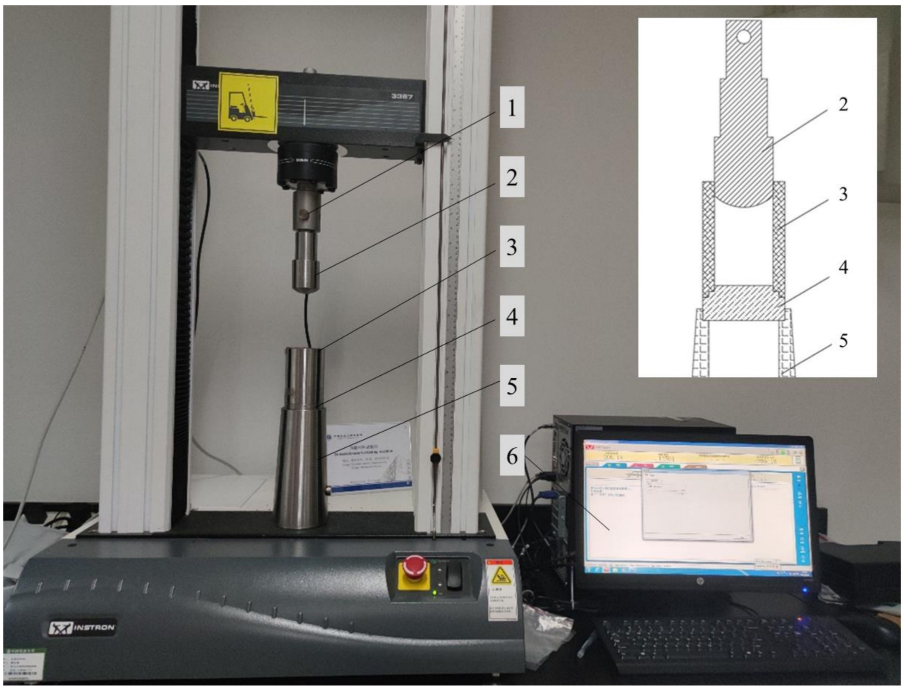


Figure 1. Test system for cold compression molding. 1. Positioning screws; 2. Punch-pin; 3. Cavity mold; 4. Die cushion; 5. Stripper; 6. Control and display system.

2.2.2. Experiment Design

In a previous experiment, the optimal proportion of rabbit manure compound growing media was determined as the rabbit manure compost:vermiculite:perlite:peat = 40:25:25:10 (v/v/v/v), according to the physiochemical properties of the growing media and plant growth performance [14]. However, the perlite may be unfavorable for molding as it becomes powder during compression [26]. Crop straw is often used as biomass for molding [27,28]. The influence of commonly used growing media materials (e.g., perlite, rice straw, and wheat straw) on the rabbit manure compost seedling nursery blocks forming effect was explored. Then, rice straw was determined according to mixing difficulty, water absorption performance, and forming energy consumption. Finally, the proportion of rabbit manure compost seedling nursery blocks was determined: rabbit manure compost:vermiculite:rice straw:peat = 40:25:25:10 (v/v/v/v). The pH of the blocks was 7.77, and the contents of C, N, P, K, Ca, and Mg were 35.75%, 1.36%, 0.78%, 2.07%, 1.67%, and 1.87% of the dry matter, respectively.

On this basis, the moisture content (factor A), binder mass fraction (factor B), molding compression ratio (factor C), and strain maintenance time (factor D) were selected as the testing factors. A general rotation combined experimental design (29 groups) was used to study the influence of these factors, interactions, and quadratic terms on the indicators through variance analysis to optimize process parameters. The actual values and codes of the tested factors are shown in Table 2.

Table 2. Actual and coded levels of cold compression molding test.

Levels	Factors			
	A Moisture Content (%)	B Binder Mass Fraction (%)	C Molding Compression Ratio	D Strain Maintenance Time (s)
2	45	5	4.5:1	120
1	40	4	4:1	90
0	35	3	3.5:1	60
−1	30	2	3:1	30
−2	25	1	2.5:1	0

The technological process for forming rabbit manure compost seedling nursery blocks is shown in Figure 2. First, rabbit manure compost, vermiculite, rice straw, and peat were mixed in a determined ratio. Second, the different contents of the binder (1%, 2%, 3%, 4%, or 5%) and deionized water (adjusting the moisture content to 25%, 30%, 35%, 40%, or 45%) were added to obtain granular growing media according to the experimental design. The mixture was then sealed and placed at 4 °C for 48 h to homogenize. Then, the granular growing media was loaded into the self-made forming mold. After the growing media was formed and filled the mold, the universal material testing machine was started to drive the punch for compression. The compression speed was 35 mm/min, and the compression displacement was converted by the compression ratio ((2.5, 3, 3.5, 4 or 4.5):1) of the experimental design. After reaching the set displacement, the strain was maintained for some time (0, 30, 60, 90, or 120 s). Then the die cushion was removed and demolded to obtain the rabbit manure compost seedling nursery blocks. The temperature during the test was room temperature, about 20 °C. Finally, seedling nursery blocks were dried at 60 °C for 4 h to obtain the finished products.

