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Quantification and Comparative Analysis of the Phenotypic and Mechanical Characteristics of Rice Straw from Diversified Varieties

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Abstract. A total of 368 rice straw samples featuring different subspecies (indica and japonica), growing seasons (early, middle, and late seasons), and growing locations (paddy land and upland) were collected and subjected to determine phenotypic (diameter, thickness, and area) and mechanical characteristics (shear, bending, and tensile). The principal component analysis and correlations analysis of these characteristics were examined. Results showed that the phenotypic and mechanical characteristics were inversely related to each other. The samples with superior mechanical characteristics were selected based on their interquartile ranges to further study the genetic differences. The characteristics quantified in this study can help to provide suggestions on the improvement of lodging resistance and rice cultivation.

Keywords. Rice straw, phenotypic characteristics, mechanical characteristics, principal component analysis, lodging resistance.

1 Introduction

Understanding the phenotypic and mechanical characteristics of rice straw is conducive to the

selection of optimal rice varieties. The phenotypic and mechanical characteristics such as diameter, thickness, and strength of plant stems can influence the stem resistance that is closely relevant to stem lodging (Torro, Breto and Garcia-Yzaguirre, 2011). The phenotypic characteristics can also impact the operation of thermochemical conversion systems (Zhang, Ghaly and Li, 2012). Mechanical characteristics dramatically depended on the phenotypic characteristics (Brigth and Kleis, 1964). Some research implied that the quantification of mechanical characteristics such as shear, bending, and tensile is essential to innovate and improve agricultural machines for collecting, controlling, threshing, harvesting, and treating crops (Chandio et al., 2013a; Dauda et al., 2014).

The phenotypic and mechanical characteristics of biomass differ significantly among the different subspecies, growing seasons, growing locations, etc (Niu et al., 2016; O'Dogherty et al., 1995). However, few studies addressed the phenotypic and mechanical characteristics of a wide variety of rice straw, which is the aim of this study.

2 Materials and methods

2.1 Sample collection and pretreatment

The specimens for the measurements of phenotypic and mechanical characteristics were prepared by selecting the first three internodes from the bottom of rice straw samples, while the rest of the samples was not considered.

2.2 Measurement methods

All the measurements of phenotypic and mechanical characteristics of rice straw were performed in the Laboratory of Biomass & Bioprocessing Engineering, College of Engineering, China Agricultural University.

2.2.1 Phenotypic characteristics

Each specimen was characterized by the large diameter (D_L), small diameter (D_S), and thickness (*thick*). The area (A) was calculated by Eq. 3-1, assuming that the cross-section of the stem was elliptical ring:

$$A = \pi[D_L D_S - (D_L - 2thick)(D_S - 2thick)]/4 \quad (1)$$

2.2.2 Mechanical characteristics

The measurements of the mechanical characteristics were performed with a universal testing machine (Instron 3367, Instron, USA) connected with specific software (Instron BlueHill2, Instron, USA). Standard methods, i.e., ASTM E4, BS 1610, DIN 51221, ISO 7500/1, EN 10002-2 JIS B7721, JIS B773, and AFNOR A03-501, were used for the measurements of mechanical characteristics including shear, bending, and tensile. The accuracy of the measurements of standard strains was equal to or exceeded the

precision provided by ASTM E83, BS 3846, ISO 9513, and EN 10002-4 standards. The setting of the machine is indicated in Table 3-1. The samples were tested 5 times for bending and shear and 10 times for tensile. The loading rate for all the mechanical characteristics was 10 mm min^{-1}. A record of force and time was acquired until the sample broken due to the applied force.

