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Parameter Optimization of a Potted Seedling Tray Prepared from a Mixture of Rice Straw and Fermented Cow Manure Using the Response Surface Methodology

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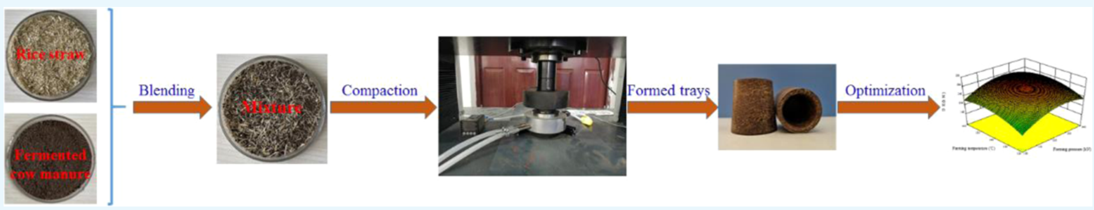

ABSTRACT: Biomass is generally regarded as a significant renewable resource, which can be used as the raw material for bioproducts. In the study, a mixture of rice straw and fermented cow manure was utilized to produce potted seedling trays, which are biodegradable and environmentally friendly. The effects of process parameters on the quality of final products were assessed by measuring damage resistance (DR) and expansion ratio (ER). Single-factor experiments and the response surface methodology (RSM) were used to optimize process parameters, including moisture content, forming pressure, mass percentage of straw (the ratio of rice straw to the mixture), and forming temperature as variables, and DR and ER of potted seedling trays as responses. The results showed that moisture content had the largest effect on DR and ER, followed by forming pressure, forming temperature, and mass percentage of straw. The optimal conditions were identified as a moisture content of 13%, forming pressure of 124 kN, mass percentage of straw equal to 8%, and forming temperature of 132 °C. There was a good agreement between the experimental data and the predicted results, indicating the reliability of the optimization process. Under the optimal conditions, the effectiveness of the regression model was further validated by the desirability of 0.97. Our findings shed new light on the perfect utilization of straws and animal manure and provided a reliable reference for the preparation of potted seedling trays from other types of biomass produced by agriculture.

1. INTRODUCTION

Biomass refers to renewable organic materials and mainly includes agricultural and forest residues, animal livestock manure, food waste, municipal sludge, etc.[1] Crop straw and livestock manure, as important renewable biomass resources, are generally composed of protein, lignin, cellulose, hemicellulose, and other organic materials and have been widely adopted as raw materials in the energy industry.[2] In China, crop straw production accounts for nearly one-fifth of the world's total straw resources.[3] In the past few decades, crop straw has been chiefly dealt with incineration, discarding, and landfilling. A number of scholars demonstrated that more than 30% of straw was directly burned or discarded in farmlands to reduce agricultural expenses.[4] Straw burning may cause environmental pollution and safety hazards. Because of the properties of high moisture content, irregular shape, and low bulk density, crop straws are mainly processed in baled forms, leading to increased expenses of handling, transportation, and storage.[5] The major limitations for the large-scale application of biomass are related to its diverse physical and chemical properties, as well as the availability of seasonal and geographical patterns. At present, due to the presence of some restrictive factors, China faces the issue regarding excessive production of straws, and the issue is further complicated by burning straws in agricultural fields.[6] A previous study reported that China's animal husbandry has rapidly developed over the recent two decades, indicating that a great amount of animal manure has been produced accordingly.[7] Animal manure, containing N, P, K, and other valuable nutrients, is an excellent biofertilizer and raw material for producing bioenergy. However, due to the lack of applicable collection and treatment equipment and the extensive production mode, a large amount of animal manure is directly discharged into the environment, leading to serious

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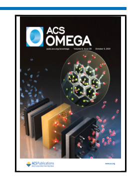

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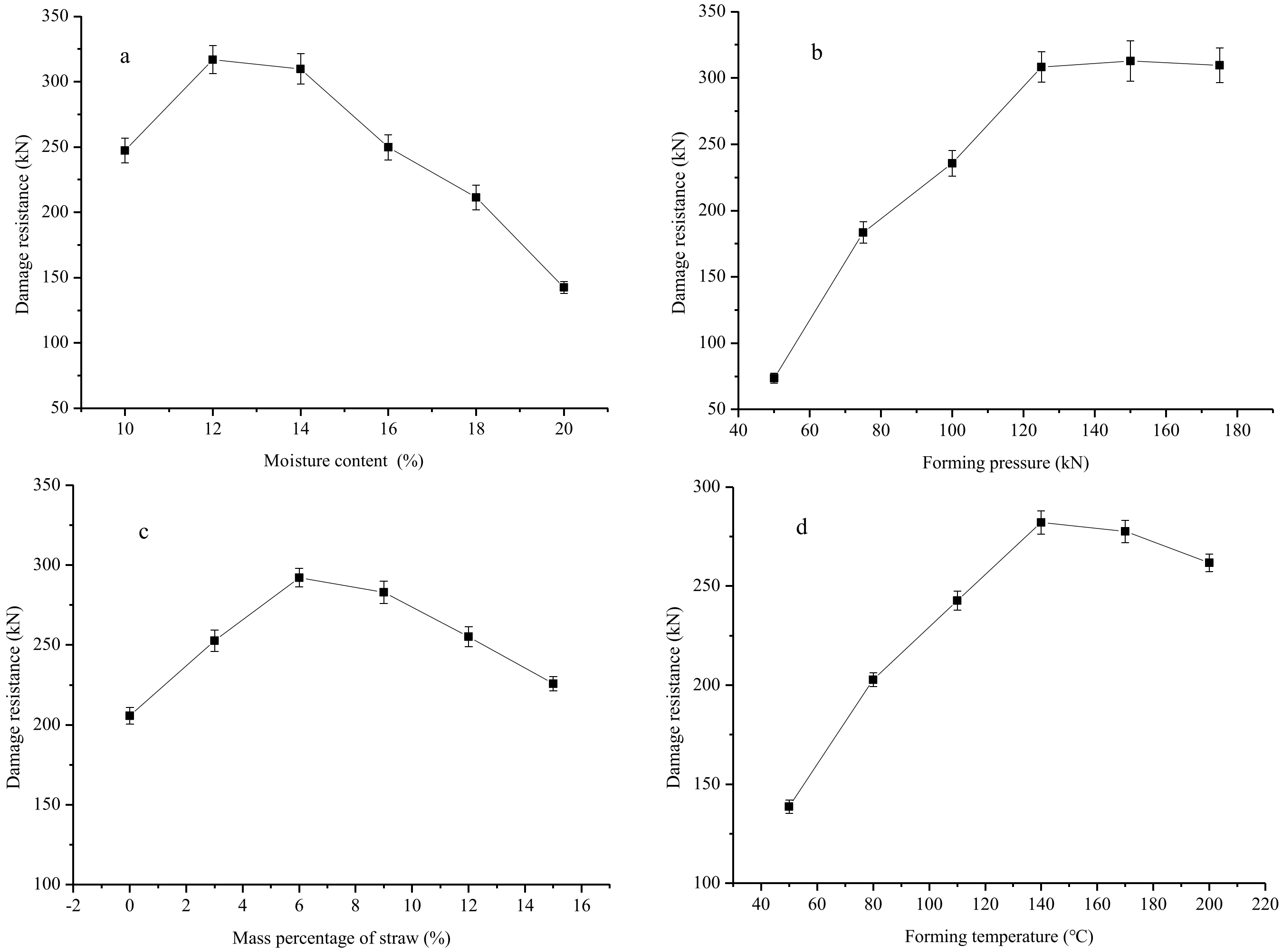