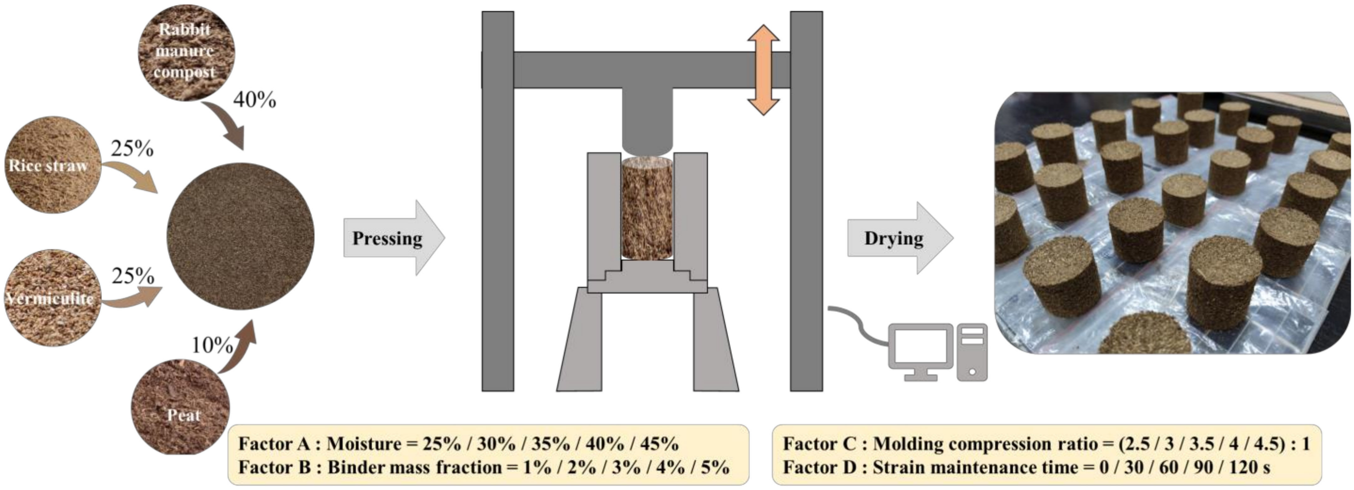


Figure 2. Technological process for forming rabbit manure compost seedling nursery blocks.

2.2.3. Evaluation Indices

(1) Relaxation density

The relaxation density (RD) reflects the stability of the seedling nursery blocks after 48 h of relaxation, which can reflect the support effect and anti-destructive strength of the seedling nursery block on seedlings [27]. This is an important evaluation index of the seedling nursery blocks molding effect, which was calculated using Equation (1) [28]:

$$RD = 4M/(\pi D^2 L) \tag{1}$$

where RD (kg/m^3) is the relaxation density of the rabbit manure compost seedling nursery blocks; M (kg) is the weight of blocks; D (m) and L (m) are the diameter and height of the blocks after relaxation.

(2) Ventilatory porosity

The aeration performance of the growing media, which directly affects the water, air, fertilizer, and other environments of the root system, is characterized by ventilatory porosity (VP). Therefore, its permeability should also be considered while ensuring the mechanical strength of rabbit manure compost seedling nursery blocks. In this study, the ring knife method [29] was used to measure ventilatory porosity and was expressed as follows:

$$VP = 100\% \times (M_1 - M_2)/V \tag{2}$$

where VP (%) is the ventilatory porosity of the rabbit manure compost seedling nursery blocks; V (cm^3) is the volume of the blocks; M_1 (g) and M_2 (g) are the weight of blocks when saturated water absorption and water no longer exudes.

(3) Specific energy consumption

Specific energy consumption (SEC) is the energy consumption per unit mass in block compression molding. This could reflect the difficulty of block molding and is related to the production cost [27]. Based on the real-time collected load-displacement data during the rabbit manure compost seedling nursery block forming process, the specific energy consumption is calculated according to Equation (3):

$$SEC = 10^{-3} \times \left(\int f \cdot dx\right)/M \tag{3}$$

where SEC (J/g) is the specific energy consumption of the rabbit manure compost seedling nursery blocks; f (N) is load; x (mm) is molding displacement; M (g) is the weight of growing media.

(4) Compressive resistance

The compressive resistance is to place the rabbit manure compost seedling nursery block sideways on the test bench of the universal material testing machine (Instron-3367, Instron, Norwood, MA, USA) and control the upper plate on the beam to move downward at a uniform speed. After the block is destroyed, the system automatically unloads and moves upward in the opposite direction. The peak value of the force received during the deformation of the block is the compressive resistance of the sample [30], and the machine automatically records this value.

2.2.4. Emergence Performance of Rabbit Manure Compost Seedling Nursery Blocks

The optimized rabbit manure compost seedling nursery blocks were used for seedling-raising experiments in order to test the seedling emergence performance. The test seeds were Beijing new No. 3 cabbage seeds (Jingyan Yinong). Four Chinese cabbage seeds were placed in the seeding hole of each seedling nursery block and covered with vermiculite. Low-level immersion irrigation combined with micro spraying was used to make the block fully absorb water without adding fertilizer. After 10 days of seedling raising, the seedling emergence rate of 76 seeds was counted.