Table 1 Machine settings for the measurements of mechanical characteristics

Load carrying capacity (kN)	Test speed (mm min^{-1})	Full speed (mm min^{-1})	Return rate (mm min^{-1})	Displacement resolution (μm)	Beam displacement load (mm)	Load test precision
30	0.005–500	250	600	0.054	1122	+/–0.5%

(1) Shear

Shear strength (S_S) was quantified by double shear in a shear box that had two parallel-hardened steel plates and a movable plate. The two parallel-hardened steel plates were lower while the movable plate of the shear box was upper. All of them were mounted in a tension-testing tool, which subjected the rice straw specimens to a shear force. The three plates contained a succession of holes ranging from 1.5 to 5.0 mm in diameter to support the specimens of rice straw of different sizes. A pair of scissors was used to cut the rice stem to 40 mm length by selecting the first three internodes from the bottom of the stem. The maximum shear force (F_S) was recorded using a loading rate of 10 mm min^{-1}. The S_S of the specimen was determined by dividing F_S into two sectional areas of the stem as described by Eq. 3-2. Three valid data of S_S were used for calculating the mean value.

$$S_S = F_S/(2A) \tag{2}$$

(2) Bending

A three-point bending test (İnce et al., 2005; Nazari Galedar et al., 2008; Shahbazi and Nazari, 2012; Tavakoli, Mohtasebi and Jafari, 2009; Tavakoli, Mohtasebi and Jafari, 2008) was adopted to determine the bending strength (S_B) and bending modulus (M_B) of rice straw. A pair of scissors was used to cut the rice stems to 90 mm length by selecting the first three internodes from the bottom of the stem. Each specimen was set according to the axis of the cross-section in a horizontal plane, placed on two vertical rounded rods, and loaded centrally between the rods with a movable blade. The maximum force was recorded using a loading rate of 10 mm min^{-1}. The S_B and M_B were determined by Eqs. 3-3, 3-4, and 3-5 ((Crook and Ennos, 1994). Three valid data of S_B (or M_B) were used for calculating the mean value.

$$S_B = 8F_B l D_S/\{\pi[D_L D_S^3 - (D_L - 2thick)(D_S - 2\ thick)^3]\} \tag{3}$$

$$M_B = F_B l^3/(48yI) = l^3 k/(48I) \tag{4}$$

$$I = \pi[D_L D_S^3 - (D_L - 2thick)(D_S - 2thick)^3]/64 \quad (5)$$

where F_B is the maximum bending force, N; l is the distance between the two metal supports, mm; y is the maximum displacement, mm; I is the second moment of area, mm^4; k is the load curve slope, N mm^{-1}.

(3) Tensile

Sheet samples were used to determine the tensile strength (S_T) and tensile modulus (M_T). Each tubular specimen was split by a blade into two parts, and each part was slightly trimmed on both sides. A pair of scissors was used to cut the stem to 80 mm length. A rubber and a piece of emery cloth were used to avoid the specimen from fracturing and skidding. To place the specimens in perpendicular to the clamping table, 10 mm on each end of the specimen was fixed by clamps; only 60 mm of the 80 mm length was subjected to a tensile load. The crosshead speed was 10 mm min^{-1} deforming the specimen until a fracture was achieved. The specimen that fractured at the center (at gaze length) or 5 mm from the clamping part was admissible for estimating S_T. The maximum load was recorded using a loading rate of 10 mm min^{-1}. S_T and M_T were determined by Eqs. 3-6 and 3-7. Three valid data of each of S_T and M_T were used for calculating the mean values.

$$S_T = F_T/(b\ thick) \quad (6)$$

$$M_T = F_T L/(b\ thick\ y) \quad (7)$$

where F_T is the maximum tensile force, N; b is the specimen width, mm; L is the length that subjected to the tensile load, mm.

2.2.3 Statistical analysis

One-way ANOVA (post hoc multiple comparisons, Scheffer's test) and the analysis of the Pearson's correlation coefficient were performed using statistical software (SPSS 20.0, SPSS, USA) and (OriginPro 8.0, Origin Lab, USA). The principal component analysis (PCA) was performed using mathematical software (Matlab R2015a, MathWorks, USA).

3 Results and discussion

The statistic results concerning the phenotypic and mechanical characteristics of the 368 rice straw samples are listed in Tables 2, 3, and 4.

