Analysis and Optimization of Process Parameters of the Degradable Fiber Mulch Paper Made from Pineapple Leaf and Rice Straw by Response Surface Method

Xianglan Ming,[a] Qichao Li,[a] Jinlong Feng,[a,]* and Wei Jiang [b]

To improve the utilization rate of pineapple leaf and crop straw, and provide technical support for making biodegradable fiber mulch paper through organic cultivation, the process and properties of the degradable fiber mulch paper made from pineapple leaf and rice straw were studied. The degradable fiber mulch paper was prepared as a hybrid composite in which pineapple leaf fiber and rice straw fiber were used as raw materials, and environmentally friendly agents were added. A four-factor five-level quadratic orthogonal rotation central composite design of the response surface method was employed. The beating degree of pineapple leaf fiber, basis weight, addition ratio of pineapple leaf fiber, and wet strength agent content were process parameters; dry tension strength, wet tension strength, and bursting strength were objective functions. The optimal technology parameters of pineapple leaf and rice straw fiber mulch paper were 70 to 90 g/m^2 basis weight of pineapple leaf fiber, 17% to 25% addition ratio of pineapple leaf fiber, 55 °SR beating degree, and 1.5% wet strength agent content. According to the tensile strength and bursting strength standards, the degradable fiber mulch paper made from pineapple leaf and rice straw was feasible. The results provide theoretical basis and technical support to use pineapple leaves and rice straw to make degradable mulch paper.

Keywords: Pineapple leaf; Rice straw; Fiber mulch paper; Response surface method; Mechanical strength

*Contact information: a: College of Mechanical and Electrical Engineering, Lingnan Normal University, Zhanjiang 524048, China; b: College of Information Engineering, Lingnan Normal University, Zhanjiang 524048, China; *Corresponding author: 792146915@qq.com*

INTRODUCTION

China has abundant straw resources, and the total output of various crop straw accounts for approximately 25% of the world's straw output (Zhu *et al.* 2012; Guo and Huang 2016). However, single utilization of crop straw and low utilization efficiency has long been a problem. As of 2018, the theoretical quantity of straw resources in China was 1.184 billion T, of which the collectable resources are approximately 736 million T, and the total amount of waste and incineration straw is approximately 237 million T. These high amounts have caused increasingly serious environmental pollution and social problems (Chen *et al.* 2015; Li *et al.* 2017). Chemical composition research has demonstrated that rice straw contains 31.51% cellulose, and it can be used to provide natural cellulose fiber (Ming *et al.* 2019a). Using rice straw as raw material to make plant fiber mulch paper can realize its high-value utilization and avoid environmental pollution—an ideal method of straw utilization. Compared with wood fiber, rice straw fiber has a high content of miscellaneous cells, a high ash content, short fiber length, and weak fiber strength. Therefore, the mechanical properties of pure rice straw fiber mulch paper are poor (Ming and Chen 2020). To improve the tensile strength of mulch paper, rice straw fiber mulch paper can be prepared by mixing with wood fiber (Han *et al.* 2011; Abdoulaye 2018). Using rice, corn, soybeans, and biogas residue fibers as raw materials, and conventional pulping and papermaking technology, biodegradable straw fiber mulch paper can be prepared by adding environmentally friendly functional addition agents (as shown in research led by Professor Haitao Chen of Northeast Agricultural University) (Chen *et al.* 2014, 2015, 2018). The results showed that the straw fiber mulch paper entirely degrades, and it meets the mechanical strength of field mulching (Yuan *et al.* 2011; Li *et al.* 2013a; Chen *et al.* 2014, 2018). Hunan Papermaking Research Institute and the Bast Fiber Research Institute of the Chinese Academy of Sciences developed environmentally friendly bast fiber mulch paper. Dalian Institute of Light Industry developed kenaf straw mulch paper (Wu *et al.* 2004). However, secondary pollution is produced in the preparation process of wood fiber, and the cost is relatively high (He and Wang 2015).

Pineapple leaf fiber is a natural plant fiber with good mechanical properties. In addition, it can be completely degraded. After extensive mechanical refining, its strength is greater than cotton fiber (Hazarika *et al.* 2017; Hamritha *et al.* 2020). Xu *et al.* studied the fiber morphology and chemical composition of pineapple leaves, and the results showed that pineapple leaves are a good long-fiber papermaking material (Xu *et al.* 1998). The average fiber length and the average fiber width of pineapple leaf fiber was found to be 2.6 to 2.9 mm and 5.7 to 6.9 μm. Pineapple leaf fiber is composed of many tightly combined fiber bundles, and each fiber bundle is composed of a collection of 10 to 20 single fiber cells. China is the world's largest pineapple producer, with the planting area of 70,000 hm^2 and the total annual discarded pineapple leaves of 10 million metric tons (Wang *et al.* 2011; Asim *et al.* 2018). In recent years, with the expanding pineapple processing industry, the resulting pineapple waste has gradually increased. Currently, the utilization of pineapple waste in China is still low, and some areas (such as Yunnan and Fujian) use none of it (Li *et al.* 2013b; Rahman *et al.* 2019; Zhu 2019). The efficient and reasonable development and utilization of pineapple waste will not only solve the problem of resource waste, but also contribute to solving the problem of environmental pollution, thereby increasing the economic benefits of the pineapple industry.

In this study, degradable fiber mulch paper was prepared using pineapple leaf fiber and rice straw fiber as raw materials. In addition, a wet strength agent and a neutral sizing agent were used to improve the mechanical properties of the degradable fiber mulch paper made from pineapple leaf and rice straw. This work sought to study the optimal technology parameters of the degradable fiber mulch paper made from pineapple leaf and rice straw. The response surface method (four-factor five-level quadratic orthogonal rotation central composite design) was applied to optimize the process parameters (beating degree of pineapple leaf fiber, basis weight, addition ratio of pineapple leaf fiber, and wet strength agent content) that affect dry tensile strength, wet tensile strength, and bursting strength.