2.2.5. Chemical Analysis

The pH value of the growing media was measured at a ratio of fresh sample to distilled water of 1:10 using a pH meter (Sartorius PB-10, Sartorius AG, Göttingen, Germany). Lignocellulose content (including cellulose, hemicellulose, and lignin) was determined according to the methods described in [31]. The content of P, K, Ca, and Mg was measured using an inductively coupled plasma spectrometer (ICPOES730, Agilent Technologies Inc., Palo Alto, CA, USA). The content of C and N was determined using an elemental analyzer (Vario EL cube, Elementar, Hanau, Germany).

2.2.6. Data Analysis

The quaternion quadratic general rotation combination test was designed, and the data (n = 3) were analyzed using Design Expert 10. The parameters were optimized using MATLAB R2021b. All figures were drawn using Origin 2021.

3. Results and Discussion

3.1. Results and Analysis of Combined Tests

The results of relaxation density, ventilatory porosity, specific energy consumption, and compressive resistance of rabbit manure compost seedling nursery blocks obtained as per the testing design and requirements are listed in Table 3. The ranges of relaxation density, ventilatory porosity, specific energy consumption, and compressive resistance were 220.93–350.04 kg/m^3, 9.18–20.98%, 0.10–0.71 J/g, and 27.65–207.53 N, respectively. The maximum forming pressure of rabbit manure compost seedling nursery blocks was 2.97 kN. Cao et al. [21] found that the seedling nursery block density of cattle manure was 769–1125 kg/m^3, and the forming pressure was 5–25 kN. Liu et al. [24] showed that the nutritious peat block density after pressing was 1801–1917.6 kg/m^3, and the forming pressure was 162.4–247.3 kN. The density and forming pressure of seedling nursery blocks in the above two studies were larger than our results, as the density was about 2–4 times larger, and the forming pressure was about 7–82 times larger. These differences were attributed to differences in material types, moisture content, and forming conditions [27]. In the above literature, the cattle manure seedling nursery block was made by mixing with straw or corncob, with a moisture content of 10–30%. The materials of the nutritious peat block included peat, vermiculite, perlite, sand, added molding curing agent, super absorbent resin, and micronutrients, with a moisture content of 0.5–2%. The materials used in this experiment were rabbit manure, vermiculite, rice straw, and peat, which were easily compressed (consistent with the expectations in the Introduction). They had a relatively high moisture content ranging from 25% to 45%. Moreover, the cattle manure seedling nursery block adopted hot pressing (80–160 °C), but cold pressing was used in this experiment.

Table 3. Test scheme and results.

Test Number	Factors and Levels				Evaluation Indicators			
	A Moisture Content (%)	B Binder Mass Fraction (%)	C Molding Compression Ratio	D Strain Maintenance Time (s)	Relaxation Density ($kg \cdot m^{-3}$)	Ventilatory Porosity (%)	Specific Energy Consumption ($J \cdot g^{-1}$)	Compressive Resistance (N)
1	−1	−1	−1	−1	261.87	11.83	0.32	27.65
2	−1	−1	1	−1	295.19	12.44	0.71	58.60
3	1	−1	−1	−1	249.80	11.10	0.20	35.34
4	1	−1	1	−1	280.04	11.70	0.49	57.68
5	−1	1	−1	−1	284.18	12.23	0.26	40.47
6	−1	1	1	−1	334.22	12.50	0.62	179.33
7	1	1	−1	−1	260.64	10.37	0.19	42.77
8	1	1	1	−1	282.60	10.39	0.48	77.22
9	−1	−1	−1	1	261.87	10.63	0.28	28.72
10	−1	−1	1	1	304.93	11.67	0.69	71.44
11	1	−1	−1	1	253.94	11.30	0.20	32.97
12	1	−1	1	1	275.59	9.18	0.49	71.94
13	−1	1	−1	1	287.76	13.33	0.26	76.90
14	−1	1	1	1	350.04	13.23	0.60	207.53
15	1	1	−1	1	262.08	10.47	0.19	44.59
16	1	1	1	1	282.40	11.48	0.45	76.19
17	0	0	−2	0	220.93	10.66	0.10	27.16
18	0	0	2	0	276.41	10.29	0.66	62.82
19	−2	0	0	0	308.90	16.27	0.60	62.47
20	2	0	0	0	272.06	12.47	0.35	46.51
21	0	−2	0	0	274.32	12.14	0.56	51.12
22	0	2	0	0	310.00	14.27	0.55	154.09
23	0	0	0	−2	246.29	10.71	0.34	30.17
24	0	0	0	2	271.87	11.32	0.36	65.24
25	0	0	0	0	270.01	20.98	0.34	62.04
26	0	0	0	0	268.12	18.09	0.34	59.84
27	0	0	0	0	265.68	18.76	0.33	66.02
28	0	0	0	0	258.31	18.50	0.36	63.84
29	0	0	0	0	262.90	18.96	0.31	60.00

3.2. Analysis of Variance and Regression Equations

Analysis of variance is a standard method for evaluating model significance and accuracy [32]. The above test results were analyzed by variance analysis, and regression models between factors and evaluation indicators were constructed. The model fit for relaxation density, ventilatory porosity, specific energy consumption, and compressive resistance are shown in Table 4. The R^2 of relaxation density, ventilatory porosity, and specific energy consumption were all ≥0.92, indicating that more than 92% of variable variations could be explained by the models. The differences between Adjusted R^2 and Predicted R^2 were all <0.2, and the Adeq Precision were all >4, indicating that the five regression models fit well and could be used to predict relaxation density, ventilatory porosity, and specific energy consumption [33]. In comparison, the model of compressive resistance could explain only 85% of the variation and lacked fitting. Therefore, the influence of factors on compressive resistance was analyzed, but no regression model was established.

