Parameters Optimization for Compressing a Mixture of Decomposed Rice Straw and Biochar into a Seedling-raising Mat

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Transplanting is the prime growing pattern for rice production, and seedling raising is an essential step of the process. However, the massive soil source and the complicated treatments needed for seedling raising are major issues. This study explored the possibility of using compressed-decomposed rice straw and biochar from rice husk into a seedling-raising mat, to replace the soil and simplify the seeding process. A quadratic rotation-orthogonal combination experiment was conducted to investigate the effect of moisture content, pressure, and residence time on the formation of seedling-raising mat. The regression models between the compressing indicators and the process factors were established. The results showed that the following factors had significant effect on bending strength of the formed mat ($P < 0.01$): the pressure and residence time have extreme effects on dimensional stability ($P < 0.01$); but the influence of moisture content was insignificant ($P > 0.05$). The process parameters for compression were optimized and verified using Design-Expert software 8.0.6. The optimized parameters were moisture content of 33%, pressure of 23.0 MPa, and residence time of 61 s. The prediction error is less than 6% under this condition. The results may provide a reference for biomass seedling-raising mat compression.

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Keywords: Seedling raising mat; Decomposed rice straw; Biochar; Compression; Dimensional stability; Bending strength

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INTRODUCTION

Rice is one of the world's major food crops, and China is the main producer and consumer. The main growing pattern of rice is transplanting, and seedling-raising is an essential step in the process (Zhao *et al*. 2017). In the massive amount of soil used for large-scale rice production, seedling-raising has become a hard issue (Wen *et al*. 2020). Meanwhile, straw resources are rich in China and its utilization rate is still low (Zhang *et al*. 2021). The straw contains abundant elements and nutrients for the germination and growth of crops (Li *et al*. 2021). Therefore, seeking a way to process crop straws into rice seedling-raising substrates is a beneficial attempt.

Studies on alternative media for seedling-growing have been carried out. Zhang *et al*. (2014) studied rice seedling-raising using a mixture of carbonized rice husk, cow dung, and nutrient soil, and the experiment showed that the mixed substrate effectively improved the growth of rice seedlings. Materials such as rice husk, corn stalk, rice straw, earthworm dung, some combined with distiller's grains, and vermiculite, were studied as substrate for rice seedling raising, and the results showed that it was practicable (Song *et al*. 2014; Sun *et al*. 2018).

Biochar is the pyrolysis product of biomass such as crop straw, which can improve soil fertility and physicochemical properties of straw seedling substrate, and is conducive to the growth of crops (Meng *et al*. 2011; Carter *et al*. 2013; Nieto *et al*. 2016; Gao *et al*. 2017; Jiao *et al*. 2020). Wen *et. al*. (2020) studied the effect of decomposed rice straw substrate and biochar from rice husk, vermiculite, and perlite on growth of rice seedlings, and the result showed that the treatment using 40% straw and 20% biochar in volume was the most favorable treatment.

However, the straw-based substrate was very low in bulk density and was inconvenient for storage and transportation purposes. Hence, densification studies have been carried out by some researchers. Xin *et al*. (2017) conducted an experimental study on parameters optimization of substrate block-forming for vegetable seedling raising. Chen *et al*. (2016) carried out experimental study on the compaction behavior of biochar from corn stalk. Zhang *et al*. (2012) studied the process for straw-based potted tray forming for rice seedling raising and the optimal pressure and residence time were obtained. Yu *et al*. (2013) investigated the drying process and parameters optimization of straw-based seedling raising *via* potted tray.

The research described above mainly considered forming vegetable raising blocks, briquettes, and potting trays using biomass substrates. This study explored the possibility of compressing the substrates into seedling-raising mat, which may be sold as commercial product and could be used seeding directly, and then transplanted together with the seedlings to reduce the use of soil and simplify the seeding process of seedling-raising.