Table 2 Phenotypic and mechanical characteristics of rice straw based on the varieties of japonica and indica

Characteristics	Japonica (n = 116)		Indica (n = 138)		ND (n = 114)		Total (n = 368)	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
D_L (mm)	2.28–5.14	3.58 ± 0.58[a]	2.65–5.15	3.61 ± 0.52[a]	2.56–5.21	3.72 ± 0.52[a]	2.28–5.21	3.64 ± 0.54
D_S (mm)	1.46–3.32	2.31 ± 0.38[ab]	1.43–3.34	2.23 ± 0.37[a]	1.69–3.26	2.40 ± 0.36[b]	1.43–3.34	2.31 ± 0.38
thick (mm)	0.24–0.50	0.36 ± 0.06[ab]	0.24–0.54	0.36 ± 0.06[a]	0.23–0.53	0.38 ± 0.06[b]	0.23–0.54	0.37 ± 0.06
A (mm^2)	1.60–5.22	2.95 ± 0.76[a]	1.47–5.19	2.87 ± 0.72[a]	1.69–5.15	3.21 ± 0.78[b]	1.47–5.22	3.00 ± 0.77
F_S (N)	5.05–45.70	19.74 ± 8.65[b]	4.34–41.90	16.60 ± 7.97[a]	6.89–54.56	18.72 ± 7.74[ab]	4.34–54.56	18.25 ± 8.21
F_B (N)	0.62–4.50	1.62 ± 0.76[a]	0.43–3.38	1.48 ± 0.63[a]	0.43–4.93	1.67 ± 0.79[a]	0.43–4.93	1.58 ± 0.73
F_T (N)	14.97–126.13	47.19 ± 18.33[b]	11.53–79.30	37.62 ± 14.05[a]	13.39–133.27	41.19 ± 16.83[a]	11.53–133.27	41.74 ± 16.80
S_S (MPa)	1.32–6.69	3.28 ± 1.18[b]	1.19–6.40	2.79 ± 1.12[a]	1.32–5.77	2.79 ± 0.93[a]	1.19–6.69	2.94 ± 1.10
S_B (MPa)	8.47–41.45	22.19 ± 6.51[a]	11.51–38.79	22.81 ± 6.25[a]	10.77–45.92	22.26 ± 7.13[a]	8.47–45.92	22.44 ± 6.60
S_T (MPa)	17.92–148.21	66.74 ± 25.49[b]	17.64–125.51	53.08 ± 21.02[a]	16.51–107.93	50.11 ± 17.57[a]	16.51–148.21	56.47 ± 22.67
M_B ($\times 10^3$ MPa)	0.92–6.90	2.81 ± 1.11[a]	0.79–6.48	2.88 ± 1.08[a]	0.97–6.50	2.75 ± 1.11[a]	0.79–6.90	2.82 ± 1.10
M_T ($\times 10^3$ MPa)	3.75–12.30	6.90 ± 1.86[ab]	3.17–13.53	7.17 ± 1.98[b]	3.22–13.93	6.46 ± 1.93[a]	3.17–13.93	6.87 ± 1.95

Note: n, sample quantity; ND, non-defined; SD, standard deviation; D_L, large diameter; D_S, small diameter; *thick*, thickness; A, area; F_S, maximum shear force; F_B, maximum bending force; F_T, maximum tensile force; S_S, shear strength; S_B, bending strength; S_T, tensile strength; M_B, bending modulus; M_T, tensile modulus.

[a,b,c]significant differences among different rice straw varieties with a significant difference level of 0.05.

Table 3 Phenotypic and mechanical characteristics of rice straw based on the varieties of early, middle, and late seasons