Table 4. Model fit for relaxation density, ventilatory porosity, specific energy consumption, and compressive resistance.

Response Variable	R^2	Adjusted R^2	Predicted R^2	Adeq Precision
Relaxation density	0.92	0.89	0.81	21.91
Ventilatory porosity	0.95	0.93	0.89	18.99
Specific energy consumption	0.98	0.97	0.95	43.72
Compressive resistance	0.85	0.79	0.68	15.04

The insignificant items (α = 0.1) of the regression equation were excluded, and the simplified regression equations of relaxation density, ventilatory porosity, and specific energy consumption are shown in Equations (4)–(6):

$$RD = 262.7 - 12.78 \times A + 9.67 \times B + 16.41 \times C - 6.5 \times AB - 5.91 \times AC + 8.43 \times A^2 + 8.85 \times B^2 \quad (4)$$

$$VP = 19.06 - 0.81 \times A + 0.35 \times B + 0.46 \times BD - 1.3 \times A^2 - 1.59 \times B^2 - 2.27 \times C^2 - 2.14 \times D^2 \quad (5)$$

$$SEC = 0.34 - 0.064 \times A - 0.015 \times B + 0.16 \times C - 0.022 \times AC + 0.029 \times A^2 + 0.049 \times B^2 \quad (6)$$

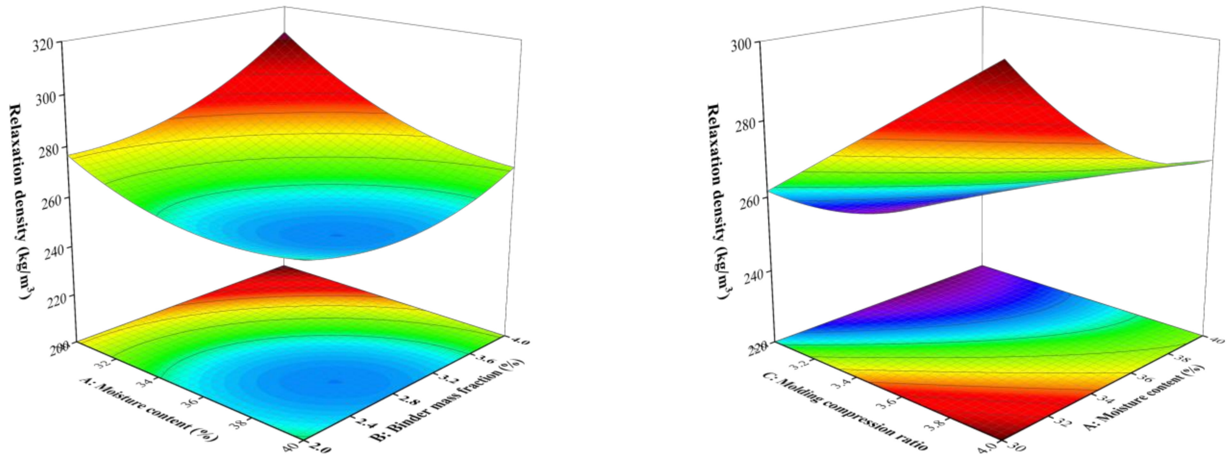
where *RD*, *VP*, and *SEC* are the relaxation density (kg/m^3), ventilatory porosity (%), and specific energy consumption (J/g) of the rabbit manure compost seedling nursery blocks; *A* and *B* are the moisture and binder content (%) of rabbit manure growing media; *C* and *D* are the molding compression ratio and strain maintenance time (s) of rabbit manure compost seedling nursery blocks. The *A*, *B*, *C*, and *D* are coded values.

3.3. Effects of Different Factors on Evaluation Indicators

3.3.1. On Relaxation Density

In Equation (4), it was shown that the moisture content, binder mass fraction, and molding compression ratio all significantly affected the relaxation density. The influence of distinct factors on the relaxation density of rabbit manure compost seedling nursery blocks was ranked as molding compression ratio > moisture content > binder mass fraction. Molding compression ratio and binder mass fraction were significantly positively correlated with relaxation density, while moisture content was significantly negatively correlated with relaxation density. In terms of interaction, the interaction between the moisture content and binder mass fraction and the moisture content and molding compression ratio significantly affected relaxation density.

The effect of moisture content and binder mass fraction on relaxation density is shown in Figure 3a. When the binder mass fraction was constant, and the moisture content was less than 35%, the relaxation density of the seedling nursery blocks decreased with the increment of the moisture content. When the moisture content was more than 35%, the relaxation density changed slightly with the increment of the moisture content. Similarly, when the moisture content was constant, the relaxation density of the seedling nursery blocks increased with increments in the binder mass fraction. The lower the moisture content and the higher the binder mass fraction, the greater the relaxation density of the rabbit manure compost seedling nursery blocks.