EXPERIMENTAL

Materials

The ground, naturally decomposed rice straw was the major component of the raw material, and the biochar from rice husk was added at ratios of 10%, 20%, and 30% by weight. The physical and chemical properties of biochar and decomposed rice straw were tested and shown in Tables 1 and 2, respectively.

The material was mixed with water at a ratio of 1:10 by weight, settled for 30 min, the solution was filtered, and then the pH value was tested with a pH meter. The electrical conductivity (EC) was tested with a portable conductometer (DDBJ-350, Shanghai Yidian Scientific Instrument Co., Ltd., Shanghai, CN).

The bulk density and porosity of the material were tested and calculated according to the methods of Guo (2005) as,

$$BD = \frac{W_2 - W_1}{V} \tag{1}$$

$$TP = \frac{W_3 - W_2}{V} \times 100\% \tag{2}$$

$$AP = \frac{W_3 - W_4}{V} \times 100\% \tag{3}$$

where, *BD* is bulk density (g/cm^3); *TP* is the total porosity (%); *AP* is the aeration porosity (%); W_1 is the weight of aluminium specimen box (g); W_2 is the total weight of the box and the naturally dried materials (g); W_3 is the weight of materials immersed in water for 24 h (g); W_4 is the weight of materials drained of water after soaking (g); and *V* is the volume of aluminium specimen box, which is 200 cm^3 in this test.

Table 1. Basic Physical and Chemical Properties of Materials

Material	Bulk Density (BD) (g/cm^3)	Total Porosity (TP) (%)	Aeration Porosity (AP)(%)	pH	EC (ms/cm)
Biochar	0.2±0.01	78.5±0.90	14.02±0.50	8.51±0.02	1.71±0.05
Decomposed Rice Straw	0.23±0.01	42.77±0.06	18.48±0.15	6.15±0.02	1.23±0.02

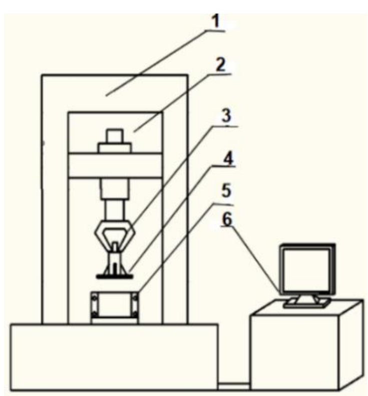
Table 2. Basic Composition of Materials

Material	C (%)	N (%)	Alkaline-Hydrolysis Nitrogen (mg·kg^{-1})	Available Phosphorus (mg·kg^{-1})	Available Potassium (g·kg^{-1})
Biochar	42.5±0.57	0.89±0.05	58.80±1.98	113.67±1.21	0.30±0.00
Decomposed Rice Straw	11.22±0.20	0.52±0.01	273.00±0.50	157.87±0.31	6.40±0.20

The mixture of the biochar and decomposed rice straw at the experimental ratios can provide a good physical environment for the normal growth of rice seedlings; the addition of biochar can greatly increase the content of carbon, while the total nitrogen and alkali hydrolysis nitrogen content of the substrate are still lower than that of the commercially available substrate, so some adjustments need to be given to the seedling substrate before production (Wen *et al*. 2020).

Densification Process

A compressing mold containing a compressing head and a die was designed and equipped on a computer controlled electronic universal testing machine (WDW-200, Jinan Shijin Group Co. Ltd., China). The experimental system is shown in Fig. 1a.



(a) (b)

Fig. 1. Substrate mat compressing system: (a) 1. Frame; 2. Beam; 3. Fixture; 4.Compressing head; 5. Die; 6. Computer; and (b) The formed seedling-raising mat

In this study, the specification for the substrate mat was set at 150 mm long, 150 mm wide, and 10 mm thick. The compression ratio of the seedling substrate ranged from 4:1 to 5:2 according to the preliminary tests. At that point the height of the substrate filled in the forming die was about 45 mm to 72 mm. The mass of each mat was set at 150 g.

