Twenty-two compositional characterizations and theoretical energy potentials of
extensively diversified China's crop residues

Wenjuan Niu^{1,2}, Lujia Han^{1*}, Xian Liu¹, Guangqun Huang¹, Longjian Chen¹, Weihua Xiao¹,
Zengling Yang¹

1. Biomass Resources and Utilization Laboratory, College of Engineering, China Agricultural University,
Beijing 100083, People's Republic of China
2. College of Engineering, Huazhong Agricultural University, Wuhan, Hubei 430070, People's Republic of
China

*Corresponding author: Lujia Han, China Agricultural University (East Campus), Box 191,
Beijing 100083, China; Fax: 86-10-6273-6778; Tel: 86-10-6273-6313.A
E-mail: hanlj@cau.edu.cn

26 **Abstract:** Knowledge of the compositional properties of crop residues feedstocks is important for
27 process control and handling of co-products and waste from energy utilization. In this study, 1076
28 crop residues were collected from 326 sites across China. Chemical analysis of five organic chemical
29 compositions, four proximate compositions, five ultimate compositions and eight mineral elements
30 were conducted. Energy potentials of crop residues in China were quantified based on their
31 compositional characterization. Results showed that the compositional characteristics of wheat straw,
32 rice straw, corn stover, rape stalk and cotton stalk were shown to be significant different ($p < 0.05$)
33 and highly variable. The coefficients of variation were negatively correlated with the means of crop
34 residues compositions. Principal component analysis reflected that the compositions could explain
35 several variations and clustering rules of the five crop residues. The correlations among parameters
36 could be briefly summarized as hemicelluloses/ash–cellulose/lignin/water soluble
37 carbohydrates/crude protein/P, water soluble carbohydrates–crude protein, crude
38 protein–N–P–Mg–Cu, volatile matter–ash–fixed carbon, C–H–O–N–S, P–K–Na–Ca and
39 ash–C/H/O/K ($p < 0.01$). The energy potentials of the five substrates were also significantly different
40 ($p < 0.05$). The higher heating values, theoretical ethanol yields, and theoretical biomethane yields of
41 the crop residues were 12.97–18.58 MJ/kg, 336.69–658.25 g/kg, and 151.48–288.45 L/kg,
42 respectively.

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49 **Keywords:** Compositional characteristics; Energy potential; Variation; Correlation; China; Crop
50 residues

51 **Nomenclature:** CP, crude protein; DM, dry matter; FC, fixed carbon; HHV, higher heating value;
52 Moist, moisture; Mt, million tons; PCA, principal component analysis; VM, volatile matter; WSC,
53 water soluble carbohydrates.

54 **1. Introduction**

55 Crop residue is one of the main biomass energy resources, is available in large quantities with
56 widespread distribution at low cost, is easy to procure, and is frequently renewed. The annual world
57 output of crop residues contains a surprising amount of energy [1–3]. Compared with fossil fuels, the
58 effective utilization of crop residues could help realize the sustainable and ecologically sound
59 development, and reduce the emissions of CO_x, NO_x, and SO_x atmospheric pollutants [4, 5]. For this
60 reason, alternatives to the disposal of crop residues are being increasingly considered attractive
61 approaches for coping with both environmental issues and the increasing global demand for energy
62 over the past decades in the worldwide [6, 7].

63 Crop residues can be used in a variety of ways for energy production, including combustion,
64 ethanol conversion, and biomethane conversion [7, 8]. However, compositional characterization of
65 crop residues is imperative as the compositions affect the energy potentials by affecting the
66 conversion processes [9–12]. For example, cellulose, hemicellulose, lignin, water-soluble
67 carbohydrates (WSC), and crude protein (CP) constitute the organic carbon materials produced by
68 photosynthesis, and their contents and structures directly affect the thermochemical and biochemical
69 conversion processes, products, and yields [13–15]. During the thermochemical conversion process
70 of crop residues, the ultimate compositions (C, H, O, N and S), proximate compositions (moisture
71 (Moist), ash, volatile matter (VM), and fixed carbon (FC)), and mineral elements (P, K, Na, Ca, Mg,
72 Fe, Cu, and Zn) differentially affect the calorific value, slagging and combustion performance of the
73 fuel [16–20]. With the complex compositions of crop residues, the conversion yields of heat energy,
74 ethanol, biomethane, and other energy potentials can be predicted [20–22]. Several studies have
75 shown that the crop varieties, agricultural systems, soil and irrigation in different regions may vary

76 the compositions and energy characteristics of crop residues [23–25]. The characteristics of crop
77 residues depend on local climate and agricultural conditions.