(**a**) (**b**)

Figure 3. Interaction effect on relaxation density. (**a**) Effect of moisture content and binder mass fraction on relaxation density with the molding compression ratio of 3.5:1 and strain maintenance time of 60 s; (**b**) Effect of molding compression ratio and moisture content on relaxation density with the binder mass fraction of 3% and strain maintenance time of 60 s.

This was because an appropriate amount of water could dissolve the binder, and the water evaporated during the drying process, which was conducive to the adhesion of the matrix materials [15], and also enhanced the role of the "solid bridge" of rabbit manure and rice straw. However, too much water diluted the binder and weakened the adhesion on the particle surface [34]. Within the test level range, relaxation density varied from 220.93 kg/m^3 to 350.04 kg/m^3, which was light in weight and met the requirements for plant germination and growth [35].

The effect of moisture content and molding compression ratio on relaxation density is shown in Figure 3b. When the molding compression ratio was constant, the relaxation density of rabbit manure compost seedling nursery blocks decreased with an increment in moisture content. This was due to part of the moisture attached to the particle surface, which increased the degree of relaxation of the matrix after molding [36]. When the moisture content of the matrix was constant, the relaxation density increased with an increase in the molding compression ratio. Especially when the moisture content was less than 35%, and the compression ratio was greater than 3.5:1, the relaxation density reached its maximum value. This phenomenon was consistent with the study reported by Cao et al. [21], where the bulk density of compressed straw-cattle manure block changed from 0.958 g/cm^3 to 1.092 g/cm^3 when the moisture content increased from 10% to 30%. In that study, the bulk density of the compressed straw-cattle manure block changed from 0.884 g/cm^3 to 1.258 g/cm^3 when the molding pressure increased from 5 kN to 10 kN.

3.3.2. On Ventilatory Porosity

In Equation (5), it was shown that the ventilatory porosity of rabbit manure compost seedling nursery blocks was significantly affected by the moisture content and binder mass fraction, and the moisture content was more important. The binder mass fraction was significantly positively correlated with ventilatory porosity, while moisture content was significantly negatively correlated. In terms of interaction, the interaction between binder mass fraction and strain maintenance time significantly affected the ventilatory porosity.

The effect of binder mass fraction and strain maintenance time on ventilatory porosity is shown in Figure 4. When the binder content was constant, the ventilatory porosity of rabbit manure compost seedling nursery blocks first increased and then decreased with an increment in the strain maintenance time. Similarly, when the strain maintenance time was constant, the air porosity first increased and then decreased with the increment of binder content. When the binder content was between 2.8% and 3.3% and the strain maintenance time was between 54 and 66 s, the ventilatory porosity reached its maximum value.

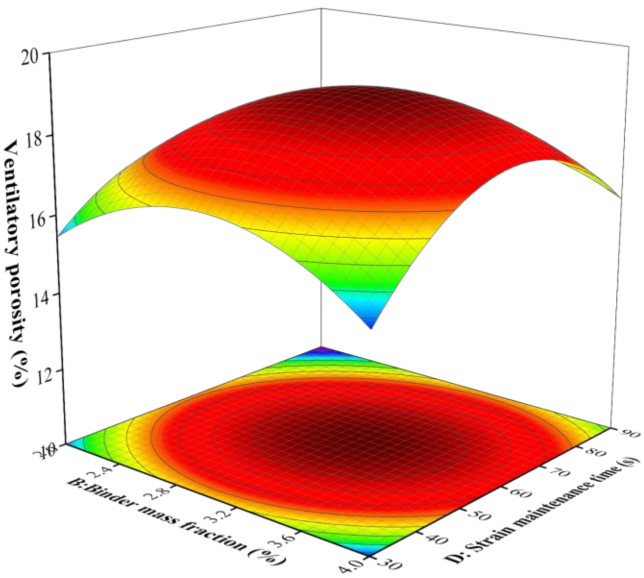


Figure 4. Interaction effect of binder mass fraction and strain maintenance time on ventilatory porosity with the moisture content of 35% and molding compression ratio of 3.5:1.

This was due to the two stages of seedling nursery block molding. The first was the compression molding stage with variable displacement, where a large amount of air between particles was discharged. The second was the strain maintenance stage, in which the rebounding of pressed growing media was relieved through the relaxation of residual stress [27]. When the strain maintenance time increased, the stress of the seedling nursery blocks gradually relaxed, the block maintained its original shape, and the expansion rate was relatively large after sufficient water absorption. When the strain maintenance time was longer than a specific range, the plastic deformation of the block was high, and swelling was slight after sufficient water absorption [28]. Since the binder had the function of water retention, which also affected the water absorption expansion of the block, its effect on ventilatory porosity was similar to the strain maintenance time.

3.3.3. On Specific Energy Consumption

In Equation (6), it was shown that the moisture content, binder mass fraction, and molding compression ratio all significantly affected the specific energy consumption, and the effects were ranked as molding compression ratio > moisture content > binder mass fraction. The molding compression ratio was significantly positively correlated with specific energy consumption, while moisture content and binder mass fraction were significantly negatively correlated. Besides, the interaction between molding compression ratio and moisture content significantly affected the specific energy consumption.