Characteristics	Early (n = 54)		Middle (n = 76)		Late (n = 73)		ND (n = 165)		Total (n = 368)	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
D_L (mm)	2.49–4.34	3.45 ± 0.40^{a}	2.50–5.15	3.65 ± 0.60^{ab}	2.55–5.14	3.64 ± 0.56^{ab}	2.28–5.21	3.69 ± 0.53^{b}	2.28–5.21	3.64 ± 0.54
D_S (mm)	1.43–2.97	2.13 ± 0.32^{a}	1.58–3.19	2.22 ± 0.35^{ab}	1.57–3.10	2.30 ± 0.38^{bc}	1.46–3.34	2.41 ± 0.37^{c}	1.43–3.34	2.31 ± 0.38
thick (mm)	0.24–0.44	0.35 ± 0.05^{a}	0.24–0.49	0.36 ± 0.06^{a}	0.24–0.54	0.36 ± 0.08^{a}	0.23–0.53	0.38 ± 0.06^{a}	0.23–0.54	0.37 ± 0.06
A (mm^2)	1.56–3.95	2.71 ± 0.58^{a}	1.47–4.65	2.91 ± 0.72^{ab}	1.73–5.22	2.94 ± 0.86^{ab}	1.60–5.15	3.16 ± 0.76^{b}	1.47–5.22	3.00 ± 0.77
F_S (N)	5.05–35.40	15.63 ± 7.59^{a}	5.00–40.73	18.17 ± 8.49^{a}	4.34–45.70	18.72 ± 8.89^{a}	6.89–54.56	18.93 ± 7.85^{a}	4.34–54.56	18.25 ± 8.21
F_B (N)	0.62–3.07	1.37 ± 0.53^{a}	0.44–3.27	1.46 ± 0.62^{ab}	0.43–3.45	1.58 ± 0.72^{ab}	0.43–4.93	1.72 ± 0.81^{b}	0.43–4.93	1.58 ± 0.73
F_T (N)	13.29–79.01	36.53 ± 16.71^{a}	11.53–126.13	44.16 ± 19.06^{b}	11.96–100.67	42.19 ± 14.60^{ab}	13.39–133.27	42.14 ± 16.41^{ab}	11.53–133.27	41.74 ± 16.80
S_S (MPa)	1.36–6.14	2.79 ± 1.15^{a}	1.19–6.69	3.01 ± 1.15^{a}	1.25–6.40	3.12 ± 1.16^{a}	1.32–6.52	2.89 ± 1.04^{a}	1.19–6.69	2.94 ± 1.10
S_B (MPa)	10.41–39.32	23.16 ± 6.81^{a}	8.47–41.45	22.44 ± 6.61^{a}	10.54–35.83	21.42 ± 5.55^{a}	10.77–45.92	22.66 ± 6.96^{a}	8.47–45.92	22.44 ± 6.60
S_T (MPa)	17.64–111.15	51.78 ± 19.57^{a}	17.92–148.21	58.68 ± 21.31^{ab}	20.98–144.51	63.61 ± 26.72^{b}	16.51–125.74	53.82 ± 21.58^{ab}	16.51–148.21	56.47 ± 22.67
M_B (×10^3 MPa)	1.34–6.33	2.88 ± 0.89^{a}	0.79–6.90	2.91 ± 1.30^{a}	0.95–6.48	2.81 ± 1.05^{a}	0.97–6.50	2.76 ± 1.08^{a}	0.79–6.90	2.82 ± 1.10
M_T (×10^3 MPa)	3.99–11.38	7.04 ± 1.56^{a}	3.28–11.30	6.84 ± 1.80^{a}	3.17–13.53	7.27 ± 2.33^{a}	3.22–13.93	6.64 ± 1.92^{a}	3.17–13.93	6.87 ± 1.95

Note: n, sample quantity; ND, non-defined; SD, standard deviation; D_L, large diameter; D_S, small diameter; *thick*, thickness; A, area; F_S, maximum shear force; F_B, maximum bending force; F_T, maximum tensile force; S_S, shear strength; S_B, bending strength; S_T, tensile strength; M_B, bending modulus; M_T, tensile modulus.

^{a,b,c}significant differences among different rice straw varieties with a significant difference level of 0.05.