Figure 1. Effects of moisture content (a), forming pressure (b), mass percentage of straw (c), and forming temperature (d) on damage resistance.

pollution of air, land, and water systems. Although a reasonable utilization of straw and manure resources may be advantageous, it may cause damage to humans and the environment.[8]

To address the abovementioned concerns, numerous scholars have devoted great efforts to develop industrial techniques to utilize biomass resources with superior efficacy. One feasible method to attain the mentioned objective is to densify biomass resources into pellets, briquettes, or cubes. Densification can increase their bulk density from the range of 40−200 to 600−800 kg/m^{-3}.[9] In recent years, significant efforts have been devoted to preparing biomass-derived products made by the straw-compression molding technique, such as solid fuel, forage, biofertilizers, etc.[10]

The seedling transplanting technique can effectively prolong the growth of crops and significantly improve their quantity and quality, particularly for high-latitude regions.[11] A transplant was defined as a seedling or sprouted vegetative propagation material grown in a substrate or in the field to transfer to the final cropping site. At present, the existing seedling trays are mainly made of plastics, which are not environmentally friendly and have a short life cycle. Furthermore, the seedlings cultivated in plastic trays should be taken out of the holes before transplanting, increasing the difficulty of mechanized agriculture and restricting their applications on a large scale.[12] Therefore, it is highly essential to develop efficient seedling trays using biodegradable materials, where they can not only simplify the replanting process but also be more environmentally friendly. However, at present, little information is available on the optimization of parameters related to the production of biomass-potted seedling trays using heat compaction, especially for potted seedling trays made of the mixture of rice straw and fermented cow manure.

The response surface methodology (RSM) is a collection of mathematical and statistical techniques, and it is of great significance to approximate and optimize stochastic models.[13] The RSM is typically used for mapping a response surface over a particular region of interest, optimizing the response, or selecting operating conditions to achieve target specifications or a customer's requirements.[14] Several scholars have successfully utilized the RSM to optimize various operational processes, and they reported acceptable outcomes.[15] In the present research, the process optimization of a potted seedling tray made from a mixture of rice straw and fermented cow manure was investigated using the RSM.

The present research aimed to investigate the influences of the main process parameters (moisture content, forming pressure, mass percentage of straw, and forming temperature) on the properties (damage resistance (DR) and expansion ratio (ER)) of the potted seedling tray made of the mixture of rice straw and fermented cow manure and optimize the process parameters using the RSM.

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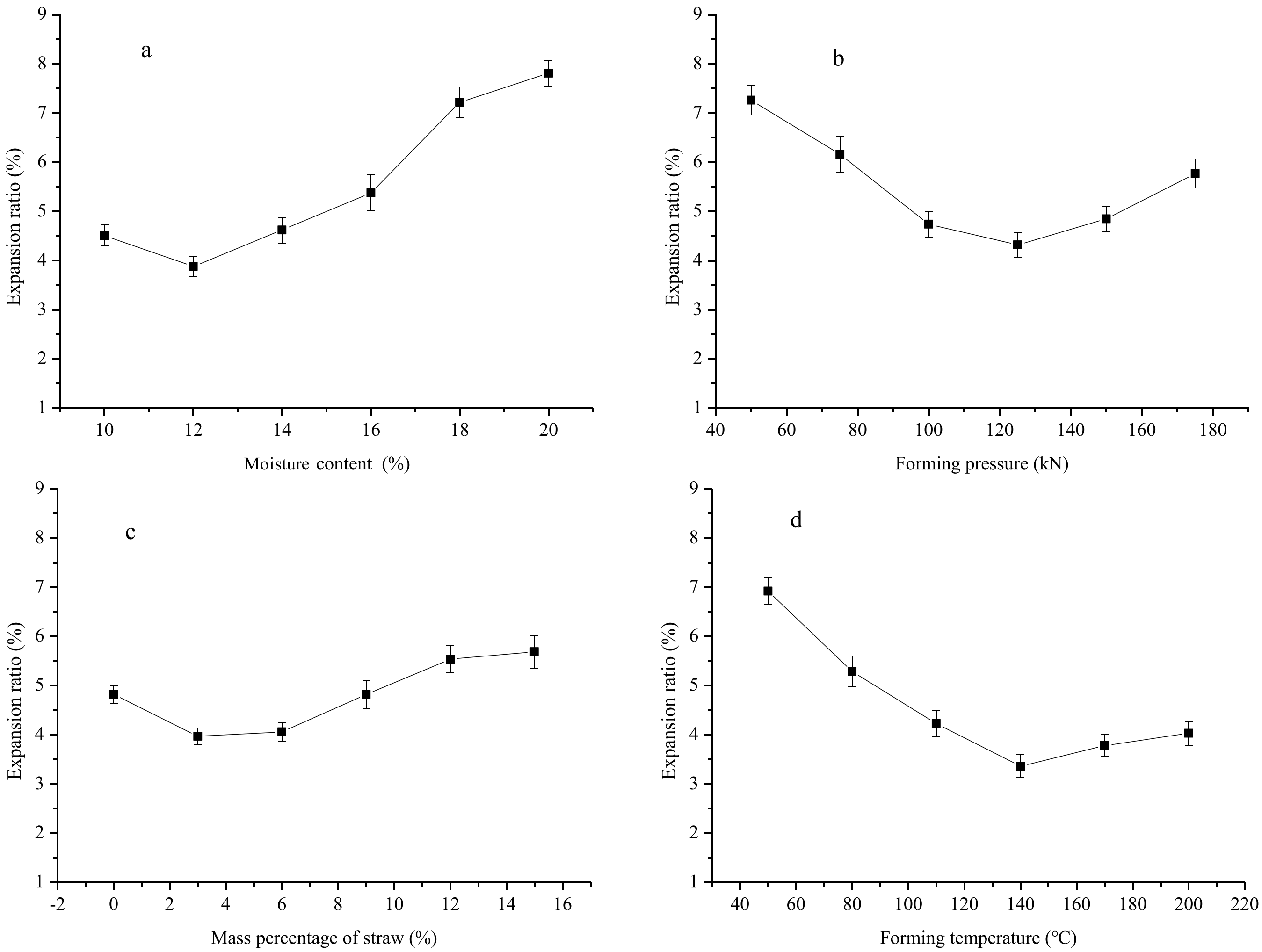