With the increase in the molding compression ratio, the work of the friction and extrusion between the matrix particles, between the matrix and the die, increased significantly, increasing the total energy consumption of the block compression molding. The moisture in the matrix material played a specific lubricating role. At the same time, the cushioning properties of the matrix can be improved by absorbing water through the matrix, thereby reducing the energy consumption of molding [37]. Yang et al. [38] reported that increasing water content could improve the uniformity of the adhesive, which was conducive to the low-pressure densification of biomass.

The effect of moisture content and molding compression ratio on specific energy consumption is shown in Figure 5. When the molding compression ratio was constant, the specific energy consumption of block compression molding decreased with increased moisture content. This phenomenon was more apparent when the moisture content was lower. When the water content was constant, the specific energy consumption increased with the molding compression ratio, which might be due to the incompressibility of water. It was found that the effect of the interaction between molding compression ratio and moisture content on energy consumption was consistent with the relaxation density, which was also shown by the research of Chen et al. [27]. Therefore, when the moisture content was more than 30%, the specific energy consumption of rabbit manure compost seedling nursery block formation was less than 0.6 J/g. Within this experiment, the maximum molding load of the rabbit manure compost seedling nursery blocks was 2974 N and did not require processes such as heating and cooling. It has relatively low energy consumption compared with the current high-pressure or high-temperature pressing [21–24].

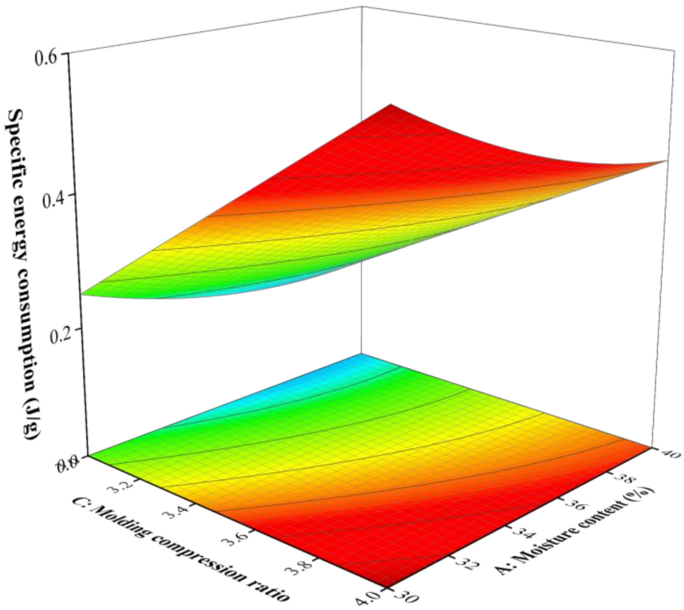
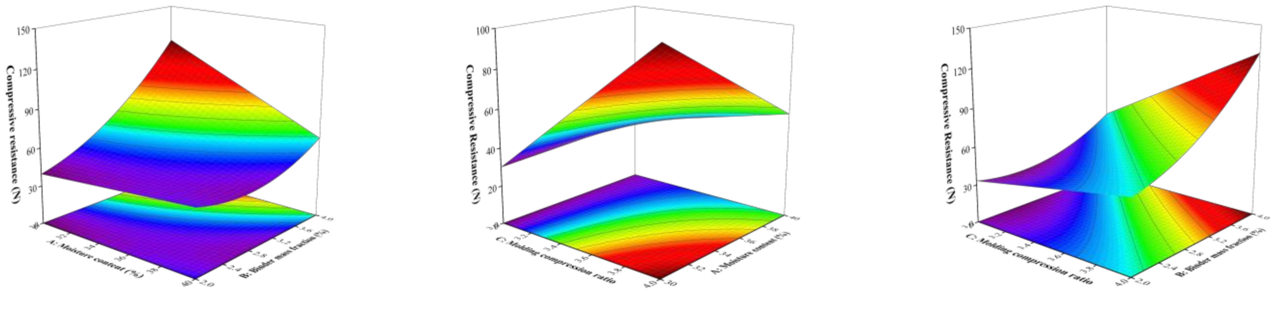


Figure 5. Interaction effect of moisture content and molding compression ratio on specific energy consumption with the binder mass fraction of 3% and strain maintenance time of 60 s.

3.3.4. On Compressive Resistance

It was shown by the variance analysis of compressive resistance that the compressive resistance was significantly affected by the moisture content, binder mass fraction, and molding compression ratio. The influence of distinct factors on the compressive resistance of rabbit manure compost seedling nursery blocks was ranked as molding compression ratio > binder mass fraction > moisture content. The molding compression ratio and binder mass fraction were significantly positively correlated with compressive resistance, while moisture content was significantly negatively correlated. Furthermore, these three factors had interactive effects on compressive resistance.