78 China is one of the largest global agricultural producers and the production of crop residues was
79 842 million tons (Mt) in 2010, which included 153.62 Mt wheat straw, 119.55 Mt rice straw, 331.83
80 Mt corn stover, 24.26 Mt rape stalk, and 22.48 Mt cotton stalk [26–28]. China has diverse and
81 complex climate conditions, planting environment and planting patterns compared with other
82 countries. Thus, a better understanding of the basic compositional characteristics of extensively
83 diversified Chinese crop residues is critical and imperative for their successful energy application
84 perspectives, including conversion processes, quality control, economic value, and eventually the
85 safe disposal of waste [6, 8, 26]. However, such understanding on a national scale to date is largely
86 limited. Thus, the present study: (1) investigated a wide variety of crop residues which were
87 extensively collected across different areas of China to present their variation and correlation in
88 compositional properties, and (2) evaluated the energy potentials of the crop residues as feedstock for
89 the production of thermal energy, ethanol, and biomethanol based on their characterization.

90 **2. Materials and methods**

91 **2.1. Samples collection and preparation**

92 Based on the planting areas and distributions of crops in China, crop residue samples were
93 selected considering different species and locations. Wheat straw, rice straw, corn stover, rape stalk
94 and cotton stalk samples were collected at the fully ripe stage during 2011–2014. The regional
95 distributions of the collected samples are shown in Fig. 1. Sampling was conducted at 326 sites in 32
96 provinces, cities, and autonomous regions in China [28]. A total of 1076 specimens were collected,
97 comprising 328 wheat straw, 142 rice straw, 341 corn stover, 130 rape stalk, and 135 cotton stalk
98 samples. Each crop residue sample was taken from different plots in the field. The samples had the
99 grains and roots removed and the middle part retained. Then, the samples were thoroughly mixed to
100 obtain a representative batch of approximately 2 kg.

101 According to American Society for Testing and Materials (ASTM) E1757-01, the collected crop
102 residue samples were dried in a forced-air drying oven at 45 °C for 36–48 h, fed into a ZM100 mill
103 (Retsch GmbH & Company, Germany), and milled through a 0.90 mm sieve. Then, the samples were
104 stored in bags prior for compositional analysis.

105 **2.2 Compositional and higher heating value analyses**

106 All the experiments were performed in duplicate and the recorded results are the averages of two
107 parallel samples, and the results are expressed on a dry matter (DM) basis after 45°C oven dried.

108 **2.2.1 Organic chemical compositions**

109 Cellulose, hemicellulose, and lignin were measured according to the National Renewable Energy
110 Laboratory method [29]. A crop residue sample (0.30 g) and deionized water (10 mL) were
111 combined in a high-pressure tube and extracted in a boiling water bath for 1 h to remove soluble
112 sugar, then hydrolyzed with 72% H₂SO₄ (3 mL) at 30 °C for 2 h. Then, the mixture was diluted to 4%
113 H₂SO₄ with deionized water (84 mL) and placed in an autoclave at 121 °C for 1 h. After cooling to
114 room temperature, a portion of the supernatant (20 mL) was neutralized to pH 5–6 by adding
115 0.82–0.85 g CaCO₃ and then filtered. The monosaccharide compositions of the hemicelluloses in the
116 neutralized, filtered liquid were determined by High Performance Liquid Chromatography using the
117 Aminex HPX-87P column (Bio-Rad) with a refractive index detector (HITACHI, L-2490) to obtain
118 cellulose and hemicellulose, whereas lignin was determined by the residue remaining after
119 combustion in a 575 ± 25 °C muffle furnace for 3 h [29]. WSC was determined using the UV-2550
120 spectrophotometer according to the anthrone sulfuric acid method. CP was analyzed using the
121 Kjeltec 2300 auto-analyzer (FOSS Tecator AB, Sweden) according to the Association of Official
122 Analytical Chemists method [30].