EXPERIMENTAL

Materials

Rice straw fiber produced by a D-200 straw fiber extruder (Northeast Agriculture University, Harbin, China) in the fall of 2019 was used as one of the raw materials (the average aspect ratio was in the range of 11.4 to 43.2, with the smallest component smaller than 1 mm and the largest component larger than 5 mm) (Ming *et al.* 2019b). Pineapple leaf fiber, made by manually scraping, cleaning, and drying pineapple leaves (Chenjia Pineapple Processing Factory, Zhanjiang, China) in the spring of 2019, was used as another of the raw materials to maintain the mechanical strength (the average fiber length was 2.6 to 2.9 mm, and the average fiber width was 5.7 to 6.9 μm) (Biswas and Nishat 2019). The wet strength agent used for tensile strength improvement (polyamide polyamine epichlorohydrin resin) was purchased from Xinghuo Chemical Plant (Mudanjiang, China). The neutral sizing agent used for hydrophobicity enhancement (alkyl ketene dimer, supplied as an emulsion of positively charged particles stabilized by a cationic polymer) was purchased from Jinhao Chemical Plant (Qingzhou, China) (Shi and He 2003). All the chemicals were of laboratory level, and triple distilled water was used for all solutions.

Preparation of Fiber Mulch Paper

The beating of pineapple leaf pulp is different from beating ordinary grass materials. The pulp beating requires a large weight at the beginning of the process to cut the fibers into short lengths and then cause fiber cell wall fibrillation. Pineapple leaf fiber was beaten to form pulps with designated beating degree. Rice straw fiber was beaten to form pulps with 40 °SR beating degree following Chinese Standard QB/T 24325 (2009). The wet strength agent and the neutral sizing agent were added to the pulp and homogeneously mixed (neutral sizing agent content of 0.7%). The mulch paper samples were prepared following Chinese Standard QB/T 24324 (2009) and were dried using a paper dryer at an applied pressure of 96 kPa, temperature about 97 °C, and drying time 5 to 7 min. Drying mulch paper samples were conditioned at room temperature (23 ± 1 °C) and 50% ± 2% relative humidity for at least 24 h before testing. The mechanical properties were tested according to Chinese Standards GB/T 12914 (2008), GB/T 465.2 (2008), and GB/T 454 (2002).

Experimental Design

The preliminary experiments were conducted according to a single factorial method to identify the major process parameters affecting the performance of the fiber mulch paper as beating degree (°SR), basis weight (g/m^2), addition ratio of pineapple leaf fiber (%), and wet strength agent content (%). The following beating degree all refers to the beating degree of pineapple leaf fiber.

The four-factor five-level quadratic orthogonal rotation central composite design of the response surface method was applied to study the effects and interactions of beating degree, basis weight, addition ratio of pineapple leaf fiber, wet strength agent content on dry tensile strength, wet tensile strength, and bursting strength of the mulch paper made from pineapple leaf fiber and rice straw fiber. Table 1 shows the five levels of beating degree (40 to 80 °SR), basis weight (50 to 90 g/m^2), addition ratio of pineapple leaf fiber (5% to 25%), and wet strength agent content (1.0% to 1.8%).

Table 1. Parameters Level Code

Level	Parameters			
	Beating Degree x_1 (°SR)	Basis Weight x_2 (g/m^2)	Addition Ratio of Pineapple Leaf Fiber x_3 (%)	Wet Strength Agent Content x_4 (%)
-2	40	50	5	1.0
-1	50	60	10	1.2
0	60	70	15	1.4
1	70	80	20	1.6
2	80	90	25	1.8

Equation 1 is a fitted empirical quadratic polynomial equation as shown:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 \quad (1)$$

where y represents the response variable, β_0 the intercept; β_1, β_2, β_3, and β_4 are the coefficients of the independent variables; β_{11}, β_{22}, β_{33}, and β_{44} are the quadratic coefficients; β_{12}, β_{13}, β_{14}, β_{23}, β_{24}, and β_{34} are the interaction coefficients; and x_1, x_2, x_3, and x_4 are the independent variables. Multivariate regression models, response surface analysis, and optimum analysis were performed using Design Expert software version 6.0.10.0 (Stat Ease Inc., Minneapolis, MN, USA).

Table 2. Experimental Design and Results

No.	Beating Degree x_1 (°SR)	Basis Weight x_2 (g/m^2)	Addition Ratio of Pineapple Leaf Fiber x_3 (%)	Wet Strength Agent Content x_4 (%)	Dry Tensile Strength y_1 (N)	Wet Tensile Strength y_2 (N)	Bursting Strength y_3 (kPa)
1	-1	-1	-1	-1	12.3	3.7	79
2	1	-1	-1	-1	16.8	5.7	87
3	-1	1	-1	-1	16.2	5.9	91
4	1	1	-1	-1	21.1	8.9	102
5	-1	-1	1	-1	17.3	6.1	89
6	1	-1	1	-1	18.1	7.2	93
7	-1	1	1	-1	25.7	9.4	92
8	1	1	1	-1	24.3	8.7	113
9	-1	-1	-1	1	14.4	4.2	77
10	1	-1	-1	1	19.2	8.1	84
11	-1	1	-1	1	18.7	7.5	91
12	1	1	-1	1	19.9	10.9	115
13	-1	-1	1	1	22.2	9.2	96
14	1	-1	1	1	25.6	11.7	121
15	-1	1	1	1	37.9	14.5	143
16	1	1	1	1	30.3	12.9	127
17	-2	0	0	0	14.7	4.4	86
18	2	0	0	0	21.5	6.1	92
19	0	-2	0	0	13.1	4.1	97
20	0	2	0	0	27.2	11.7	122
21	0	0	-2	0	12.7	3.9	81
22	0	0	2	0	28.1	12.2	119
23	0	0	0	-2	13.2	4.3	70
24	0	0	0	2	23.2	9.9	109
25	0	0	0	0	19.7	8.7	89
26	0	0	0	0	20.3	8.9	94
27	0	0	0	0	21.1	9.3	92
28	0	0	0	0	18.8	8.1	83
29	0	0	0	0	19.3	8.6	99
30	0	0	0	0	20.1	8.8	104
31	0	0	0	0	23.7	10.1	112
32	0	0	0	0	21.1	9.1	91
33	0	0	0	0	24.2	11.7	97
34	0	0	0	0	19.9	8.8	121
35	0	0	0	0	23.3	10.7	111
36	0	0	0	0	20.8	7.9	107

A value of $P < 0.05$ was considered statistically significant. Interactive effects of process parameters were found by 3D-response surface analysis of the process parameters and the objective function (Bezerra *et al.* 2008; Montgomery 2017; Matias-Guiu *et al.* 2018). The 36 experiments, the values of dry tensile strength, wet tensile strength, and bursting strength at each experimental designed condition are shown in Table 2.