Table 4 Phenotypic and mechanical characteristics of rice straw based on the varieties of paddy land and upland

Characteristics	Paddy land (n = 226)		Upland (n = 27)		ND (n = 115)		Total (n = 368)	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
D_L (mm)	2.28–5.15	3.56 ± 0.54[a]	2.84–5.09	3.90 ± 0.55[b]	2.56–5.21	3.72 ± 0.52[ab]	2.28–5.21	3.64 ± 0.54
D_S (mm)	1.43–3.19	2.25 ± 0.37[a]	1.76–3.34	2.40 ± 0.40[a]	1.69–3.26	2.40 ± 0.36[a]	1.43–3.34	2.31 ± 0.38
thick (mm)	0.24–0.54	0.36 ± 0.06[a]	0.24–0.49	0.36 ± 0.06[a]	0.23–0.53	0.38 ± 0.07[a]	0.23–0.54	0.37 ± 0.06
A (mm^2)	1.47–5.22	2.88 ± 0.74[a]	2.14–5.00	3.12 ± 0.72[a]	1.69–5.15	3.20 ± 0.78[a]	1.47–5.22	3.00 ± 0.77
F_S (N)	4.34–45.70	17.80 ± 8.40[a]	6.95–40.73	20.10 ± 8.56[a]	6.89–54.56	18.69 ± 7.71[a]	4.34–54.56	18.25 ± 8.21
F_B (N)	0.43–3.54	1.52 ± 0.68[a]	0.71–4.50	1.76 ± 0.84[a]	0.43–4.93	1.67 ± 0.79[a]	0.43–4.93	1.58 ± 0.73
F_T (N)	11.53–126.13	41.79 ± 16.97[a]	16.95–80.90	43.34 ± 15.82[a]	13.39–133.27	41.27 ± 16.78[a]	11.53–133.27	41.74 ± 16.80
S_S (MPa)	1.19–6.69	2.98 ± 1.15[a]	1.42–5.99	3.28 ± 1.33[a]	1.32–5.77	2.79 ± 0.92[a]	1.19–6.69	2.94 ± 1.10
S_B (MPa)	8.47–41.45	22.72 ± 6.31[a]	10.54–30.34	20.32 ± 5.87[a]	10.77–45.92	22.40 ± 7.26[a]	8.47–45.92	22.44 ± 6.60
S_T (MPa)	17.64–144.51	58.66 ± 23.78[ab]	32.31–148.21	64.47 ± 26.97[b]	16.51–107.93	50.27 ± 17.58[a]	16.51–148.21	56.47 ± 22.67
M_B (×10^3 MPa)	0.79–6.90	2.89 ± 1.09[a]	0.95–4.04	2.45 ± 0.94[a]	0.97–6.50	2.77 ± 1.13[a]	0.79–6.90	2.82 ± 1.10
M_T (×10^3 MPa)	3.17–13.53	7.07 ± 1.95[a]	4.00–11.13	6.90 ± 1.81[a]	3.22–13.93	6.46 ± 1.92[a]	3.17–13.93	6.87 ± 1.95

Note: n, sample quantity; ND, non-defined; SD, standard deviation; D_L, large diameter; D_S, small diameter; *thick*, thickness; A, area; F_S, maximum shear force; F_B, maximum bending force; F_T, maximum tensile force; S_S, shear strength; S_B, bending strength; S_T, tensile strength; M_B, bending modulus; M_T, tensile modulus.

[a,b,c]significant differences among different rice straw varieties with a significant difference level of 0.05.

Table 5 Pearson's correlation between the phenotypic and mechanical characteristics of rice straw

Characteristics	D_L	D_S	*thick*	A	F_S	F_B	F_T	S_S	S_B	S_T	M_B	M_T
D_L	1.00											
D_S	0.72**	1.00										
thick	0.28**	0.29**	1.00									
A	0.78**	0.75**	0.78**	1.00								
F_S	0.46**	0.47**	0.30**	0.50**	1.00							
F_B	0.57**	0.68**	0.32**	0.62**	0.28**	1.00						
F_T	0.21**	0.24**	0.32**	0.33**	0.34**	0.20**	1.00					
S_S	0.09	0.10	–0.17**	–0.04	0.80**	0.03	0.17**	1.00				
S_B	–0.33**	–0.25**	–0.13*	–0.28**	–0.05	0.13*	–0.03	0.02	1.00			
S_T	–0.03	0.02	–0.47**	–0.29**	0.08	0.00	0.44**	0.30**	0.03	1.00		
M_B	–0.51**	–0.41**	–0.28**	–0.48**	–0.17**	–0.17**	–0.04	0.02	0.79**	0.12*	1.00	
M_T	–0.14**	–0.16**	–0.71**	–0.52**	–0.16**	–0.17**	–0.33**	0.16**	0.02	0.50**	0.09	1.00