123 **2.2.2. Proximate compositions**

124 Moist was determined in a 105 °C oven according to the weight difference before and after heating.
125 The ash content was measured after burning the samples to a constant weight in a muffle furnace at

126 575 ± 25 °C for 3 h [31]. VM was analyzed at 900 °C after 7 min combustion in a muffle furnace,
127 and FC was determined by using Eq. (1) [32]:

$$128 \quad FC = 100\% - VM - Ash \quad (1)$$

129 2.2.3. Ultimate compositions

130 The C, H, N and S contents were determined using the Elementar Vario EL II (Vario Macro,
131 Germany). The O content was obtained by using Eq. (2) [18, 33]:

$$132 \quad O = 100\% - (C + N + H + S) \quad (2)$$

133 2.2.4. Mineral elements

134 Crop residue samples were digested using an advanced microwave digestion instrument
135 (Milestone Ethos Touch Control, equipped with an HPR 1000/6S rotor) with a 1200 W microwave
136 oven. The crop residue sample (0.50 g) was digested in concentrated HNO₃ (7 mL) in a closed
137 reactor in the microwave oven. Then, the reactor was heated at 160 °C on a hot plate to remove the
138 acid, and the digested liquid was transferred to a 100 mL volumetric flask. After the preparation of
139 standard curves, inductively coupled plasma-mass spectrometry (ICP-MS, Analytik Jena AG, Jena,
140 Germany) was used for P, K, Na, Ca, Mg, Fe, Cu and Zn analyses.

141 2.2.5. Higher heating value

142 Higher heating value (HHV) was determined by bomb calorimetry according to ASTM E-711 [34].
143 A crop residue sample (1.00 g) was placed in the bomb, and the HHV was determined by the
144 oxygen-bomb combustion method.

145 2.3. Calculation of the theoretical energy potentials of crop residues

146 2.3.1. Theoretical thermal energy conversion

147 The annual production of wheat straw, rice straw, corn stover, rape stalk, and cotton stalk in China
148 in 2014 was estimated by multiplying the crop grain outputs in the China statistical yearbook by the
149 ratios of crop residue to grain [27, 28]. The thermal energy conversion potentials of the five crop
150 residues in 2014 were calculated on the basis of the annual outputs and HHVs of the materials.

151 2.3.2. Theoretical ethanol conversion

152 Ethanol can be produced from the fermentation of the soluble sugar, cellulose and hemicellulose
153 fractions after crop residue hydrolysis. The measurement of the ethanol conversion yield of crop
154 residues is highly time-consuming. The theoretical ethanol conversion yields can be calculated on the
155 basis of the methods proposed by Spatari and Godin [21, 35, 36], based on (1) expected yields from
156 hydrolysis of glucose of 91% for cellulose and 96% for WSC, and of xylose, galactose, and
157 arabinose of 81% for hemicellulose; (2) conversion of the monosaccharides to ethanol at rates of
158 92.5% for glucose, and 86% for xylose, galactose, and arabinose; (3) and an ethanol recovery yield
159 of 99.5%. Thus, Eq. (3) can be written as follows:

$$160 \text{ Ethanol conversion yield} = 9.95(0.925(0.91\text{Cellulose} + 0.96\text{WSC}) + 0.86(0.81\text{Hemicellulose})) \quad (3)$$

161 The units for cellulose, hemicellulose, and WSC are %, and the unit for ethanol conversion yield is
162 g/kg. The ethanol conversion potentials of the five crop residues in 2014 were calculated according
163 to the annual outputs and ethanol conversion yields of the straws.

164 2.3.3. Theoretical biomethane conversion

165 Biomethane can be obtained by fermentation of crop residues as up to 90 days are required as a
166 standard incubation time [37]. Therefore, we used the prediction method of Thomsen [14], which has
167 been verified, to calculate the theoretical biomethane conversion yields of crop residues. The
168 theoretical biomethane conversion yield of the crop residue by anaerobic fermentation can be
169 estimated using Eq. (4) by their compositions ($R^2 > 0.96$) [14]:

$$170 \text{ Biomethane conversion yield} = (0.65\text{Cellulose} + 0.41\text{Hemicellulose} - 5.07\text{Lignin} + 313)(1 - 0.01\text{Ash}) \quad (4)$$

171 The units for cellulose, hemicellulose, lignin, and ash are %, and the unit for methane conversion
172 yield is L/kg. The biomethane conversion potentials of the five crop residues in 2014 were calculated
173 on the basis of the annual outputs and biomethane conversion yields of the materials.