RESULTS AND DISCUSSION

Chemical Composition

Table 3 shows the chemical composition characteristics of rice straw fiber and pineapple leaf fiber.

Table 3. Comparing the Composition of Two Kinds of Fibers

Compositions	Rice Straw	Pineapple Leaf
Mass Fractions of Cellulose (%)	31.5	60.7
Mass Fractions of Hemicellulose (%)	25.3	21.5
Mass Fractions of Lignin (%)	15.4	7.0
Mass Fractions of Pectin (%)	1.4	2.4
Mass Fractions of Wax (%)	4.1	6.5
Mass Fractions of Hydrotrope (%)	22.4	1.8
Mass Fractions of Ash Content (%)	11.2	1.9

Regression Models

A four-factor five-level quadratic orthogonal rotation central composite design of the response surface method was adopted to optimize the manufacturing process parameters of the degradable fiber mulch paper made from pineapple leaf and rice straw.

Table 4. Parameters Level Code

Source		Sum of Squares	DF	Mean Square	F Value	P Value	Critical Value
Dry Tensile Strength (N)	Model	875.64	8	109.46	F_2 = 29.08	< 0.0001	$F_{0.05}(8,27)$ = 2.31
	Residual	101.62	27	3.76			
	Lack of fit	66.82	16	4.18	F_1 = 1.32	0.3255	$F_{0.05}(16,11)$=2.706
	Pure Error	34.80	11	3.16			
	Total	977.26	35				
Wet Tensile Strength (N)	Model	226.84	7	32.41	F_2 = 24.89	< 0.0001	$F_{0.05}(7,28)$ = 2.36
	Residual	36.46	28	1.30			
	Lack of fit	23.22	17	1.37	F_1 = 1.13	0.4262	$F_{0.05}(17,11)$ = 2.692
	Pure Error	13.24	11	1.20			
	Total	263.30	35				
Bursting Strength (kPa)	Model	5549.67	4	1387.42	F_2 = 12.34	< 0.0001	$F_{0.05}(4,31)$ = 2.682
	Residual	3486.33	31	112.46			
	Lack of fit	2114.33	20	105.72	F_1 = 0.85	0.6408	$F_{0.05}(20,11)$ = 2.65
	Pure Error	1372.00	11	124.73			
	Total	9036.00	35				

The regression analysis was carried out to build an empirical relationship between process parameters and objective function. The regression model results indicated the best models were the 2FI model for dry tensile strength, the quadratic model for wet tensile strength, and the linear model for bursting strength. Table 4 shows the variance analysis of the regression models.

The model P values were all less than 0.0001, showing that the models were highly significant, and there was only 0.01% chance of occurrence of the model F-value due to noise. The *lack of fit* was not significant, with P values greater than 0.05 for all three models. $F_{0.05}$ means the F-distribution of upper 0.05 points. The F-distribution is dependent on the F-ratio of the DF of the variance in the numerator and the DF of the variance in the denominator. The model F-value (F_2) was larger than $F_{0.05}$, showing that the regression equation was extremely significant. The *lack of fit* F-value (F_1) was less than $F_{0.05}$, showing that the model fits well.

The three regression equations are expressed by Eqs. 2 through 4:

$$y_1 = 20.72 + 1.01x_1 + 3.18x_2 + 3.90x_3 + 2.35x_4 - 1.03x_1x_2 - 1.26x_1x_3 + 1.36x_2x_3 + 1.55x_3x_4 \quad (2)$$

$$y_2 = 8.90 + 0.71x_1 + 1.58x_2 + 1.72x_3 + 1.44x_4 - 0.77x_1^2 - 0.69x_1x_3 + 0.65x_3x_4 \quad (3)$$

$$y_3 = 99.33 + 4.00x_1 + 8.25x_2 + 9.33x_3 + 7.75x_4 \quad (4)$$

where y_1, y_2, and y_3 are dry and wet tensile strengths (N) and bursting strength (kPa), respectively; x_1, x_2, x_3, and x_4 are beating degree (°SR), basis weight (g/m^2), addition ratio of pineapple leaf fiber (%), and wet strength agent content (%), respectively.

For the regression equation established by the test data, the equation coefficients can be used to judge the degree that the process parameters effect objective function, referring to Xu's calculation method of the importance of each parameter in multiple quadratic regression (Xu 1998). The contribution rate of each parameter to each objective function is shown in Table 5.

Table 5. Importance of the Parameters Effecting Objective Function

Source	Dry Tensile Strength y_1 (N)	Wet Tensile Strength y_2 (N)	Bursting Strength y_3 (kPa)
Beating Degree x_1 (°SR)	1.66	2.24	0.71
Basis Weight x_2 (g/m^2)	1.81	0.98	0.93
Addition Ratio of Pineapple Leaf Fiber x_3 (%)	2.30	1.80	0.95
Wet Strength Agent Content x_4 (%)	1.42	1.38	0.92

The results showed the rank of contribution rate of the four process parameters on dry tensile strength was, from highest to lowest: addition ratio of pineapple leaf fiber, basis weight, beating degree, and wet strength agent content. The rank of the contribution rate of the four process parameters on wet tensile strength was, from highest to lowest: beating degree, addition ratio of pineapple leaf fiber, wet strength agent content, and basis weight. The rank of contribution rate of four process parameters on bursting strength, from highest to lowest, was: addition ratio of pineapple leaf fiber, basis weight, wet strength agent content, and beating degree.