The mixed materials were then filled into the die followed by presetting the pressure head at a speed of 100 mm/min downwards. The pressure head dwelled for a certain time after reaching the preset pressure, and then returned. The die was opened, and the formed mat was taken out for parameters measurement. The prepared seedling-raising mats are shown in Fig. 1b.

The experiment was carried out in the Agricultural Engineering Laboratory of Shenyang Agricultural University in June 2020, at room temperature of 25 °C, and the relative humidity was 40%.

Experimental Design

The review article from Mostafa *et al.* (2019) showed that the characteristics of produced pellets depend mainly on particle size, moisture content, pressure, and die temperature. Moisture content (25% to 35%), pressure (20 to 24 MPa), and residence time (50 to 70 s) were selected as the process factors for the compression of seedling-raising mat from the standpoint of engineering operation and energy consumption; and bending strength and dimensional stability of the formed substrate mat were tested as indicators. The effects of the factors on the compression indicators were investigated through a ternary quadratic-regression orthogonal-rotation combination experiment, and the compression process was determined by multi-index optimization method. According to the general rotation combination test method, $\gamma = 1.682$ was obtained. The factor level coding is shown in Table 3. The mean value is taken after 3 replications of each test.

Table 3. Factor Level Coding

Factors	Moisture Content X_1 (%)	Pressure X_2 (MPa)	Residence Time X_3 (s)
+γ	35	24	70
+1	33	23	66
0	30	22	60
-1	27	21	54
-γ	25	20	50

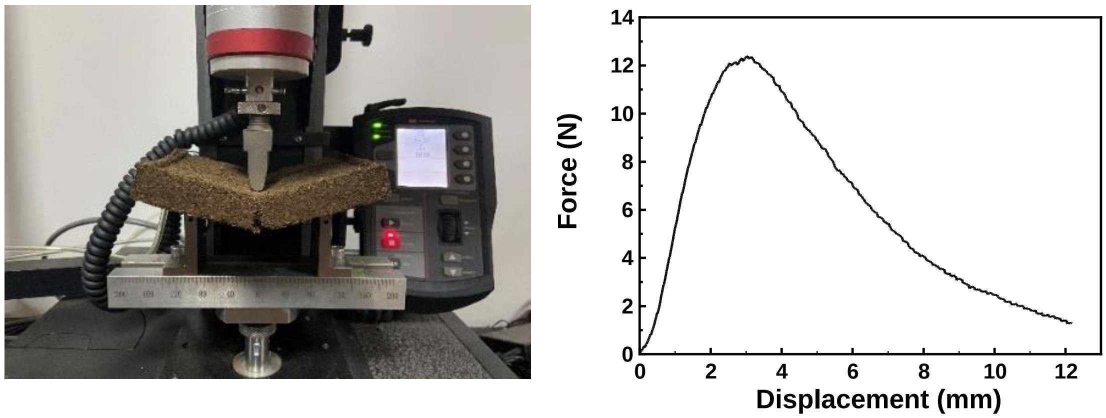
Evaluation Indices and their Measurement

Bending strength

The destructive strength is one of the important indexes that affects the transportation and subsequent storage and utilization of seedling-raising mats (Chen *et al.* 2016; Xin *et al*. 2017). In this study, the bending strength of the formed substrate mat was tested using a universal testing machine (3344R4161, Instron Corp., Canton, OH, USA). The mat was supported with two boards of 100 mm apart (as shown in Fig. 2a), and the loading speed was set at 100 mm/min downwards. The load was increased until the mat fractures completely, and then the loading head returned automatically. A computer as shown in Fig. 2b recorded the curve of loading-force and displacement. The peak of the curve was taken as the bending strength of the substrate mat.

$$P = \frac{F}{A} \tag{4}$$

where P is bending strength (MPa), F is bending force (N), and A is area of cross section of the mat (mm^2).