Note: D_L is the large diameter, mm; D_S is the small diameter, mm; *thick* is the thickness, mm; A is the area, mm^2; F_S is the maximum shear force, N; F_B is the maximum bending force, N; F_T is the maximum tensile force, N; S_S is the shear strength, MPa; S_B is the bending strength, MPa; S_T is the tensile strength, MPa; M_B is the bending modulus, MPa; M_T is the tensile modulus, MPa.

*Correlation is significant at the 0.05 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed).

3.1 Phenotypic characteristics of rice straw

As shown in Tables 2 and 3, there were no significant differences in D_L, *thick*, and A between the varieties of indica and japonica and among the varieties of early, middle, and late seasons, while significant difference found in D_S between early and late seasons ($P > 0.05$). As shown in Table 3-4, there were significant differences in D_L between paddy land and upland ($P < 0.05$). The D_L of upland (3.90 mm) is significantly larger than that of paddy land (3.56 mm). For all the 368 samples, D_L ranged from 2.28 to 5.21 mm with an average of (3.64 ± 0.54) mm, D_S ranged from 1.43 to 3.34 mm with an average of (2.31 ± 0.38) mm, *thick* ranged from 0.23 to 0.54 mm with an average of (0.37 ± 0.06) mm, and A ranged from 1.47 to 5.22 mm^2 with an average of (3.00 ± 0.77) mm^2.

These values are in agreement with the previous findings (Chandio et al., 2013a; Chandio et al., 2013b), where the D_L of rice straw ranged from 3.96 to 4.31 mm, D_S from 3.56 to 3.91 mm, *thick* from 0.40 to 0.50 mm. However, the diameter of rice stem was between 2.66 and 9.36 mm and the A between 4.61 and 50.13 mm^2 (Alizadeh, Rahimi-Ajdadi and Dabbaghi, 2011). The difference may be attributed to the different varieties studied and different internode positions tested.

3.2 Mechanical characteristics of rice straw

3.2.1 Shear force and strength

As shown in Table 2, there were significant differences in S_S and F_S between indica and japonica ($P < 0.05$). As shown in Tables 3 and 4, there were no significant differences in S_S and F_S among the varieties of early, middle, and late seasons and between the varieties of paddy land and upland ($P > 0.05$). For all the 368 samples, F_S ranged from 4.34 to 54.56 N with an average of (18.25 ± 8.21) N, and S_S ranged from 1.19 to 6.69 MPa with an average of (2.94 ± 1.10) MPa. According to previous research, the ranges of F_S and S_S of rice straw have been reported as 8.81–20.22 MPa and 7.12–11.16 MPa, respectively (Tavakoli et al., 2010). The difference between this study and previous studies may be due to the difference in rice straw varieties and genetic traits. The shear data of rice straw can be used in harvesting operations, industrial operations, and the manufacture of building materials.

3.2.2 Bending force, strength, and modulus

As shown in Tables 2, 3, and 4, there were no significant differences in F_B, S_B, and M_B among the different varieties ($P > 0.05$). For all the 368 samples, F_B ranged from 0.43 to 4.93 N with an average of (1.58 ± 0.73) N, S_B ranged from 8.47 to 45.92 MPa with an average of (22.44 ± 6.60) MPa, M_B ranged from 787.43 to 6898.50 MPa with an average of (2817.99 ± 1096.99) MPa. It has been reported that the S_B of rice straw was around 8 MPa and M_B ranged from 180 to 1250 MPa (Chandio et al., 2013a; Tavakoli et al., 2010). The difference between this study and the earlier literature can be attributed to the difference in rice straw varieties and climatic factors. The higher S_B found in this study implied that the rice straw used here was more brittle than the previous.