The effect of moisture content and binder mass fraction on compressive resistance is shown in Figure 6a. When the moisture content was constant, the compressive resistance of rabbit manure compost seedling nursery blocks increased with an increase in the binder content, especially when the moisture content was low. When the content of the binder was constant, the compressive resistance of rabbit manure compost seedling nursery blocks decreased with an increase in moisture content, especially when the binder content was high. Great compressive resistance of the rabbit manure compost seedling nursery blocks was obtained at lower matrix moisture content and higher binder content due to the greater relaxation density at this time (Figure 3a).



(**a**) (**b**) (**c**)

Figure 6. Interaction effect on compressive resistance. (**a**) Effect of moisture content and binder mass fraction on compressive resistance with the molding compression ratio of 3.5:1 and strain maintenance time of 60 s; (**b**) Effect of moisture content and molding compression ratio on compressive resistance with the binder mass fraction of 3% and strain maintenance time of 60 s; (**c**) Effect of binder mass fraction and molding compression ratio on compressive resistance with the moisture content of 35% and strain maintenance time of 60 s.

The effect of moisture content and molding compression ratio on compressive resistance is shown in Figure 6b. When the moisture content was constant, the compressive resistance of rabbit manure compost seedling nursery blocks increased gradually with an increase in the compression ratio, especially when the moisture content was low. When the molding compression ratio was constant, the compressive resistance decreased gradually with an increase in moisture content. The highest compressive resistance of rabbit manure compost seedling nursery blocks was obtained under molding conditions of a high compression ratio and low moisture content. This is consistent with the variation law of the relaxation density (Figure 3a) and specific energy consumption (Figure 5) of rabbit manure compost seedling nursery blocks.

The effect of binder mass fraction and molding compression ratio on compressive resistance is shown in Figure 6c. When the binder content was constant, the compressive resistance increased with an increase in the compression ratio, especially when the binder content was higher. When the compression ratio was constant, the compressive resistance increased with the increase in the binder content, especially when the molding compression ratio was large. The compressive resistance increased with binder content and compression ratio due to increased molding pressure and bonding force to improve the molding effect.

3.4. Comprehensive Optimization and Verification Tests

In order to obtain rabbit manure compost seedling nursery blocks with good molding effect and good use effect, it is required that the seedling nursery blocks have sufficient stability (e.g., the bulk density of the seedling matrix should be 200–600 g/cm [35]), adequate aeration (e.g., the requirement of ventilatory porosity is 15–30% [35]), and low energy consumption in the molding process. Although the compressive resistance of the block was an important quality indicator, the influence of the molding parameters on compressive resistance was consistent with the relaxation density, and the accuracy of the regression model of compressive resistance was low. Therefore, the following five objective functions (F_1, F_2, F_3, F_4, and F_5) were constructed, and the regression equations (Equations (4)–(6)) of relaxation density, ventilation porosity, and specific energy consumption were brought into the objective functions to obtain the optimal parameter combination.

$$\begin{cases} F_1 = RD_{\max} \\ F_2 = VP_{\max} \\ F_3 = SEC_{\min} \\ F_4 = \left(\frac{RD-200}{600-200} + \frac{VP-15}{30-15} - \frac{SEC-0.2}{0.6-0.2}\right)_{max} \\ F_5 = \left(2 \times \frac{RD-200}{600-200} + 2 \times \frac{VP-15}{30-15} - \frac{SEC-0.2}{0.6-0.2}\right)_{max} \\ 1 \le A \le 2 \\ -2 \le B \le 2 \\ -0.5 \le C \le 2 \\ -1 \le D \le 1 \\ 200 \le RD \le 600 \\ 15 \le VP \le 30 \\ 0.2 \le SEC \le 0.6 \end{cases}$$

Among them, F_1, F_2, F_3, F_4, and F_5 represented the maximum relaxation density, maximum ventilatory porosity, and minimum specific energy consumption, the comprehensive maximum value when the indicator weights are consistent. The comprehensive maximum value when the density and porosity weights were doubled on the premise that other indicators met the requirements. *RD*, *VP*, and *SEC* are the relaxation density (kg/m^3), ventilatory porosity (%), and specific energy consumption (J/g) of the rabbit manure compost seedling nursery blocks; *A* and *B* are the moisture and binder content (%) of rabbit manure growing media; *C* and *D* are the molding compression ratio and strain maintenance time (s) of rabbit manure compost seedling nursery blocks. The *A*, *B*, *C*, and *D* are coded values. The optimization solution was conducted using MATLAB, and the five optimized parameter combinations were used for the test. The test results and theoretical prediction values are shown in Table 5.

Table 5. Prediction and test results of rabbit manure compost seedling nursery blocks after parameter optimization.