Response Surface Analysis

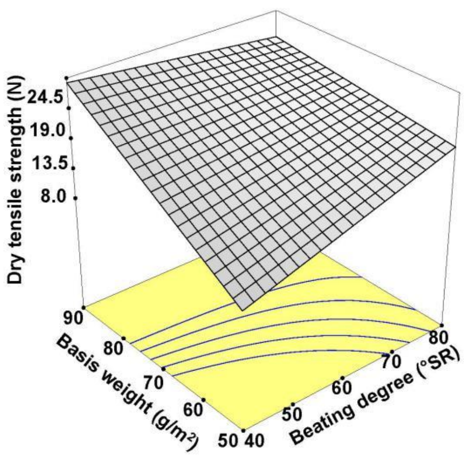
Interactive effects of four parameters on dry tensile strength

Figure 1a displays the 3D response surface graph showing the interactive effect of the beating degree and basis weight on the dry tensile strength of the mulch paper with the other variables remaining constant (15% addition ratio of pineapple leaf fiber and 1.4% wet strength agent content). As shown, the dry tensile strength increased as the basis weight increased; however, the increase was not obvious at high beating degree. This phenomenon may have occurred because the dry tensile strength of the mulch paper was proportional to the number of fibers per unit area of the sample. As the basis weight increased, its increased effect on the mulch paper's fiber number enhanced the bonding ability between the fibers and resulted in increasing dry tensile strength. However, the excessive beating degree shortened the fiber and weakened the strength of a single fiber; thus, the dry tensile strength decreased (Ikeda and Bao 1978; Ming *et al.* 2019c). With this decrease, the positive effect of the basis weight on the dry tensile strength was greater than the negative effect of the beating degree. Figure 1a also shows that the interactive effect of beating degree and basis weight had significant effect on dry tensile strength based on Eq. 2. The highest value of dry tensile strength was reached at 40 °SR beating degree and 90 g/m^2 basis weight.

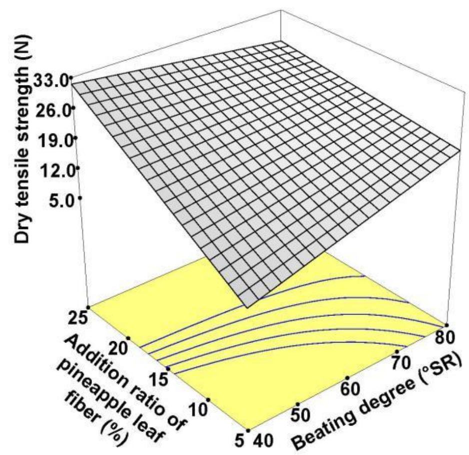
The 3D response surface graph demonstrating the interactive effect of the beating degree and addition ratio of pineapple leaf fiber on the mulch paper's dry tensile strength with other variables remaining constant (70 g/m^2 basis weight and 1.4% wet strength agent content) is represented in Fig. 1b. The dry tensile strength increased as the addition ratio of pineapple leaf fiber increased. This increase was mainly because pineapple leaf fiber was being used as long fiber to maintain the mechanical strength of the mulch paper. The strength of the pineapple leaf fiber is higher than cotton fiber. The increased number of pineapple leaf fibers enhanced the dry tensile strength. However, the increase was not obvious at high beating degree, probably because the excessive beating degree shortened the fiber and weakened the strength of the single fiber, thus decreasing the dry tensile strength (Chen *et al.* 2004; Ozaki *et al.* 2006). In this situation, the positive effect of pineapple leaf fiber's addition ratio on dry tensile strength was greater than the negative effect of the beating degree. Figure 1b also shows the interactive effect between the beating degree and addition ratio of pineapple leaf fiber also had significant effect on dry tensile strength based on Eq. 2. The maximum dry tensile strength appeared in pineapple leaf fiber at 40 °SR beating degree and 25% addition ratio.

The 3D response surface graph indicating the interactive effect between basis weight and pineapple leaf fiber's addition ratio on the mulch paper's dry tensile strength while keeping other parameters constant (60 °SR beating degree and 1.4% wet strength agent content) is shown in Fig. 1c. It was observed that the dry tensile strength increased as both the basis weight and the addition ratio of pineapple leaf fiber improved, especially with a high basis weight and large addition ratio of pineapple leaf fiber. This improvement occurred mainly because the number increase of the fiber and the pineapple leaf fiber of mulch paper enhanced the bonding ability between the fibers, thus improving dry tensile strength. The effect of the pineapple leaf fiber's addition ratio on dry tensile strength was stronger than that of basis weight based on the contribution rate analysis. The interactive effect between the basis weight and addition ratio of pineapple leaf fiber had significant effect on dry tensile strength based on Eq. 2. Figure 1c clearly shows the mulch paper had maximum dry tensile strength values when the highest basis weight (90 g/m^2) and highest addition ratio of pineapple leaf fiber (25%) were used.

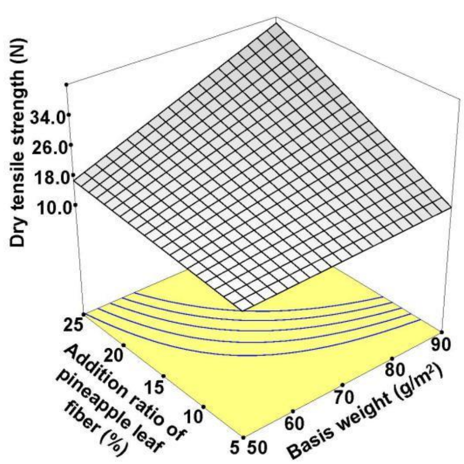
Figure 1d shows the 3D response surface graph illustrating the interactive effect of pineapple leaf fiber's addition ratio and wet strength agent content on the mulch paper's dry tensile strength while other parameters remained constant (60 °SR beating degree and 70 g/m^2 basis weight). At low wet strength agent content and pineapple leaf fiber's addition ratio, the dry tensile strength had small improvement as the addition ratio of pineapple leaf fiber and wet strength agent content increased. However, at high wet strength agent content and addition ratio of pineapple leaf fiber, the dry tensile strength increased obviously as addition ratio of pineapple leaf fiber and wet strength agent content improved. This finding is probably attributable to the strong cross-links formed by cationic wet strength agent and anionic fibers that strengthened the fiber network, thus improving dry tensile strength (Xu *et al.* 2006).