Figure 2. Effects of the moisture content (a), forming pressure (b), mass percentage of straw (c), and forming temperature (d) on the expansion ratio.

2. RESULTS AND DISCUSSION

2.1. Single-Factor Experiment. *2.1.1. Effects of Independent Variables on DR.* The roles of independent variables (moisture content, forming pressure, mass percentage of straw, and forming temperature) in the DR of the formed pot seedling tray are shown in Figure 1.

It was found that the DR increased first and then decreased when the moisture content, mass percentage of straw, and forming temperature were 12%, 6%, and 140 °C, respectively. Appropriate moisture content can promote the softening and plasticizing of lignin; moreover, under the synergistic effect of heat and water, a variety of physical and chemical changes can be induced, such as protein denaturation and starch gelation, promoting the formation of van der Waals forces among particles. The proper increase of the ratio of rice straw to fermented cow manure improved the DR, which indicates that the particle size played a decisive role in improving the damage resistance of the potted seedling trays. The energy provided by increasing the forming temperature promoted the softening of lignin and cellulose, increasing the adhesion between particles and promoting the DR. As the forming pressure increased from 73.6 to 308.2 kN, DR markedly increased; however, when the pressure continually increased from 125 to 175 kN, DR did not change. This phenomenon demonstrated that a proper increase of pressure can reduce the gap between particles, and the particles were brought close together, leading to interparticle bonding. According to the results, the values of independent variables for the RSM were 10−14%, 125 kN, 4−8%, and 120−170 °C for moisture content, forming pressure, mass percentage of straw, and forming temperature, respectively, with the aim of maximizing DR.

2.1.2. Effects of Independent Variables on the ER. The roles of independent variables in the ER of the formed pot seedling tray are displayed in Figure 2.

The ER first decreased and then increased at a moisture content of 12% (Figure 2a), forming pressure of 120 kN (Figure 2b), and mass percentage of straw equal to 6% (Figure 2c), respectively. Besides, the ER decreased as the temperature increased from 50 to 140 °C and then increased with its elevation. Water acts as both a binding agent and a lubricant. It can improve van der Waals forces and then increase the bonding between particles as the moisture content was at a proper level. However, when the moisture content exceeded the reasonable value, the role of water as a lubricant dominated. The increases of forming pressure and temperature benefited the softening and diffusion of lignin, causing the formation of a solid bridge. As fermented cow manure has smaller particle sizes and rice straw has natural binder components, the minimum ER can be obtained when the

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mass percentage of straw reached a reasonable value. Consequently, based on the criteria defined for minimizing ER, the rational values of independent variables for the RSM were 10−14%, 120 kN, 6%, and 120−160 °C for moisture content, forming pressure, mass percentage of straw, and forming temperature, respectively.

On the basis of the experimental results, the values of independent variables used for the RSM were finally identified to be 14%, 120 kN, 8%, and 140 °C for moisture content, forming pressure, mass percentage of straw, and forming temperature, respectively.

2.2. RSM Experiment. The results of the RSM are presented in Table 1.

Table 1. Experimental Values of DR and ER from RSM

	variable levels					
run	x_1	x_2	x_3	x_4	DR, y_1 (kN)	RR, y_2 (%)
1	12	100	6	120	221.4	5.10
2	16	100	6	120	89.9	10.17
3	12	140	6	120	283.6	4.98
4	16	140	6	120	187.5	6.66
5	12	100	10	120	217.2	4.49
6	16	100	10	120	136.9	8.86
7	12	140	10	120	228.1	4.03
8	16	140	10	120	168.9	6.48
9	12	100	6	160	231.7	5.89
10	16	100	6	160	127.8	8.99
11	12	140	6	160	284.9	5.48
12	16	140	6	160	213.2	4.35
13	12	100	10	160	253.9	6.17
14	16	100	10	160	215.4	8.97
15	12	140	10	160	264.1	5.66
16	16	140	10	160	218.9	6.37
17	10	120	8	140	302.5	4.84
18	18	120	8	140	166.3	8.52
19	14	80	8	140	103.2	6.03
20	14	160	8	140	198.7	4.50
21	14	120	4	140	291.6	8.10
22	14	120	12	140	289.0	6.66
23	14	120	8	100	160.3	2.82
24	14	120	8	180	220.3	6.76
25	14	120	8	140	297.5	3.16
26	14	120	8	140	288.0	2.67
27	14	120	8	140	296.6	2.21
28	14	120	8	140	289.0	3.51
29	14	120	8	140	283.6	4.26
30	14	120	8	140	290.3	3.70
31	14	120	8	140	290.8	3.25

As previously reported, analysis of variance (ANOVA) is generally used to examine the accuracy and significance of the regression models. The results of ANOVA are summarized in Tables 2 and 3.