	Moisture Content (%)	Binder Mass Fraction (%)	Molding Compression Ratio	Strain Maintenance Time (s)	Relaxation Density (kg·m^{-3})		Ventilatory Porosity (%)		Specific Energy Consumption (J·g^{-1})	
					Test Value	Theoretical Value	Test Value	Theoretical Value	Test Value	Theoretical Value
1	4.1:1	34.5	3.8	60	364.80	298.38	18.85	15.12	0.54	0.56
2	4.0:1	39.0	2.8	48	338.47	269.01	18.13	14.87	0.39	0.45
3	4.0:1	39.5	3.0	45	348.67	269.12	18.19	14.47	0.41	0.45
4	3.5:1	39.0	2.8	54	321.61	257.33	16.37	17.38	0.26	0.31
5	4.0:1	39.0	2.9	57	351.30	269.19	16.60	15.24	0.36	0.45

It can be seen from Table 5 that the theoretical values of RD and VP were generally higher than the test values, and the theoretical values of SEC were usually lower than the test values. Therefore, the constant term of the model was modified according to Equation (7) [36]. The final modified models are shown in Equations (8)–(10).

$$c = c_0 + \sum_{1}^{n} (I_t - I_e)/n \tag{7}$$

where c is the corrected value of the model constant term; c_0 is the original constant term of the model; I_t is the test value of indices; I_e is the theoretical value of indices; n is the number of tests.

$$RD = 335.06 - 12.78 \times A + 9.67 \times B + 16.41 \times C - 6.5 \times AB - 5.91 \times AC + 8.43 \times A^2 + 8.85 \times B^2 \tag{8}$$

$$VP = 21.27 - 0.81 \times A + 0.35 \times B + 0.46 \times BD - 1.3 \times A^2 - 1.59 \times B^2 - 2.27 \times C^2 - 2.14 \times D^2 \tag{9}$$

$$SEC = 0.29 - 0.064 \times A - 0.015 \times B + 0.16 \times C - 0.022 \times AC + 0.029 \times A^2 + 0.049 \times B^2 \tag{10}$$

where *RD*, *VP*, and *SEC* are the relaxation density (kg/m^3), ventilatory porosity (%), and specific energy consumption (J/g) of the rabbit manure compost seedling nursery blocks; *A* and *B* are the moisture and binder content (%) of rabbit manure growing media; *C* and *D* are the molding compression ratio and strain maintenance time (s) of rabbit manure compost seedling nursery blocks. The *A*, *B*, *C*, and *D* are coded values.

When pressing loose growing media into seedling nursery blocks while seeking higher mechanical strength of blocks, their ventilatory porosity should be improved as much as possible to improve the root environment of seedlings. After the models were modified, the optimization conditions of indicators were set: the ventilation porosity was the largest, the compression ratio was 4, the water content was 33.5%, the binder mass fraction was 3.1%, and the strain maintenance time was 60 s. The test was conducted using the optimized parameter values. The verification results are shown in Table 6.

Table 6. Prediction and test results of rabbit manure compost seedling nursery blocks optimized with ventilatory porosity as the target.

	Relaxation Density ($kg \cdot m^{-3}$)	Ventilatory Porosity (%)	Specific Energy Consumption ($J \cdot g^{-1}$)
Test value	363.31	18.72	0.44
Theoretical value	354.55	19.09	0.45
Error	2.47%	−1.91%	−3.23%

The relative error predicted by the three models was less than 5%. This indicated that the modified model could realize the prediction of relaxation density, ventilatory porosity, and specific energy consumption of rabbit manure seedling matrix blocks and provided a reference and basis for the production of blocks that met the requirements of seedling raising and transplanting operations.

3.5. Seedling Emergence Performance of Rabbit Manure Compost Seedling Nursery Blocks

The seedling experiments were conducted with rabbit manure compost seedling nursery blocks prepared after the above optimization parameters. It was shown by the results that the emergence rate of Chinese cabbage seeds was 97.4%, which met the requirements of the vegetable seedling matrix (i.e., 90%, which is usually the minimum requirement for commercially applied substrates) [35]. During the nursery period, the rabbit manure compost seedling nursery blocks repeatedly absorbed water more than 40 times without loose or deformed situations (Figure 7). Generally, a mature commercial seedling-raising substrate can maintain a stable structure under the seedling-raising cycle of >20 days [39,40], with watering >30 times. The seedling emergence rate and the overall state of the blocks preliminarily proved the feasibility of the rabbit manure compost seedling nursery blocks. Plant growth, not only germination, may also need to be further evaluated in future studies for comprehensive evaluation. Then, how to meet the needs of different seedlings and be more conducive to market promotion and commercial application of the matrix block needs further research.

Figure 7. Nursery test of rabbit manure compost seedling nursery blocks.

4. Conclusions

In this study, the decomposed rabbit manure, vermiculite, rice straw, and peat were mixed and molded to manufacture rabbit manure compost seedling nursery blocks for replacing plug trays and improving the mechanization of seedling transplanting. The influences of cold pressing process parameters (e.g., moisture content, binder content, molding compression ratio, and strain maintenance time) on the evaluation indices (e.g., ventilatory porosity, relaxation density, compressive resistance, and specific energy consumption) of the blocks were analyzed. The regression equations were constructed among molding compression ratio, moisture content, binder content, strain maintenance time and relaxation density, ventilation porosity, and specific energy consumption. The relative errors between the experimental and predicted values of each model were within 5%. The optimal combination of parameters for forming rabbit manure compost seedling nursery blocks was that the molding compression ratio, moisture content, mass fraction of the binder, and strain maintenance time were 4:1, 33.5%, 3.1%, and 60 s. The relaxation density, ventilation porosity, and specific energy consumption were 363.31 kg/m^3, 18.72%, and 0.44 J/g, which had an adequate seedling performance.

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