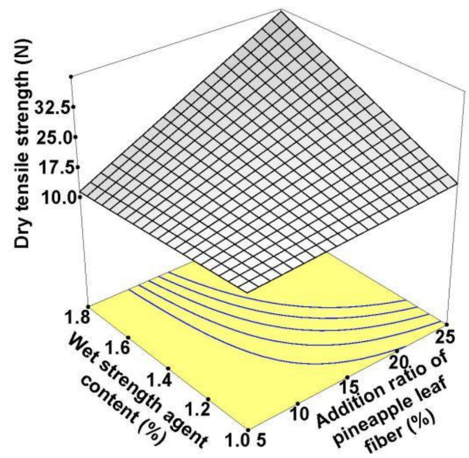
(a) Beating degree and basis weight



(b) Beating degree and addition ratio of pineapple leaf fiber



(c) Basis weight and addition ratio of pineapple leaf fiber



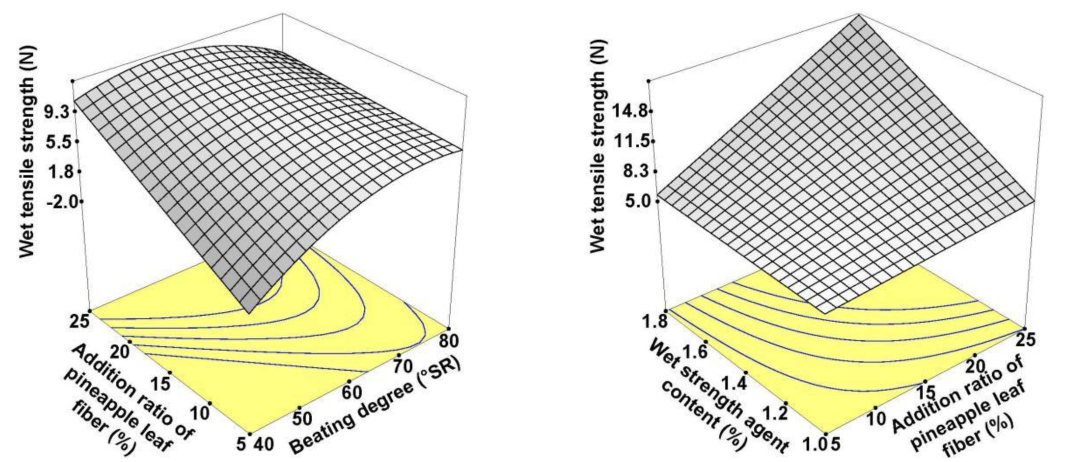
(d) Addition ratio of pineapple leaf fiber and wet strength agent content

Fig. 1. Interactive effects of four parameters on dry tensile strength: (a) Beating degree and basis weight, (b) Beating degree and addition ratio of pineapple leaf fiber, (c) Basis weight and addition ratio of pineapple leaf fiber, (d) Addition ratio of pineapple leaf fiber and wet strength agent content

According to Fig. 1d, the effect of the addition ratio of pineapple leaf fiber on the dry tensile strength was greater than that of the wet strength agent content based on the contribution rate analysis. The interactive effect of the addition ratio of pineapple leaf fiber and the wet strength agent content was significant on dry tensile strength, based on Eq. 2. The highest dry tensile strength appeared at 25% addition ratio of pineapple leaf fiber and 1.8% wet strength agent content.

Interactive effects of four parameters on wet tensile strength

Figure 2a illustrates the interactive effect of pineapple leaf fiber's beating degree and addition ratio on the wet tensile strength of the mulch paper with other parameters remaining constant (70 g/m^2 basis weight and 1.4% wet strength agent content). The wet tensile strength increased as beating degree increased at a low addition ratio of pineapple leaf fiber. However, at a high addition ratio of pineapple leaf fiber, wet tensile strength improved initially when beating degree increased from 40 to 55 °SR, and then it decreased slightly when beating degree increased from 55 to 80 °SR. These results may have occurred because of the following reasons. As the beating degree increased, the fibrillation of fiber became higher, which increased the exposure of hydrogen bonds on the fiber's surface, increased the bonding ability between the fibers, and increased the wet tensile strength of the mulch paper (Müller *et al.* 2009; Ismail *et al.* 2011). However, the continuous increase of beating degree gradually weakened the strength of a single fiber, resulting in the decrease of wet tensile strength. The effect of the beating degree on the wet tensile strength was greater than the effect of the addition ratio based on the contribution rate analysis. As is shown in Fig. 2a, the interactive effect between the beating degree and addition ratio of pineapple leaf fiber was significant on wet tensile strength based on Eq. 3. The highest value of wet tensile strength was achieved at 55 °SR beating degree and 25% addition ratio of pineapple leaf fiber.



(a) Beating degree and addition ratio of pineapple leaf fiber

(b) Addition ratio of pineapple leaf fiber and wet strength agent content

Fig. 2. Interactive effects of four parameters on wet tensile strength: (a) Beating degree and addition ratio of pineapple leaf fiber, (b) Addition ratio of pineapple leaf fiber and wet strength agent content

Figure 2b presents the interactive effect between the addition ratio of pineapple leaf fiber and the wet strength agent content on the mulch paper's wet tensile strength while other variables remained constant (60 °SR beating degree and 70 g/m^2 basis weight). It was easily observed that the wet tensile strength increased as both the addition ratio of pineapple leaf fiber and wet strength agent content improved, especially at a high addition ratio of pineapple leaf fiber and wet strength agent content (Reddy and Yang 2007; Ma *et al*. 2010). The effect of the pineapple leaf fiber's addition ratio on wet tensile strength was greater than that of the wet strength agent content based on the contribution rate analysis, which is confirmed by the image shown in Fig. 2b. The interactive effect between pineapple leaf fiber's addition ratio and wet strength agent content was also significant on wet tensile strength based on Eq. 3. The highest wet tensile strength was achieved at the highest addition ratio of pineapple leaf fiber (25%) and the highest wet strength agent content (1.8%).

Effects of four parameters on bursting strength

The regression model shows a linear relationship between the bursting strength and processing factors (Eq. 4). Figure 3 presents the detailed effect of those processing factors on the bursting strength. Bursting strength was positively correlated with basis weight (Fig. 3b), addition ratio of pineapple leaf fiber (Fig. 3c), and wet strength agent content (Fig. 3d), but negatively correlated with beating degree (Fig. 3a).