(a) (b)

Fig. 2. Bending strength testing: (a) Bending strength testing system; and (b) Force-displacement curve of bending strength testing.

Dimensional stability

Biomass is viscoelastic when compressed, and the formed seedling-raising mat may expand, which may affect the physical and mechanical properties, and its stability in storage, transportation, and applications (Chen *et al*. 2016; Xin *et al*. 2017). Therefore, dimensional stability was tested in this study. The thickness of the mat was measured and recorded immediately after compression, and it was measured and recorded again after 24 h. The dimensional stability of the mat can be obtained using Eq. 5,

$$R = 1 - \frac{h - h_0}{h_0} \times 100\% \tag{5}$$

where R is the dimensional stability (%), h is the thickness of the mat immediately after forming (mm), and h_0 is the thickness of the mat 24 h after being formed (mm).

RESULTS AND DISCUSSION

The experimental plan and results are shown in Table 4. The bending strength of the mat ranged from 2.50 to 4.60 kPa, and the dimensional stability ranged from 94.0% to 99.3%.

Effects of Factors on Bending Strength and Dimensional Stability

The variance analysis was carried out with Design-Expert software, and the results are shown in Table 5. It can be observed that the regression models of bending strength and dimensional stability were significant ($P < 0.05$), and the lack of fit was not significant ($P > 0.05$), indicating that the parameters and index in the model were closely correlated, and the models can be used to predict the bending strength and dimensional stability of the formed mat. All factors exhibited significant effects on the bending strength ($P < 0.01$), and the degree of influence was pressure > moisture content > residence time; the pressure and residence time had enormous significant effects on the dimensional stability ($P < 0.01$), and moisture content had a significant effect on the dimensional stability ($P < 0.05$), the influence degree was pressure > residence time > moisture content. The effects of interaction of factors on bending strength and dimensional stability were not significant ($P > 0.05$).

Table 4. Experimental Plan and Results

Level	Factor			Index	
	Moisture Content X_1 (%)	Pressure X_2 (MPa)	Residence Time X_3 (s)	Bending Strength Y_1 (kPa)	Dimensional Stability Y_2 (%)
1	-1	-1	-1	2.50	94.0
2	1	-1	-1	3.60	95.6
3	-1	1	-1	4.20	97.0
4	1	1	-1	4.22	96.7
5	-1	-1	1	3.50	95.0
6	1	-1	1	4.00	97.5
7	-1	1	1	4.30	98.7
8	1	1	1	4.60	99.3
9	-γ	0	0	3.20	95.8
10	γ	0	0	4.40	97.0
11	0	-γ	0	3.00	93.5
12	0	γ	0	4.60	96.5
13	0	0	-γ	2.80	94.0
14	0	0	γ	3.40	97.0
15	0	0	0	3.50	97.0
16	0	0	0	3.80	96.4
17	0	0	0	3.60	96.2
18	0	0	0	4.00	96.1
19	0	0	0	3.62	97.8
20	0	0	0	3.65	94.0
21	0	0	0	4.10	95.6
22	0	0	0	3.90	97.0
23	0	0	0	3.80	96.7

The regression model was set up based on the analysis of variance. Ignoring the insignificant items, the regression equations of bending strength and dimensional stability were obtained using Eqs. 6 and 7,

$$Y_1 = 3.77 + 0.29X_1 + 0.47X_2 + 0.21X_3 - 10.171{X_3}^2 \quad (6)$$

$$Y_2 = 96.59 + 0.47X_1 + 1.07X_2 + 0.9X_3 \quad (7)$$

where Y_1 is bending strength (kPa), Y_2 is dimensional stability (%), X_1 is moisture content (%), X_2 is compression pressure (MPa), X_3 is residence time (s), and ${X_3}^2$ is a quadratic term.