174 2.4. Data processing and analysis

175 OriginPro 8.0, SPSS 17.0, and Matlab R2012b were used for the statistical calculations of the

176 compositions and energy potentials of the five plant materials. One-way analysis of variance and
177 Pearson's correlation coefficient analysis were conducted using SPSS 17.0. Box charts and nonlinear
178 curve fittings were applied to analyze the compositions and energy potentials by OriginPro 8.0.
179 Principal component analysis (PCA) in Matlab R2012b was also used for cluster analysis of the five
180 crop residues.

181 **3. Results and discussion**

182 **3.1. Differences and variations of the compositions of crop residues**

183 Table 1 shows the means, standard deviations (SD), and multiple comparisons of the compositions
184 of the five crop residues. Significant differences are observed among the compositions of different
185 crop residues ($p < 0.05$), and the composition means for each crop residue are shown. The SD values
186 of the compositions are large, illustrating the variability of their contents. Table 1 also shows the
187 compositions of grasses, animal manure, wood and coal reported in the literatures.

188 **3.1.1. Organic chemical compositions**

189 The organic chemical compositions of the five crop residues were evaluated according to their
190 median, mean, and percentiles (25 and 75, 5 and 95, and <5 and >95, respectively) (Fig. 2). The
191 organic chemical compositions of the five crop residues overlap to some extent. The cellulose
192 content is the highest in rape stalk and is the lowest in corn stover, whereas hemicellulose in wheat
193 straw is the highest and is the lowest in cotton stalk. The lignin contents in cotton stalk, corn stover,
194 wheat straw, rape stalk, and rice straw are 17.58–33.36%, 14.66–31.38%, 15.13–30.39%,
195 12.07–26.96%, and 10.40–27.47%, respectively. The content order observed for wheat and rice
196 straws is cellulose > hemicellulose > lignin, whereas the content order observed for corn stover, rape
197 and cotton stalks is cellulose > lignin > hemicellulose, which may be caused by the high lignification
198 degree of the rinds of the latter stalks. Fig. 2d shows that the WSC contents in rice straw and corn
199 stover are higher and have larger variation ranges. The CP in cotton stalk is the highest, followed by
200 corn stover, whereas the CP in wheat straw is the lowest (Fig. 2e). WSC and CP constitute

201 nonstructural components (Fig. 2g). The variation ranges of cellulose (24.91–54.26%), hemicellulose
202 (8.33–32.74%), lignin (10.40–33.36%), WSC (0.32–19.85%), and CP (1.15–13.98%) contents are
203 wider than the variation range values of crop residues reported previously [21, 38–41]. However, the
204 cellulose, hemicellulose, and lignin contents of crop residues are lower than the lignocellulose
205 contents of wood, whereas hemicellulose and WSC contents of crop residues are lower than grasses
206 [6, 7] (Table 1).

207 Table 1 and Fig. 2f show that the total lignocellulose contents of cellulose, hemicellulose, and
208 lignin in wheat straw and cotton stalk are higher than the contents in the other three. The cellulose in
209 crop residues comprises a linear structure formed by glucose monomers linked by β (1 $\rightarrow$ 4)
210 glucosides, and is integral in the formation of cell wall skeletons. Hemicellulose is composed of
211 xylan, arabinan, galactan, and mannan, and is interspersed between cellulose and lignin in the plant
212 cell. Cellulose, hemicellulose, and lignin can be considered structural components, which impart
213 toughness and mechanical resistance that can affect the processing performance of crop residues. The
214 lignocellulose contents of crop residues depend on the lignification of cells. Most of the nutrients in
215 crop residues are involved in the collection and storage of solar energy by photosynthesis [42]. Crop
216 residues with higher cellulose, hemicellulose, and WSC contents, such as wheat straw, rice straw,
217 and corn stover, are more beneficial and preferred for ethanol fermentation and liquefaction [21, 35].
218 Crop residues with higher lignin levels have higher energy values, but are unsuitable for gasification
219 [14]. WSC and CP can be nutritionally useful, especially for animal feeds. For example, the higher
220 WSC and CP contents of corn stover explain its frequent use as feed. CP can also act as a N source
221 for the anaerobic fermentation of crop residues, producing large amounts of ammonia N and
222 maintaining pH stability within a certain range [43].