3.2.3 Tensile force, strength, and modulus

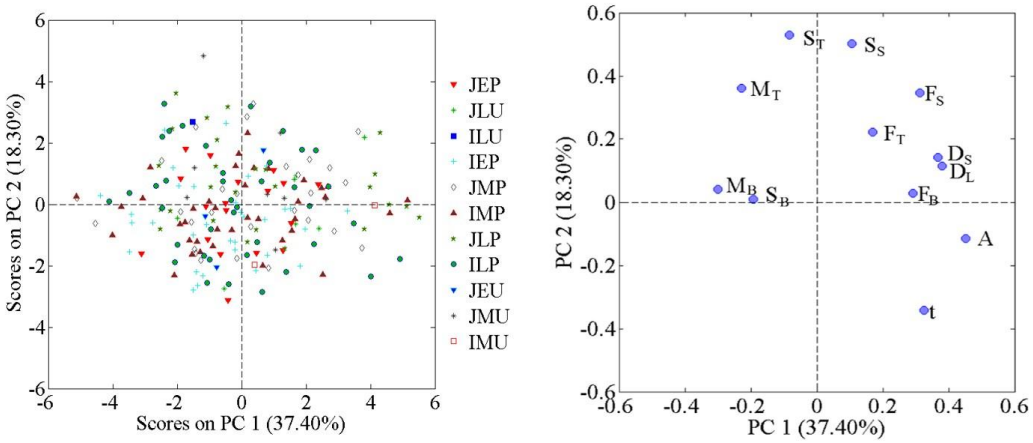
As shown in Tables 2 and 3, there were significant differences in F_T and S_T between indica and japonica and among the varieties of early, middle, and late seasons ($P < 0.05$). The F_T and S_T of japonica (47.19 N and 66.74 MPa, respectively) are significantly larger than those of indica (37.62 N and 53.08 MPa, respectively). For the rice straw of different growing seasons, the middle season had the highest F_T (44.16 N), followed by the late season (42.19 N) and the early season (36.53 N). The S_T of the late season (63.61 MPa) is higher than those of the middle (58.68 MPa) and early seasons (51.78 MPa). As shown in Table 3-4, the differences in the tensile characteristics between paddy land and upland were not significant ($P > 0.05$). For all the 368 samples, F_T ranged from 11.53 to 133.27 N with an average of (41.74 ± 16.80) N, S_T ranged from 16.51 to 148.21 MPa with an average of (56.47 ± 22.67) MPa, and M_T ranged from 3173.77 to 13929.92 MPa with an average of (6865.26 ± 1945.22) MPa. These results are in agreement with the previous study (Reddy and Yang, 2006), where the S_T and M_T of rice straw ranged from 74.60 to 450 MPa and from 2467 to 26330 MPa, respectively. The results of this study can be used for the development of handling equipment, such as rice harvesters and cutting machines.

3.3 Principal component analysis and correlation analysis of phenotypic and mechanical characteristics

The PCA and correlation analysis of the phenotypic and mechanical characteristics of rice straw are illustrated in Figure 1. The score plots of PCA indicate the score distributions of different varieties of rice straw based on the values. The loading plots reflect the correlations and contribution rates of different phenotypic and mechanical characteristics for the distributions.

For the phenotypic and mechanical characteristics of rice straw, the overall variation explained by PC1 and PC2 was 55.70% for the varieties of subspecies (indica and japonica), growing seasons (early, middle, and late seasons), and growing locations (paddy land and upland). The PC1 and PC2 cannot effectively cluster the same varieties. All the samples were in mixed conditions. The varieties of rice straw were similar in terms of each characteristic.

As shown in Table 5, there were significant pair-wise correlations among the phenotypic and mechanical characteristics: D_L–D_S–A–F_B, D_L–M_B, *thick*–A, *thick*–M_T, A–F_S, A–M_T, F_S–S_S, S_B–M_B, and S_T–M_T, whose correlation coefficients were higher than 0.5 ($P < 0.01$). Among these characteristics, D_L–M_B, *thick*–M_T, and A–M_T presented negative correlations for each other. A was positively correlated with F_B and F_S. Most of the correlations were relevant to the equations used.