As shown in Table 2, the p-values of DR and ER regression models are <0.01, indicating that the two regression models were significantly different. The p-values of the lack of fit (LF) of DR and ER were 0.061 and 0.2128, respectively, demonstrating that the LF was not statistically significant at the level of 5%, and also confirmed the acceptable accuracy of the polynomial models.

Besides, the coefficients of determination (R^2) were 0.9913 and 0.9120 (Table 5), highlighting that more than 99.13 and 91.20% of the response variability could be sufficiently explained by the experimental data, as well as supporting a good accuracy and noticeable capability of the regression model.[16] In addition, the values of the adjusted determination coefficients (Adj-R^2) indicated that the experimental data were in good agreement with the predicted results (Table 3); meanwhile, the predicted and actual values confirmed the truth (Table 2). "Adeq Precision" determines the signal-to-noise ratio (SNR), in which SNR > 4 is desirable.[17] In the current study, the values of Adeq Precision for DR and ER were 37.022 and 10.456, respectively, confirming the appropriateness of SNR.

2.2.1. Analysis of DR. For DR, the values ranged from 89.9 to 302.5 kN at different conditions. According to the results of ANOVA, x_1, x_2, x_4, x_1x_3, x_1x_4, x_2x_3, x_3x_4, x_1^2, x_2^2, and x_4^2 were extremely significant items (p < 0.01), and x_1x_2 was the significant item (p < 0.05). It indicates that moisture content had the highest influence on DR, followed by forming pressure, forming temperature, and mass percentage of straw. Thus, it can be concluded that the parameter of moisture content exhibited the greatest effect on DR. On removing the statistically insignificant items at the level of 5%, the relationship between DR (y_1) and moisture content (x_1), forming pressure (x_2), mass percentage of straw (x_3), and forming temperature (x_4) can be formulated by eq 1.

$$y_1 = -2494.82 + 27.35x_1 + 25.20x_2 + 16.31x_4 + 0.13x_1x_2 + 2.81x_1x_3 + 0.17x_1x_4 - 3.84x_1^2 - 0.09x_2^2 - 0.07x_4^2 \quad (1)$$

To intuitively appreciate the coupled influences of each pair of variables on DR, three-dimensional (3D) response surfaces and plots are displayed in Figure 3.

As shown in Figure 3a, the coupled effects of moisture content and forming pressure on DR were presented, as the mass percentage of straw and forming temperature were kept at a constant level. Additionally, a higher DR of the formed trays could be obtained when the moisture content was at a lower level and forming pressure was 120−130 kN. A reduction in DR with an increase of moisture content may be attributed to the fact that when the moisture content is at a higher level, it may prevent the complete release of natural binders, such as lignin, cellulose, and hemicellulose, hindering the formation of adhesion forces between particles, resulting in the decrease of DR, and this result is consistent with the finding of Kaliyan et al.[18] Moreover, a water film may be formed between particles, as hydrogen bonds between the polymers of the particles can be replaced by the bonds of water molecules, which may justify the reduction of DR.[19] DR initially increased from 89.9 to 302.5 kN as the forming pressure was elevated from 100 to 120 kN and then decreased to 228.1 kN as the pressure continuously increased. Moreover, the increase of DR was significantly associated with the elevation of the forming pressure from 100 to 120 kN, while its variation was insignificant as the pressure further increased. This phenomenon can be explained by the fact that the increase of the forming pressure can cause the particles to be squeezed into the gaps of adjacent particles, reducing the empty space among particles, as well as causing the formation of solid bridges, hydrogen bonds, and van der Waals forces, resulting in the increase of DR.[20] A previous study demonstrated that pressure is one of the factors that positively

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Table 2. ANOVA Evaluation of Linear, Quadratic, and Interaction Terms for each Response and Coefficient of Predicted Models

		DR			ER		
source	df	coefficient	sum of squares	p-value	coefficient	sum of squares	p-value
model	14	290.83	1.16×10^5	<0.0001	3.25	119.88	<0.0001
x_1	1	−37.45	33660.06	<0.0001	1.1	29.06	<0.0001
x_2	1	22.75	12421.5	<0.0001	−0.74	13.04	0.0006
x_3	1	2.43	141.14	0.1559	−0.14	0.5	0.4171
x_4	1	16.52	6547.21	<0.0001	0.37	3.37	0.0464
x_1x_2	1	5.12	420.25	0.0206	−0.73	8.45	0.0035
x_1x_3	1	11.25	2025	<0.0001	0.1	0.16	0.6423
x_1x_4	1	6.74	726.3	0.0038	−0.51	4.09	0.0302
x_2x_3	1	−15.11	3654.2	<0.0001	0.17	0.47	0.4339
x_2x_4	1	−3.15	158.76	0.1338	−0.11	0.18	0.626
x_3x_4	1	7.87	992.25	0.0012	0.34	1.9	0.1247
x_1^2	1	−15.36	6747.73	<0.0001	0.92	24.29	<0.0001
x_2^2	1	−36.22	37522.32	<0.0001	0.57	9.22	0.0025
x_3^2	1	−1.39	54.96	0.3666	1.1	34.39	<0.0001
x_4^2	1	−26.39	19909.42	<0.0001	0.45	5.77	0.0122
residual	16		1018.35			11.57	
lack of fit	10		876.66	0.061		8.85	0.2128
pure error	6		141.69			2.72	
total	30		1.17×10^5			131.45	