223 3.1.2. Proximate compositions

224 The Moist variation in the crop residues is 1.08–8.94% (Fig. 3). A low Moist content indicates that
225 the DM in crop residues is high, and the dried samples are suitable for storage and raw energy

226 materials. The VM in rape stalk is the highest, followed by cotton stalk and corn stover. The Ash
227 content in rice straw is the highest, followed by wheat straw, and ash in cotton stalk is the lowest.
228 Compared with the others, the ash in cotton stalk has the tightest variation range over the 25–75%
229 distribution. The ash in rice straw and wheat straw must be treated in a timely manner after burning.
230 The FC in cotton stalk is the highest, followed by wheat straw and corn stover. The proximate
231 compositions of crop residues are VM (55.82–80.25%), ash (1.81–19.93%), and FC (8.30–27.45%).
232 As shown in Table 1, the VM in crop residues is lower than that in wood and higher than that in coal,
233 and the ash in crop residues is higher than that in wood and lower than that in animal manure and
234 coal [33, 44–47] (Table 1). Finally, the FC in crop residues is evidently higher than that in animal
235 manure and lower than that in coal [33, 44–47] (Table 1).

236 As shown in Table 1, the Moist/VM/ash/FC ratios are: (1) wheat straw, 0.59:7.41:1:1.82; (2) rice
237 straw, 0.32:5.77:1:1.24; (3) corn stover, 0.61:9.98:1:2.37; (4) rape stalk, 0.67:10.76:1:2.21; and (5)
238 cotton stalk, 0.79:14.61:1:3.75. A crop residue has a higher energy potential with a higher ratio of
239 VM to ash, and the ratios of VM to ash in cotton stalk, rape stalk, corn stover, wheat straw, and rice
240 straw are in descending order (Fig. 3). Crop residues biomass has characteristically high levels of
241 VM and low levels of ash. Crop residue has a lower ignition point and is easier to burn initially with
242 a higher ratio of VM to FC [48], and this ratio is also in descending order for rape stalk, rice straw,
243 corn stover, wheat straw, and cotton stalk. Rape stalk is rich in lipids, and cotton stalk has a high
244 lignin level, therefore both stalks have high VM contents. Ash content, which is inorganic matter
245 absorbed from the soil, is closely related to the characteristics of fuel. Leaf tissues contain nearly
246 twice as much ash as stems [49, 50], and the proportions of leaves in wheat, rice, and corn straws are
247 larger than the proportions in rape and cotton stalks. High levels of ash in rice and wheat straws may
248 be due to their epidermal layers containing siliceous materials [49]. Ash can easily lead to incomplete
249 pyrolysis and slagging in pyrolysis equipment; therefore, the effect of heat transfer and slag cleaning
250 from the reactor should be fully considered in the design of combustion equipment for crop residues.

251 3.1.3. Ultimate compositions

252 The ultimate compositions are important for determining the theoretical air–fuel ratio in
253 thermo-conversion systems [33]. As shown in Fig. 4, the C content in cotton stalk is the highest,
254 followed by corn stover, and the lowest in rice straw. The H contents in cotton and rape stalks are the
255 highest, and H in rape stalk has a narrow range of variation over the 25–75% distribution. O in rape
256 stalk is the highest and that in rice straw is the lowest, whereas the O contents in the other three crop
257 residues are similar. Cotton stalk has the highest N level, followed by corn stover. S is not normally
258 distributed because of its low levels in the five crop residues, resulting in bias. S contents in corn
259 stover and cotton stalk have wider ranges of variation. The variation ranges of the ultimate
260 compositions in crop residues were C (34.65–53.91%), H (3.17–7.94%), O (30.82–50.84%), N
261 (0.13–2.23%), and S (0.15–1.44%). Crop residues, grasses, and wood all have high levels of C and O,
262 whereas animal manure and coal present high C contents but low O contents; N and S contents of
263 crop residues are higher than those in wood and lower than those in coal [33, 45, 47, 51, 52] (Table
264 1).