(a) Score plot (b) Loading plot

Figure 1 Principal component analysis of rice straw

Note: J, Japonica; I, Indica; E, early season; M, middle season; L, late season; P, paddy land; U, upland.

3.4 Selected samples with superior characteristics

As plotted in Figure 2, samples with superior mechanical characteristics can be selected based on the interquartile ranges of S_S, S_B, and S_T. According to Figure 2, 27 samples for S_S, 5 samples for S_B, and 9 samples for S_T were selected. In terms of the phenotypic characteristics of the selected samples, the D_L ranged from 2.67 to 4.49 mm with an average of (3.55 ± 0.50) mm, D_S ranged from 1.68 to 2.76 mm with an average of (2.31 ± 0.26) mm, *thick* ranged from 0.24 to 0.52 mm with an average of (0.35 ± 0.07) mm, and A ranged from 1.63 to 4.65 mm^2. The differences in the phenotypic characteristics between the selected samples and total samples were not significant, while the S_S and S_T of the selected samples are significantly larger than those of the total samples. It can be noted that the rice straw samples with superior mechanical characteristics had no significant differences in the phenotypic characteristics. The contents of lignin in japonica and indica rice subspecies was significant (Table 2-1) and also significant differences were found between japonica and indica rice in F_S, F_T, S_T and S_T (Table 3-2), means that these mechanical characteristics have some correlations with the lignin contents. Possibly, this observation could justify the superior mechanical characteristics of rice straw samples selected and their strength could be attributed to their higher lignin contents.

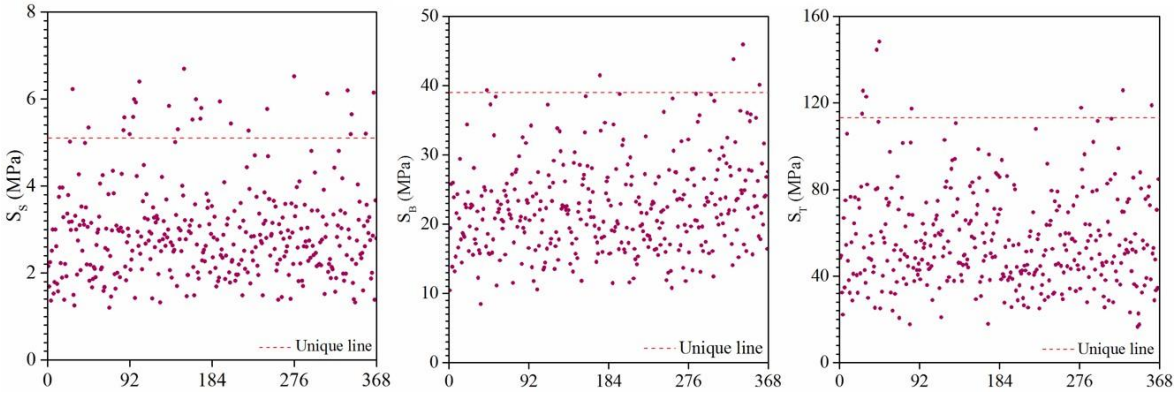


Figure 2 Selection of rice straw samples with superior mechanical characteristics

Note: S_S is the shear strength, MPa; S_B is the bending strength, MPa; S_T is the tensile strength, MPa.

4 Conclusions

The phenotypic (diameter, thickness, and area) and mechanical characteristics (shear, bending, and tensile) of a wide variety of rice straw featuring different subspecies, growing seasons, and growing locations were investigated. Results showed that the phenotypic and mechanical characteristics were inversely related to each other. There were almost no significant differences in the phenotypic characteristics among different rice straw varieties. The samples with superior mechanical characteristics were selected based on their interquartile ranges and their differences in genetic characteristics need to be further investigated. The quantification of these characteristics can be used to elucidate the mechanisms of rice cultivation, provide a sustainable resource for fiber, and thereby benefit to our environment.

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