Table 3. RSM Model Fit Summary Output for DR and ER

response	mean	std. dev.	R^2	adj R^2	C.V. %	adeq precision
DR (kN)	229.39	7.98	0.9913	0.9837	3.48	37.022
ER (%)	5.60	0.85	0.9120	0.8350	15.189	10.456

influence physical properties, such as density, strength, hardness, and durability.[21] Thus, natural binders (lignin, cellulose, hemicellulose, protein, and other components) can be extruded at a higher pressure. Pressure is mainly applied to promote adhesion by enhancing the molecular contact between adjacent particles.[22] However, the variation of DR was found insignificant, when the forming pressure exceeded the rational value (130 kN in the current study), which might be related to the fact that the density of the formed tray reached the peak value as the pressure reached a certain level, highlighting that the pressure had no influence on DR.[23] As depicted in Figure 3b,d,f, changes in DR were not significantly associated with the increase of the mass percentage of straw under different conditions concerning moisture content and temperature, as the other two independent variables were kept constant. This is consistent with the p-value of the mass percentage of straw ($p > 0.05$). DR decreased in a smaller range as the mass percentage increased from a lower level to a higher level. This might be related to the higher contents of lignin, cellulose, hemicellulose, and other components (serving as natural binders) in rice straw than those in fermented cow manure. The interaction between temperature and other variables on DR under different conditions is illustrated in Figure 3c,e,f. DR first increased and then decreased with the elevation of temperature. As the temperature increased from 100 to 150 °C, DR was consequently elevated from 89.9 to 302.5 kN, indicating that temperature had an important effect on DR. The increase in DR might be related to the fact that lignin, cellulose, and hemicellulose were softened and liberated at a certain temperature in the heating process, causing the formation of cohesive forces between the adjacent particles, thereby leading to the increase of DR.[24] Previous studies have reported that the components of biomass, such as hemicellulose, lignin, protein, starch, and sugar could be activated as natural binders when the temperature is 70−150 °C.[25]

However, DR decreased when the temperature exceeded 150 °C, which might be related to the rapid evaporation of the moisture in the feedstock at a higher temperature, negatively influencing the physical characteristics of the formed tray, such as density, hardness, durability, etc., consistent with the result of Gilbert et al.[26]

2.2.2. Analysis of ER. For ER, the values ranged from 2.21 to 10.17% at different conditions. According to the results of ANOVA, the terms of x_1, x_2, x_1x_2, x_1^2, x_2^2, and x_3^2 were extremely significant items ($p < 0.01$), and x_4, x_{14}, and x_4^2 were the significant items ($p < 0.05$). It indicates that moisture content had the greatest influence on ER, followed by forming pressure, forming temperature, and mass percentage of straw. After removing the statistically insignificant items at the level of 5%, the relationship among ER (y_2) and moisture content (x_1), forming pressure (x_2), mass percentage of straw (x_3), and forming temperature (x_4) can be formulated by eq 2.

$$Y_2 = 59.90 - 2.15X_1 - 0.12X_2 - 0.16X_4 - 0.02X_1X_2 + 8.60 \times 10^{-3}X_1X_4 + 0.23X_1^2 + 1.42 \times 10^{-3}X_2^2 + 0.27X_3^2 + 1.12 \times 10^{-3}X_4^2 \quad (2)$$

To intuitively assess the coupled influences of each pair of variables on ER, Figure 4 showed 3D response surfaces and plots.

Expansion of the formed trays, also called the spring-back effect, mainly occurs after extrusion from the die and the storage, which may be associated with density, hardness, particle size, forming pressure, temperature, initial moisture contents of the formed trays, etc. As displayed in Figure 4a, the coupled effects of moisture content and forming pressure on ER could be observed, as the mass percentage of straw and temperature were kept constant. Furthermore, lower values of

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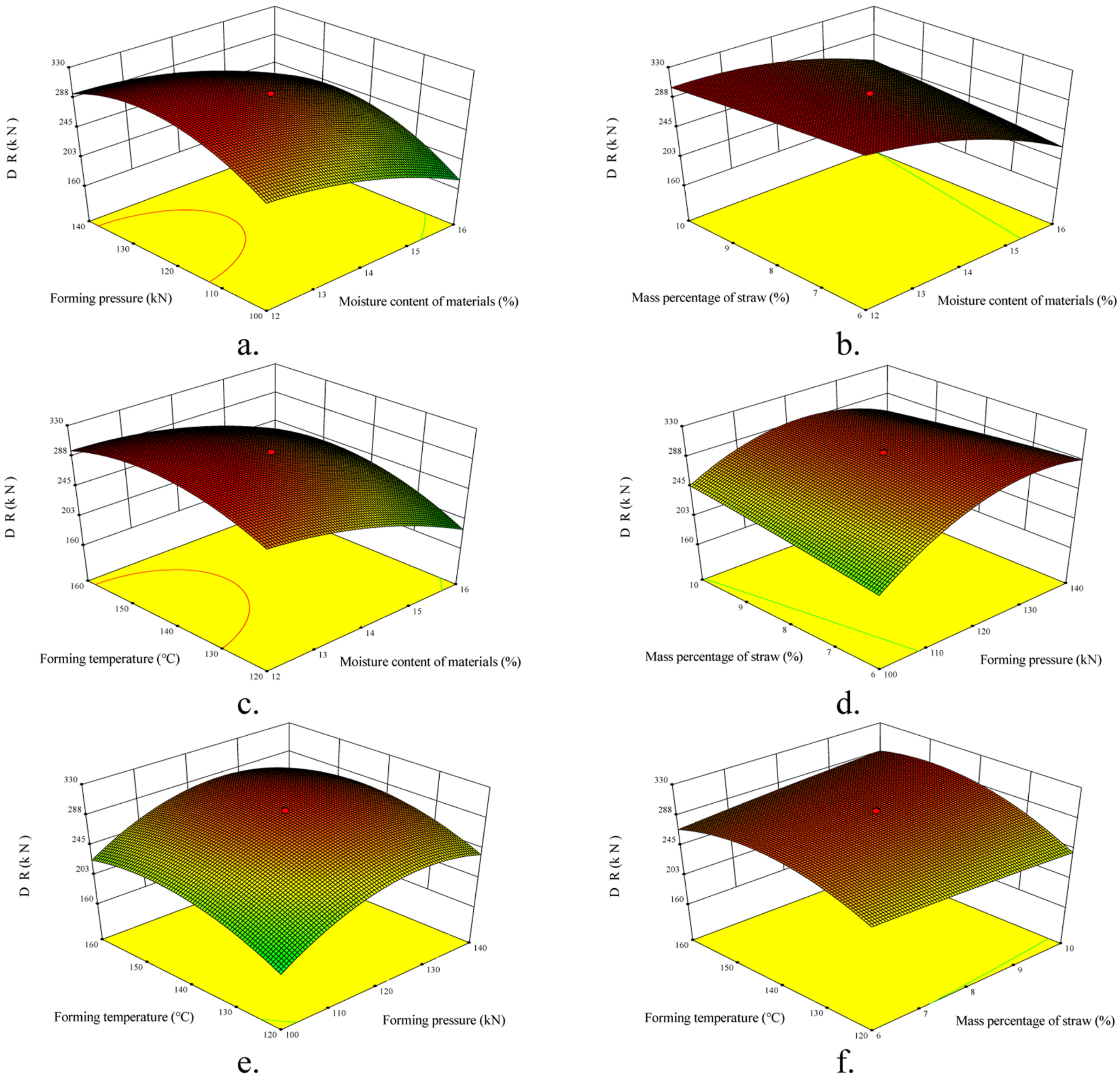