265 C, H, O, N, and S are the main components of solid fuels. The combustion of C, H, and O
266 involves an exothermic reaction that generates CO₂ and H₂O. Therefore, C, H, and O contribute in a
267 positive manner to the energy content of fuel. C–C bonds contain higher energy than C–H and C–O
268 bonds in crop residues, and cotton stalk has a higher energy value because of its high level of C. A
269 high concentration of S can cause sulfation and lead to Cl release [33, 53]. The concentrations of N
270 and S in crop residues are important because NO_x and SO₂ atmospheric pollutants are easily
271 generated during combustion [20, 54]. Compared with fossil fuels, the lower contents of N and S in
272 crop residues are particularly important for environmental protection. The generation and emission
273 of pollutants should be controlled in crop residue combustion.

274 3.1.4. Mineral elements

275 Fig. 5 shows that wheat straw has the lowest P content and highest K content, whereas cotton stalk

276 has the highest P content and lowest K content. The Na contents in wheat straw and corn stover are
277 significantly lower than the contents in the other samples, and corn stover has the narrowest variation
278 range. Ca in rape stalk is the highest and has larger variation ranges, whereas corn stover has the
279 highest level of Mg. The Fe contents are higher in wheat and rice straw than others, and Fe in crop
280 residues is mainly present in the oxide form. Cu and Zn are present at low levels, and the variation
281 ranges of Cu and Zn in crop residues are 0.20–19.88 mg/kg and 0.75–93.41 mg/kg, respectively.
282 Table 1 and Fig. 5 show that the total content of P, K, Na, Ca, Mg, Fe, Cu, and Zn in cotton stalk is
283 the lowest, whereas that in wheat straw is the highest, which may be due to its high K content. The
284 variation ranges of the major mineral elements in crop residues are P (0.04–5.38 g/kg), K
285 (2.04–49.53 g/kg), Na (0.00–10.97 g/kg), Ca (0.03–19.63 g/kg), Mg (0.05–5.97 g/kg), and Fe
286 (0.03–2.39 g/kg) (Fig. 5). The P and K contents in crop residues are higher than those in wood and
287 coal, and the P, Ca, and Mg contents in crop residues are lower than those in animal manure, whereas
288 the Ca and Fe contents in crop residues are lower than those in coal [33, 45, 52, 55, 56] (Table 1).
289 However, the heavy metals, Cu (<50 mg/kg) and Zn (<100 mg/kg), in crop residues, grasses, wood,
290 and coal are all at low levels, and can be considered as trace elements [20, 45] (Table 1).

291 The mineral elements in crop residues are important for the control of combustion process and
292 product recovery. Slagging, fouling, sintering, and corrosion are related to the presence of mineral
293 elements in crop residues. P and water vapor together easily form pyrophosphate ($\text{H}_4\text{P}_2\text{O}_7$), which
294 can combine with fly ash to form hard and insoluble phosphate deposits during combustion [57]. K
295 has a negative effect on the ash melting behavior, lowering its melting point, and can also cause the
296 formation of higher aerosols, thereby enhancing the formation of sediments and emission of particles
297 [58]. Therefore, the emission of harmful exhaust gases should be of larger concern during cotton
298 stalk combustion, and the formation of aerosols and sediments should be better controlled during
299 wheat straw combustion. Na is present mainly as ions of volatile substances, but at a content only 4.5%
300 that of K. The slagging of crop residues is more apparent with high levels of K and Na, but occurs to

a lesser extent with high levels of Ca and Mg [59]. The high ash levels and severe slagging observed after the combustion of rice straw are due to the high K and Na contents and low Ca content, whereas the lower ash content and reduced slagging from cotton stalk combustion results from its low levels of K and Na, and high level of Ca. Therefore, slag removal devices should be fully considered in the selection of combustion equipment for crop residues burning. Ca can affect soil pH and function as a cation exchange agent after the combustion of crop residues [60]; thus, the high Ca content in rape stalk has the largest effect. The heavy metals Cu and Zn have important effects on ash quality and particle emissions. In the anaerobic fermentation of crop residues, Ca, Mg, Fe, Cu, and Zn can effectively promote the degradation of organic matter and the formation of soluble microbial products, and can also enrich acid-producing microorganisms [14].