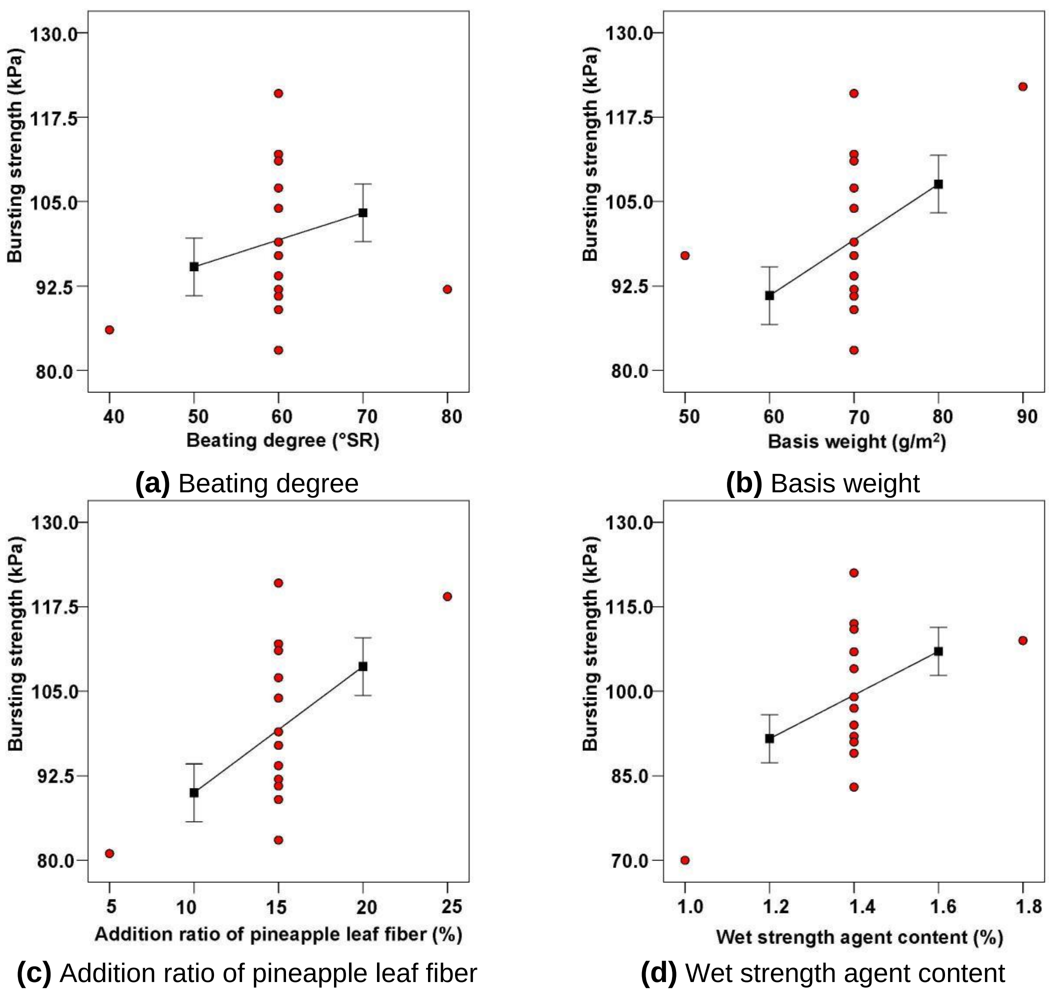


Fig. 3. Effects of four parameters on bursting strength: (a) Beating degree, (b) Basis weight, (c) Addition ratio of pineapple leaf fiber, (d) Wet strength agent content

It is clearly seen in Fig. 3c that the addition ratio of pineapple leaf fiber was the most influential process parameter on bursting strength. Bursting strength refers to the uniformly increased maximum pressure that paper or cardboard can withstand per unit area. Bursting strength is mainly determined by the fiber of paper or cardboard, and is related to fiber length and the bonding ability between fibers. The increase in fiber length and the bonding ability between fibers increase bursting strength (Mavruz and Ogulata 2010). In the present study, the increase in the number of pineapple leaf fibers enhanced the bonding ability between the fibers, and resulted in increased bursting strength.

Optimum Analysis

The pineapple leaf and rice straw fiber mulch paper that yielded desired results (dry and wet tensile strengths larger than 32 N and 12 N, respectively, and bursting strength larger than 120 kPa) was obtained by the optimization of processing conditions. Based on the design model, economy, ecological balance, and possibility of subsequent treatment, graphic optimum analysis was carried out with Design Expert software. The optimum conditions were 70 to 90 g/m^2 basis weight, 17% to 25% addition ratio of pineapple leaf fiber, 55 °SR beating degree, and 1.5% wet strength agent content (Fig. 4). At the optimum conditions, dry and wet tensile strengths were larger than 32 N and 12 N, respectively, and bursting strength was larger than 120 kPa.

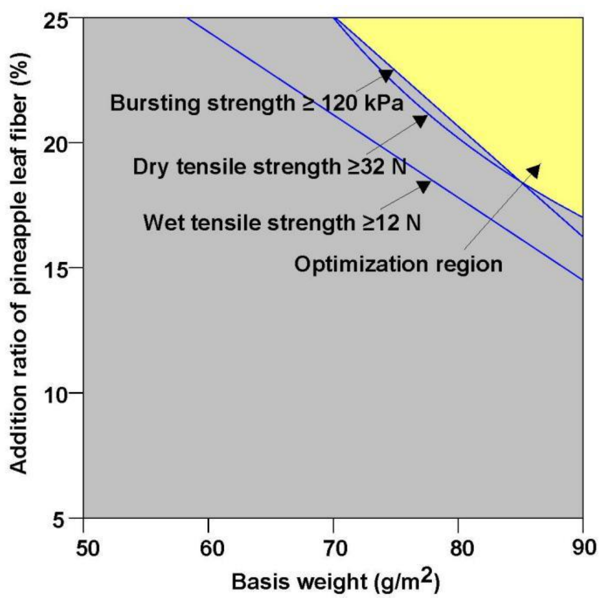


Fig. 4. Optimum analysis of process parameters (note: 55 °SR beating degree and 1.5% wet strength agent content)

Verification Test

The optimum conditions were validated by manufacturing the mulch paper at 85 g/m^2 basis weight, 20% addition ratio of pineapple leaf fiber, 55 °SR beating degree, and 1.5% wet strength agent content. The dry tensile strength, wet tensile strength, and bursting strength obtained from the 10 parallel verification tests were 34.6 N, 13.9 N, and 123 kPa, respectively, which highly agreed with the desired results (dry and wet tensile strengths higher than 32 N and 12 N, and bursting strength larger than 120 kPa). Meanwhile, according to Chinese Standard GB/T 5405 (2002), the sizing value of the mulch paper was

107 s. Hence, the optimum conditions obtained from the method of four-factor five-level quadratic orthogonal rotation central composite design were reliable and applicable.