Figure 3. Response surface plots of damage resistance between every pair of variables: (a) moisture content and forming pressure; (b) moisture content and mass percentage of straw; (c) moisture content and forming temperature; (d) forming pressure and mass percentage of straw; (e) forming pressure and forming temperature; and (f) mass percentage of straw and forming temperature.

ER could be found as the moisture content was 13% and the forming pressure was 120−130 kN. The elevation of ER with a higher moisture content may be advantageous owing to the evaporation of internal water in the formed trays during storage at room temperature for 48 h, resulting in the formation of empty spaces among particles. Besides, the higher moisture content and the greater formation of empty spaces result in the increase of ER, which is consistent with previously reported findings.[27] When the forming pressure increased from 100 to 130 kN, ER decreased from 10.17 to 2.21%, and the minimum value of ER was found when the applied pressure was equal to 120 kN. During the formation process of pot seedling trays, diverse natural binding components, such as starch, cellulose, protein, and lignin, in the materials were detected, and they generated stronger bonding forces among the particles, leading to higher values of density and hardness of the formed tray, and then the expansions of the formed tray in diameter and length were reduced.[28] Hence, the reasonable increase of the temperature can effectively enhance the density and hardness of a formed tray, thereby reducing the expansion ratio.[29] Further attention should be paid to the slight reduction of ER with the increase of the forming pressure, which may be related to the fact that the density of a formed tray reaches the peak value as the released pressure changes in a rational range. However, the pressure may negatively affect the increase of the density when it is beyond a certain value, resulting in a slight decrease of ER. A previous study confirmed the above-mentioned finding as well.[23] The association of mass

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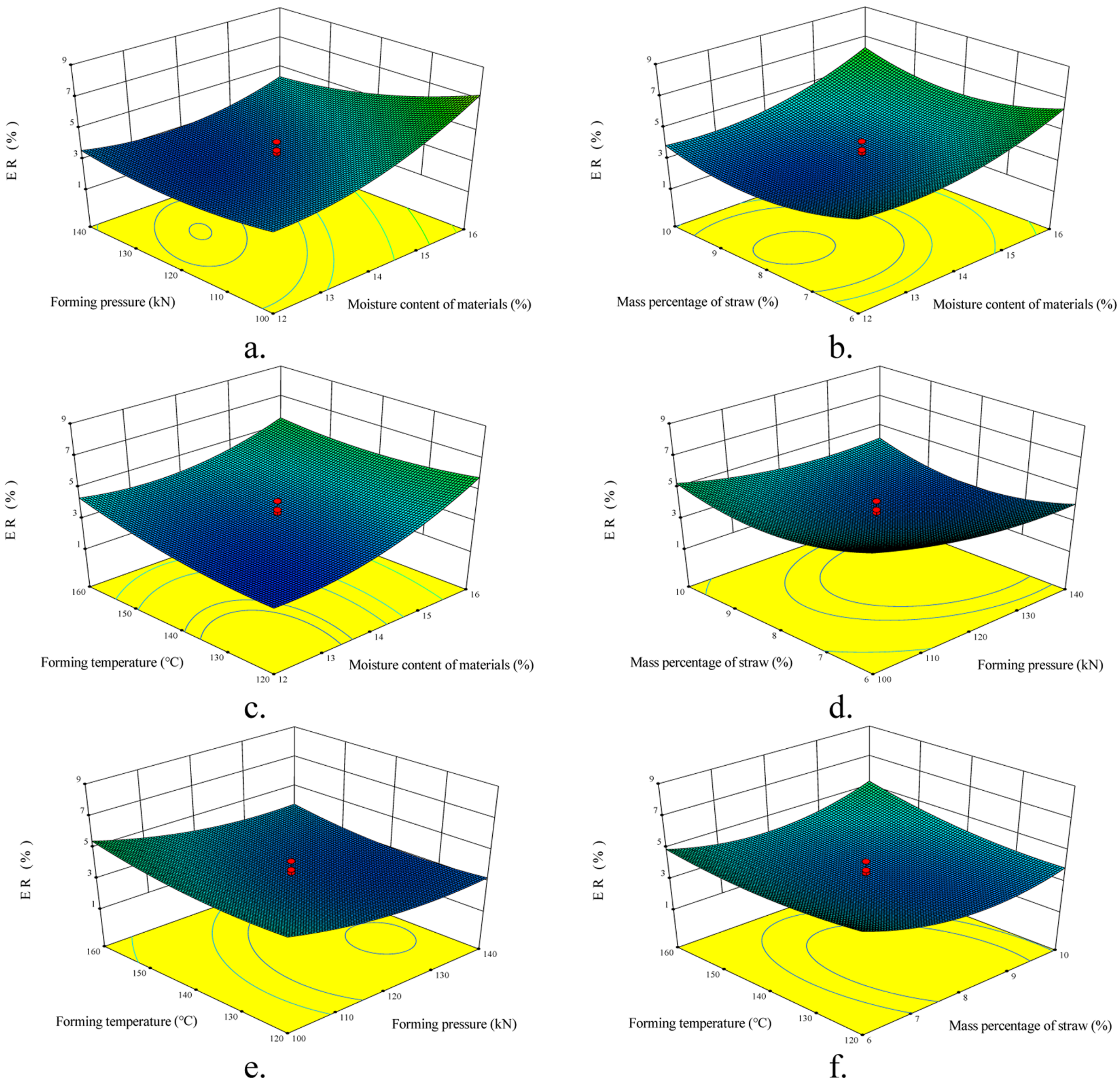