Table 5. Analysis of Variance

Source	Bending Strength		Dimensional Stability	
	P value	Significance	*P* value	Significance
Model	< 0.01	**	0.02	*
X_1	< 0.01	**	0.12	N
X_2	< 0.01	**	< 0.01	**
X_3	< 0.01	**	< 0.01	**
X_1X_2	0.09	N	0.21	N
X_1X_3	0.65	N	0.55	N
X_2X_3	0.21	N	0.64	N
X_1^2	0.25	N	0.32	N
X_2^2	0.25	N	0.39	N
X_3^2	0.01	**	0.84	N
Lack of fit	0.14	N	0.59	N

Note: *Represents significant (P < 0.01); **represents extremely significant (P < 0.05); N represent not significant (P > 0.05).

Regression Model, Parameter Optimization, and Verification

In Design-Expert software, considering the bending strength and dimensional stability as indices, the goal of the regression model was set at "Maximize" position. Then the optimal parameters for maximal bending strength, which is 4.52 kPa, at moisture content of 33%, pressure of 23.8 MPa, and residence time of 62.5 s was obtained. In addition, the optimal parameters for maximal dimensional stability, which is 98.64% was obtained at moisture content of 33%, pressure of 23.0 MPa, and residence time of 66 s.

Verification experiments for maximal bending strength were also carried out since the predicted maximal levels of factors for dimensional stability were included in the planed experiment (No. 8), and the values of the parameters were rounded for convenience of operation. The parameters were set respectively as moisture content of 33%, pressure of 24 MPa, and residence time of 63 s. The tests were repeated for 3 times and the average bending strength was obtained as 4.30 kPa. There were differences between the experimental values and the prediction values, indicating that there were errors of the prediction of the regression models, and the degree of discrepancy was calculated by Eq. 8 (Lu *et al*. 2014),

$$P_E = \frac{|Y_O - Y_P|}{Y_P} \times 100\% \tag{8}$$

where P_E is percentage of error, Y_P is the prediction of index, and Y_o is the experimental results of index.

The percentage errors of bending strength and dimensional stability under single index optimization were 4.87% and 0 respectively. The error was mainly caused by the differences in biomass compression characteristics.

In Design-Expert software, double index optimization was also conducted. For this purpose, again the goals of bending strength and dimensional stability were set at "Maximize", whereas both weights were at 0.5. The optimum process parameters obtained were as follows: Moisture content 33%, pressure 23.0 MPa, residence time 61.4 s, then the bending strength was 4.52 kPa and dimensional stability was 97.70%.

Considering the operability, the parameters were adjusted as moisture content of 33%, pressure of 23 MPa, and residence time of 61 s. The test was repeated for 3 times. And the experimental results were obtained as bending strength of 4.27 kPa and dimensional stability of 98.12%. Then the percentage of discrepancy was worked out with Eq. 5, giving values of 5.53% and 0.43%. These values were found to be within the reasonable range, and hence the model can be used to provide prediction of the compression.

CONCLUSIONS

1. The comprehensively optimized compression process parameters of substrate seedling-raising mat prepared from decomposed rice straw and rice husk biochar were moisture content of 33%, pressure of 23.8 MPa, and residence time of 60 s. Then the bending strength was 4.27 kPa and the dimensional stability was 98.1%. The error between the experimental and the predicted values was less than 6%, which is within a reasonable range, indicating that the optimal parameters achieved are practical.
2. All factors revealed extremely significant effects on the bending strength and dimensional stability values of the formed seedling raising mat ($P < 0.01$). Pressure and residence time had extremely significant effects on dimensional stability ($P < 0.01$). The moisture content also had a significant effect on dimensional stability ($P < 0.05$) and the effects of each interaction on bending strength and dimensional stability were not significant ($P > 0.05$).
3. The variance and regression analysis showed that the regression models of bending strength and dimensional stability were significant ($P < 0.05$), and the lack of fit was not significant ($P > 0.05$), specifying that the model parameter values and experimental values were in close correlation, and the model can be used to predict the bending strength and dimensional stability.

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