CONCLUSIONS

1. The rank of contribution rate of the four process parameters on dry tensile strength, in descending importance, were: addition ratio of pineapple leaf fiber, basis weight, beating degree, and wet strength agent content; on wet tensile strength: beating degree, addition ratio of pineapple leaf fiber, wet strength agent content, and basis weight; on bursting strength: addition ratio of pineapple leaf fiber, basis weight, wet strength agent content, and beating degree.
2. The process parameters were optimized using the four-factor five-level quadratic orthogonal rotation central composite design of the response surface method. The optimum conditions were 70 to 90 g/m^2 basis weight, 17% to 25% addition ratio of pineapple leaf fiber, 55 °SR beating degree, and 1.5% wet strength agent content. Under the optimum conditions, the high dry tension strength (34.6 N), high wet tension strength (13.9 N), and high bursting strength (123 kPa) were achieved.
3. It was concluded from the current work that the degradable fiber mulch paper made from pineapple leaf and rice straw would be feasible.

ACKNOWLEDGMENTS

The authors thank Chenjia Pineapple Processing Factory in Guangdong for providing the pineapple leaves and their valuable support in processing the pineapple leaves.

REFERENCES CITED

Abdoulaye, A. (2018). *Chemical Composition, Mechanical Properties and Near Infrared Spectroscopy Characterization of Rice Straw*, Ph.D. Dissertation, China Agricultural University, Beijing, China.

Asim, M., Jawaid, M., Abdan, K., Ishak, M., and Alothman, O. (2018). "Effect of hybridization on the mechanical properties of pineapple leaf fiber/kenaf phenolic hybrid composites," *Journal of Renewable Materials* 6(1), 38-46. DOI: 10.7569/JRM.2017.634148

Bezerra, M. A., Santelli, R. E., Oliveira, E. P., Villar, L. S., and Escaleira, L. A. (2008). "Response surface methodology (RSM) as a tool for optimization in analytical chemistry," *Talanta* 76(5), 965-977. DOI: 10.1016/j.talanta.2008.05.019

Biswas, P., and Nishat, S. A. (2019). "Production and export possibility of canned pineapple and pineapple leaf fiber in Bangladesh," *IOSR Journal of Business and Management* 21(9), 17-23. DOI: 10.9790/487X-2109041723

Chen, B., Tatsumi, D., and Matsumoto, T. (2004). "Sedimentation method to evaluate PFI mill beating degree of wood pulp fibers," *Sen'i Gakkaishi* 60(4), 112-117. DOI: 10.2115/fiber.60.112

Chen, H. R., Chen, H. T., Liu, S., Dun, G. Q., and Zhang, Y. (2014). "Effect of plasticizers on properties of rice straw fiber film," *Journal of Northeast Agricultural University (English Edition)* 21(4), 67-72. DOI: 10.1016/S1006-8104(15)30022-2

Chen, H. T., Ming, X. L., Liu, S., Zhang, Y., and Zhang, H. C. (2015). "Optimization of technical parameters for making mulch from waste cotton and rice straw fiber," *Transactions of the Chinese Society of Agricultural Engineering* 31(13), 292-300. DOI: 10.11975/j.issn.1002-6819.2015.13.041

Chen, H. T., Zhu, X. X., and Liu, S. (2018). "Optimization of technical parameters for rice straw fiber-based mulch," *Transactions of the Chinese Society of Agricultural* 34(7), 271-279. DOI: 10.11975/j.issn.1002-6819.2018.07.035

GB/T 454 (2002). "Paper – Determination of bursting strength," Standardization Administration of China, Beijing, China.

GB/T 465.2 (2008). "Paper and board – Determination of tensile strength after immersion in water," Standardization Administration of China, Beijing, China.

GB/T 12914 (2008). "Paper and board – Determination of tensile properties," Standardization Administration of China, Beijing, China.

GB/T 5405 (2002). "Paper – Determination of the sizing value (Liquid permeance method)," Standardization Administration of China, Beijing, China.

Guo, D. S., and Huang, C. H. (2016). "Spatial and temporal distribution of crop straw resources in past 10 years in China and its use pattern," *Southwest China Journal of Agricultural Sciences* 29(4), 948-954. DOI: 10.16213/j.cnki. Scjas.2016.04.039

Hamritha, S., Hemanth, M., and Rajesh, B. (2020). "Characterization of mechanical behavior of pineapple leaf fiber composite," *IOP Conference Series: Materials Science and Engineering* 872, Article ID 012172. DOI: 10.1088/1757-899X/872/1/012172

Han, Y. J., Chen, H. T., Liu, L. X., and Li, H. (2011). "Optimization of technical parameters for making mulch from rice straw fiber," *Transactions of the Chinese Society of Agricultural Engineering* 27, 242-247. DOI: 10.3969/j.issn.1002-6819.2011.03.046

Hazarika, P., Hazarika, D., Kalita, B., Gogoi, N., Jose, S., and Basu, G. (2017). "Development of apparels from silk waste and pineapple leaf fiber," *Journal of Natural Fibers* 15(3), 416-424. DOI: 10.1080/15440478.2017.1333071

He, X., and Wang, D. (2015). "Tensile property of corn stalk rind based on analysis of fiber morphology," *Transactions of the Chinese Society of Agricultural Engineering* 31(10), 92-98. DOI: 10.11975/j.issn.1002-6819.2015.10.013

Ikeda, M., and Bao, L. Q. (1978). "Effects of mulching with black plastic film and rice straw on moisture and temperature in soil in Mekon delta," *Japanese Journal of Tropical Agriculture* 21(2), 77-81. DOI: 10.11248/jsta1957.21.77

Ismail, M. R., Yassen, A. A. M., and Afify, M. S. (2011). "Mechanical properties of rice straw fiber-reinforced polymer composites," *Fibers & Polymers* 12, Article Number 648. DOI: 10.1007/s12221-011-0648-5

Li, H., Wang, C., Sun, H., Yan, X., and Liang, Q. (2017). "Comprehensive utilization and sustainable development of agriculture straw," *Journal of Agricultural Mechanization Research* 39, 256-262. DOI: 10.13427/j.cnki.njyi.2017.08.054

Li, L., Ji, W., Chen, H., and Zhou, C. (2013a). "Technology optimization for manufacturing biodegradable mulch using soybean straw fiber," *Transactions of the Chinese Society of Agricultural Engineering* 29, 220-226. DOI: 10.3969/j.issn.1002-6819.2013.14.028

Li, M., Wang, D., and Zhou, H. (2013b). "Recent advances in feeding utilization of agricultural waste," *Chinese Journal of Tropical Agriculture* 33(10), 62-64.