3.2. Correlations and associations of the compositions of crop residues

3.2.1. Relationship between the coefficients of variation and the means of the compositions

The function diagrams between the coefficients of variation and the means of the compositions are shown in Fig. 6. The composition values, given in descending order, are as follows: VM > C/O/cellulose > hemicellulose/lignin/FC > ash > Moist/H/CP/WSC > K > N > S > Ca > Na/Mg > P > Fe > Zn > Cu. The stability of the crop residue compositions can be demonstrated by the coefficient of variation [61]. The variability of the VM, C, and O contents is relatively small (coefficient of variation < 10%), whereas the other compositions exhibit larger variations. In particular, the coefficient of variation values for WSC and mineral elements, usually have larger coefficient of variation values (Fig. 6f). Fig. 6 shows that the coefficient of variation values of crop residues compositions have significant negative correlations with the mean concentrations of the compositions, that is, the compositions with larger mean values usually have smaller coefficient of variation values. Through nonlinear fitting, significant exponential functions can be derived between the coefficient of variation values and the means of the compositions. Several differences exist among the exponential functions: the correlation coefficient values of the exponential functions are

0.63, 0.55, 0.57, 0.81, and 0.64 ($p < 0.05$) for wheat straw, rice straw, corn stover, rape stalk, and cotton stalk, respectively, and that for the total crop residues is 0.55. ExpDec1 exponential functions were obtained between the coefficient of variation values and the means of the compositions of wheat straw, rice straw and cotton stalk, whereas ExpDec2 exponential functions were observed for corn stover and rape stalk. These results may be caused by the variabilities of the compositions of the five collected crop residue samples. The compositional variability of the five crop residues is large, as shown in Figs. 2–5 ($p < 0.05$), which may be caused by the differences in the species, cultivars, irrigations, and local climates and soil conditions [61]. Crop residues collected for this study contain many varieties, large quantities, and wide distributions. Thus, the compositions of wheat straw, rice straw, corn stover, rape stalk, and cotton stalk are representative and reflect the basic characteristics of these five crop residues across China.

3.2.2. Principal component analysis and correlation analysis

The score plots of PCA reflect the score distributions of the five crop residues based on their compositions, and the loading plots reflect the correlation and contribution rates of the compositions for the distributions (Fig. 7). Table 2 shows the correlations among the compositions of all crop residues. The variations explained by PC1 and PC2 are 34.08% and 19.80% based on cellulose, hemicellulose, lignin, WSC, CP, and ash, which together explain 53.88% of the overall variation (Fig. 7a). The distributions of wheat straw, rice straw, rape stalk, corn stover and cotton stalk are not arranged randomly and show some regularity. An evident trend is observed along the PC1, which can be mostly attributed to the hemicellulose, WSC, and lignin values. Cotton stalk, belonging to the Malvaceae, can be distinguished from wheat straw, corn stover, and rice straw, belonging to the Gramineae, and rape stalk, belonging to the Cruciferae. In the family Gramineae, corn stover is a C4 plant, and wheat and rice straws are C3 plants [19, 62], and PCA distribution trends could be observed. Fig. 7a and Table 2 show that hemicellulose and ash are in the negative direction of PC1 and PC2, with significant negative correlation to cellulose, lignin, WSC, and CP ($p < 0.01$) (i.e.,

351 hemicellulose/ash–cellulose/lignin/WSC/CP). WSC and CP are in the positive direction of PC1, and
352 WSC is significantly positively correlated with CP ($p < 0.01$) (i.e., WSC–CP).

353 The PCA score plot in Fig. 7b shows that the overall variation explained by PC1 and PC2 together
354 is 84.48% based on the proximate compositions. PCA could not be used as an identification tool, but
355 it could demonstrate that the clustering rules of the five crop residues were a visualizing dimension
356 space. Fig. 7b and Table 2 show that VM is in the negative direction of PC1 and PC2, and is
357 significantly negatively correlated with Moist, ash, and FC ($p < 0.01$) (i.e., VM–Moist/ash/FC).

358 Fig. 7c shows that the overall variation explained by PC1 and PC2 together is 64.71% based on
359 the ultimate compositions and ash. Ash contributes largely to the sequential distributions of rice straw,
360 wheat straw, rape stalk, corn stover, and cotton stalk. Fig. 7c and Table 2 show that O is in the
361 negative direction of PC1 and PC2, whereas C, H, N, and S are in the positive direction of PC1. Thus,
362 O has a significant negative correlation with C, H, N, and S, and significant positive correlations
363 among C, H, N, and S exist ($p < 0.01$) (i.e., C–H–O–N–S).