Figure 4. Response surface plots of the expansion ratio between each pair of variables: (a) moisture content and forming pressure; (b) moisture content and mass percentage of straw; (c) moisture content and forming temperature; (d) forming pressure and mass percentage of straw; (e) forming pressure and forming temperature; and (f) mass percentage of straw and forming temperature.

percentage of straw with other independent variables is depicted in Figure 4b,d,f. ER initially decreased and then increased with the elevation of the mass percentage of straw, and the maximum ER could be achieved at a mass percentage of straw of 8%. As a result, the density and hardness of the formed trays are closely correlated with the contents of natural binders in the compacted materials and the size of particles. Although the particle size of fermented cow dung was smaller than that of rice straw, the contents of natural binders in rice straw used in the current research were higher than those in the fermented cow dung, confirming that the mass percentage of straw plays a pivotal role in the decrease of ER when it increases from 6 to 8%. Nevertheless, when the rate of rice straw in the compacted materials continuously increased to more than 8%, the mean particle size was enlarged, which resulted in the increase of ER. As shown in Figure 4e,f, with the increase of temperature, the changes of ER were not significant and ER was slightly elevated (Figure 4c). A number of scholars demonstrated that the mean glass transition temperature for protein and lignin in biomass is as high as 75 °C.[30] In the present research, the temperature was 100−160 °C, which is higher than the glass transition temperature. The protein and lignin in the materials were softened and liberated upon compression process, and the softening effect resulted in the increase of elasticity of the formed tray, and it enhanced the flexibility of the formed tray. This might justify the slight increase of ER when the temperature of the formed tray was reduced for 48 h.

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2.3. Optimization and Verification. The criteria defined to maximize DR and minimize ER were employed to solve the second-order regression model and to determine the optimal conditions for the formation of the potted seedling tray made of the mixture of rice straw and fermented cow dung. Equal weights were applied to all of the independent variables and responses. Optimal conditions were indicated as the moisture content of 13%, forming pressure of 124 kN, mass percentage of straw of 8%, and forming temperature of 132 °C; meanwhile, the predicted values of DR and ER were 3,025 kN and 2.68%, respectively. Under the optimal conditions, the verification tests were performed in triplicate, and the test results are presented in Table 4.

Table 4. Predicted and Test Values of Responses under Optimal Conditions

	values			
responses	predicted	desirability	experimental	error[a]
y_1 (DR, kN)	302.5	0.97	307.3	0.016
y_2 (ER, %)	2.68	0.97	2.61	0.027

[a] $\text{error} = \frac{|\text{predicted value} - \text{experimental value}|}{\text{experimental value}}$.

The difference between the predicted and experimental responses was less than 3%, indicating that the experimental data could be accurately predicted using the RSM. Besides, the regression model could be further confirmed by the desirability of 0.97.

3. CONCLUSIONS

In the present research, the RSM was applied to determine the optimal conditions of a potted seedling tray made of a mixture of rice straw and fermented cow manure. The results indicated that the regression model with an R^2 value > 0.91 could precisely predict DR and ER under the optimal conditions. The following variables subsequently exhibited the highest effects on DR: moisture content, forming pressure, forming temperature, and mass percentage of straw; the above-mentioned sequences of the variables could be observed for their influences on ER. The optimal conditions could be achieved with a moisture content of 13%, forming pressure of 124 kN, mass percentage of straw equal to 8%, and temperature of 132 °C. Under such conditions, the predicted and experimental values of DR and ER were 302.5 kN and 2.68%, respectively, and the difference between the predicted and experimental values was less than 3%. Furthermore, the desirability of optimal conditions was 0.97, which confirmed the precision of the regression model.

4. MATERIALS AND METHODS

4.1. Preparation of Materials. Rice straws were collected from the rice test fields located at Heilongjiang Bayi Agricultural University (Daqing, China). They were cut into small fragments of 100−150 mm in length with a straw chopper after natural drying. Then, the straw was crushed into powders using a hammer-type crusher, and then the particles with a size of 5 mm could be achieved (Figure 5b). The fermented cow manure manufactured by Shandong Feiwo Agricultural Materials Co., Ltd., (Jinan, China) was rubbed and passed through a 1.5 mm sieve to remove impure substances (Figure 5c). According to the requirements of experiments, the rice straw and fermented cow manure were weighed and then mixed manually to make the blended samples (Figure 5a). The percentage of the blends was calculated on a dry weight basis. Prior to the experiment, the moisture contents of the samples were adjusted by adding a predetermined amount of deionized water onto the materials, kept in a sealed plastic container, and were stored in a refrigerator at 4 ±0.5 °C for 48 h to equilibrate the moisture.

4.2. Experimental Apparatus and Procedure. The device used to prepare potted seedling trays was manufactured by Heilongjiang Bayi Agricultural University (Figure 6).

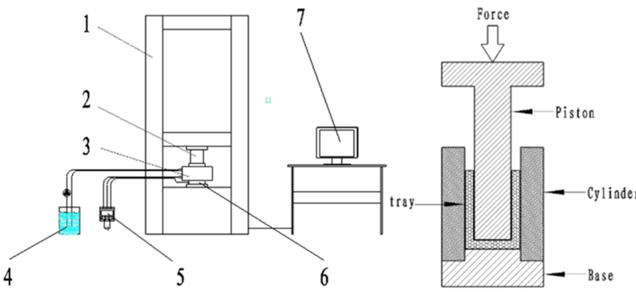

Figure 6. Schematic diagram of the hot compaction molding machine: (1) frame, (2) forming mold, (3) heating device, (4) cooling water circulation pump, (5) temperature controller, (6) temperature sensor, and (7) controlling computer.