Ma, H., Zheng, C., and Li, Y. (2010). "Preparation and characterization of cellulose/chitosan composite film," *Journal of Cellulose Science and Technology* 2(18), 33-37. DOI: 10.16561/j.cnki.xws.2010.02.004

Matias-Guiu, P., Rodríguez-Bencomo, J. J., Pérez-Correa, J. R., and López, F. (2018). "Aroma profile design of wine spirits: Multi-objective optimization using response surface methodology," *Food Chemistry* 245, 1087-1097. DOI: 10.1016/j.foodchem.2017.11.062

Mavruz, S., and Ogulata, R. (2010). "Taguchi approach for the optimization of the bursting strength of knitted fabrics," *Fibres and Textiles in Eastern Europe* 18(2), 78-83. DOI: 10.1007/s12221-010-0321-4

Ming, X. L., and Chen, H. T. (2020). "Experiment on cultivation performance of plant fiber-based degradable film in paddy field," *Applied Sciences* 10(2), Article Number 495. DOI: 10.3390/app10020495

Ming, X. L., Chen, H. T., and Ju, D. M. (2019a). "Performance and environmental impact of rice straw fiber mulching films manufactured with a warming agent," *Transactions of the ASABE* 62(2), 315-320. DOI: 10.13031/trans.13094

Ming, X. L., Chen, H. T., and Wei, Z. P. (2019b). "Optimization of technical parameters for making light-basis-weight and environment-friendly rice straw fiber film," *Transactions of the Chinese Society of Agricultural Engineering* 35(19), 259-266. DOI: 10.11975/j.issn.1002-6819.2019.19.032

Ming, X. L., Chen, H. T., Han, Y. J., and Wang, D. H. (2019c). "Optimization of technical parameters for making temperature-increasing film from titanium dioxide and rice straw fiber," *AIP Advances* 9(2), Article ID 025033. DOI: 10.1063/1.5085031

Montgomery, D. C. (2017). *Design and Analysis of Experiments*, Wiley, Hoboken, NJ, USA, pp. 121-135.

Müller, C. M. O., Laurindo, J. B., and Yamashita, F. (2009). "Effect of cellulose fibers addition on the mechanical properties and water vapor barrier of starch-based films," *Food Hydrocolloids* 23(5), 1328-1333. DOI: 10.1016/j.foodhyd.2008.09.002

Ozaki, Y., Bousfield, D., and Shaler, S. (2006). "The characterization of polyamide epichlorohydrin resin in paper—Relationship between beating degree of pulp and wet strength," *Appita Journal* 59(4), 326-329. DOI: 10.1007/s00226-006-0077-6

QB/T 24324 (2009). "Pulps – Preparation of laboratory sheets – Conventional sheet-former method," Standardization Administration of China, Beijing, China.

QB/T 24325 (2009). "Pulps – laboratory beating. Valley beater method," Standardization Administration of China, Beijing, China

Rahman, H., Alimuzzaman, S., Sayeed, M. M. A., and Khan, R. A. (2019). "Effect of gamma radiation on mechanical properties of pineapple leaf fiber (PALF)-reinforced low-density polyethylene (LDPE) composites," *International Journal of Plastics Technology* 23, 229-238. DOI: 10.1007/s12588-019-09253-4

Reddy, N., and Yang, Y. (2007). "Preparation and characterization of long natural cellulose fibers from wheat straw," *Journal of Agricultural & Food Chemistry* 55(21), 8570-8575. DOI: 10.1021/jf071470g

Shi, S. L., and He, F. W. (2003). *Analysis and Detection of Pulping and Papermaking*, Chinese Light Industry Press, Beijing, China.

Wang, G., Li, M., Wang, J., Deng, Y., Sun, W., Zheng, Y., and Jiao, J. (2011). "Present

situation and analysis on utilization of tropical agricultural wastes resources—Complex use of pineapple wastes," *Guangdong Agricultural Sciences* 38(1), 23-26.
Wu, X. E., Zhou, J. H., and Wang, J. (2004). "Chitosan: Wet strength agent of kenaf based paper mulch," *Transactions of China Pulp and Paper* 19(2), 92-95. DOI: 1000-6842(2004) 02-0092-04
Xu, G. G., Yang, C. Q., and Den, Y. (2006). "Mechanism of paper wet strength development by polycarboxylic acids with different molecular weight and glutaraldehyde/poly (vinyl alcohol)," *Journal of Applied Polymer Science* 101(1), 277-284. DOI: 10.1002/app.23298
Xu, K. S., Wang, S. F., Yang, Q. F., Song, H. N., Bin, F., and Yang, Z. Y. (1998). "Study on the technology of alkaline pulping and bleaching of pineapple leaf," *Journal of Guangxi University for Nationalities (Natural Science Edition)* 4(3), 26-28. DOI: 10.16177/j.cnki.gxmzzk.1998.03.010
Xu, Z. R. (1998). *Regression Analysis and Experimental Design*, China Agriculture Press, Beijing, China, pp. 159-172.
Yuan, Q. S., Chen, H. T., Han, Y. J., Li, L. X., and Huang, Z. H. (2011). "Optimization of technology parameters of making mulch from corn straw fiber," *Heilongjiang Pulp & Paper* 2, 1-5.
Zhu, J. C., Li, R. H., Yang, X. Y., Zhang, Z. Q., and Fan, Z. M. (2012). "Spatial and temporal distribution of crop straw resources in 30 years in China," *Journal of Northwest Agriculture and Forestry University (Natural Science Edition)* 40(4), 139-145. DOI: 10.13207/j.cnki.jnwafu.2012.04.009
Zhu, M. (2019). *The Preparation of Pineapple Waste-Based Activated Carbons and Their Capture Performance Toward Low Temperature CO_2*, Master's Thesis, Wuhan University of Technology, Wuhan, China.

Article submitted: January 6, 2021; Peer review completed: March 13, 2021; Resived version received and accepted: March 20, 2021; Published: March 23, 2021.
DOI: 10.15376/biores.16.2.3454-3468