It is mainly composed of four components: a ram or screw-type plunger for injection molding, a heating system, a water-cooling system, and a computer control system. The ram or screw-type plunger is replaceable to meet different needs, with an inner diameter of 50 ± 0.1mm, an operating radius of 0−100 mm, and a pressure of 0−200 kN. The electromagnetic

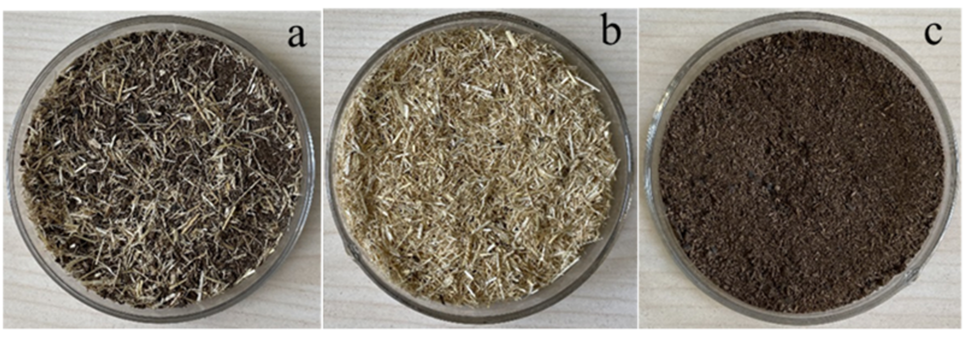

Figure 5. Experimental materials of (a) mixture made from (b) rice straw and (c) fermented cow manure.

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heating principle was adopted in the heating system, and the temperature was 0−400 °C. The water-cooling pipes were arranged in a spiral way to decrease the temperature of the formed mold in a short period of time. The preparation of the pot seedling trays was performed as follows: before each test, the heating system was run for 15−20 min to stabilize the die at the target temperature. Then, the blended materials with a specific mix ratio were added into the die. The piston started to press the materials at a loading rate of 10 mm/min via applying the load, and the load force was monitored and controlled by the computer control system. After reaching the preset loading force, the pressure was maintained at a constant level for 20 s. After that, the water-cooling system started to operate. When the temperature of the die reached 25 °C or below, the water-cooling system was turned off, and the formed sample was removed from the mold. Finally, the formed sample was cooled at an ambient temperature for 10 minutes, which was then packed into a plastic bag and stored in a refrigerator (the temperature was kept at 4 ± 0.5 °C) for evaluation of DR and ER.

4.3. Measure of DR. DR, sometimes called crushing resistance or compressive resistance, indicating the maximum crushing load that the formed tray can withstand before cracking and breaking, is an essential parameter for seedling cultivation and transplanting. It can be measured using the WDW-200E Computerized Electronic Universal Testing Machine. Herein, the formed trays were placed on the universal testing machine, and then the sample was crushed at a loading rate of 10 mm/min. After data processing, a force−displacement curve was plotted, and DR could be determined using the peak value of the force in the curve.

4.4. Measure of ER. For formed trays, ER is an important parameter, reflecting its practicability during transportation, seedling cultivation, and transplanting. It is defined as the ratio of diameter-to-length.[25] As the tray was removed from the mold, the initial height was measured. The height was measured again after the tray was placed at room temperature for 48 h. The ER was eventually calculated using eq 3.[21]

$$\mathrm{ER} = \frac{h_2 - h_1}{h_1} \times 100\% \tag{3}$$

where h_1 refers to the initial height of the formed tray (mm) and h_2 denotes the height of the formed tray measured after the tray was placed at room temperature for 48 h (mm).

4.5. Experimental Design and Optimization. In the present study, moisture content, forming pressure, mass percentage of straw, and forming temperature were considered as process parameters and were shown with codes x_1, x_2, x_3, and x_4; meanwhile, DR and ER with the codes of y_1 and y_2 were taken as responses into account. Single-factor experiments were first carried out to determine the reasonable range of variables used in the RSM. The process parameters and their corresponding values used in single-factor experiments are presented in Table 5.

According to the experimental results, the RSM was employed to characterize the mutual effects of various variables and to investigate the optimal conditions during the process of formation of the pot seedling trays. The process parameters and their corresponding values are listed in Table 6.

During the RSM, a total of 31 experimental runs were randomly performed to minimize the effects of unexplained variability on the observed responses. The RSM basically aims to gain the response surface model of the objective function on the variables through the experimental data of selected points, to predict the values of nonexperimental points, and finally obtain the optimal values of process parameters under constraint conditions. The response surface model is generally between the first- and fourth-order. With the increase of the order, the ability to simulate a nonlinear model becomes stronger. Among them, the response surface model with the second-order polynomial approximation has a higher computational accuracy and problem-solving efficiency.[31] In the current research, to fit the experimental data, the below second-order polynomial approximation was used.[32]

Table 5. Variables and Levels for the Single-Factor Experiment

variables	levels					
moisture content of the material (%)	10	12	14	16	18	20
forming pressure (kN)	50	75	100	125	150	175
mass percentage of straw (%)	0	3	6	9	12	15
forming temperature (°C)	50	80	110	140	170	200

Table 6. Variables and Levels for the RSM Design

		levels				
variables	symbols	−2	−1	0	+1	+2
moisture content of the material (%)	x_1	10	12	14	16	18
forming pressure (kN)	x_2	80	100	120	140	160
mass percentage of straw (%)	x_3	4	6	8	10	12
forming temperature (°C)	x_4	100	120	140	160	180

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{i<j=1}^{k} \beta_{ij} x_i x_j \tag{4}$$

where y refers to the objective function, β_{ij}, β_{ii}, β_i, and β_0 are the polynomial coefficients, x_i and x_j indicate the independent variables, and k denotes the number of independent variables.

The following steps were employed to optimize the objective functions: (1) absent dimension of response variables, (2) determination of weighting coefficients, (3) construction of desirability solution and function, and (4) optimization of the model (fuzzy inferior ratio method).[33]

The objective function was herein developed by maximizing DR and minimizing ER.

4.6. Statistical Analysis. The graph-based analysis was undertaken by Origin 8.5 software. Design Expert 8.0.6 software was used to conduct ANOVA and plot the response surface. The least significant difference at a 95% confidence level ($p < 0.05$) was calculated by Duncan's multiple range test. All tests were conducted in triplicate.

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Notes

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