364 Fig. 7d shows that the overall variation explained by PC1 and PC2 together is 43.63% based on
365 the mineral elements. The distributions of wheat straw and corn stover, mostly at the negative end of
366 PC2, are attributed to K and Fe, whereas rape stalk is evidently along the positive direction of PC2
367 and mostly attributable to Na and Ca. Fig. 7d and Table 2 show that P, Na, and Ca are in the positive
368 direction of PC2, and significant positive correlations exist among them ($p < 0.01$) (i.e., P–Na–Ca). P,
369 Mg, Fe, Cu, and Zn are in the negative direction of PC1, with significant positive correlations among
370 them ($p < 0.01$) (i.e., P–Mg–Fe–Cu–Zn). P is in the positive directions of PC1 and PC2, and K is in
371 the negative directions of PC1 and PC2, and K is significantly negatively correlated with P ($p < 0.01$)
372 (i.e., K–P).

373 Table 2 shows that, among the different compositions of crop residues, the correlated groups are
374 hemicellulose–lignin/P, CP–N–P/Mg/Cu, VM–ash–FC, and ash–C/H/O/K, with correlation
375 coefficient values $R > 0.50$. Hemicellulose and lignin interact through covalent and hydrogen bonds,

and are important parts of the cell wall. Hemicellulose is significantly negatively correlated with lignin and P. CP, N, P, Mg, and Cu components can chelate, and significant positive correlations are observed between them ($p < 0.01$). VM is the combusted organic matter, and VM is significantly negatively correlated with FC and ash ($p < 0.01$). C, H, and O are important constituents of organic matter, and K is an important component of ash. Thus, ash is significantly negatively correlated with C, H, and O, and ash has significant positive correlation with K

3.3. Energy conversion potentials of different crop residues

The HHV was used to assess the potential of crop residue conversion into heat by combustion. The HHV of cotton stalk is the highest, and the HHVs of wheat straw and rape stalk are equivalent, and that of rice straw is the lowest (Fig. 8a). The HHVs of crop residues mainly depend on the combustion of organic matter. The thermal energies of cellulose, lignin, and CP are relatively high, and those of hemicellulose and WSC are relatively low. HHV increases by 0.20 MJ/kg with each 1% ash decrease [63]. HHV is highly positively correlated with lignin and C and is inversely correlated with ash and K ($R > 0.45$) (Table 2). The highest HHV for cotton stalk may be due to its high lignin and C contents and low ash content. The variation range of the HHV of crop residues is 12.97–18.58 MJ/kg, which is lower than the HHV ranges of wood (19.40–20.70 MJ/kg) and coal (24.24–28.60 MJ/kg) [6, 58].

Biological fermentation and liquefaction technologies can convert crop residues into high-value-added ethanol. The variation range of the theoretical ethanol conversion yields of crop residues is 336.69–658.25 g/kg (Fig. 8b), with rice straw at the top of the range, followed by that of corn stover, and cotton stalk exhibits the lowest conversion yield. Ethanol or other products made from crop residues are usually derived by the bioconversion of hydrolyzed sugar. Therefore, straws with higher amounts of cellulose, hemicellulose, and WSC components will be better raw materials for ethanol fermentation and liquefaction. The theoretical ethanol conversion yields of rice straw and corn stover are higher because of their higher cellulose, hemicellulose, and WSC contents, whereas

the theoretical ethanol conversion potential of cotton stalk is the lowest for the opposite reasons (Fig. 2).

Biomethane is one of the main conversion products of the anaerobic fermentation of crop residues, and generally accounts for more than 50% of all gas products [64]. Fig. 8c shows that, the variation range of the theoretical biomethane conversion yield of crop residues is 151.48–288.45 L/kg. The theoretical biomethane conversion yield of rape stalk is higher, perhaps because it is an oil crop residue with more organic matter. The theoretical biomethane conversion yield of crop residues is positively correlated with cellulose and hemicellulose [14], and rice straw has a higher theoretical biomethane conversion yield because of its higher cellulose and hemicellulose contents. The theoretical biomethanol conversion yield of crop residues is negatively correlated with lignin [14]; thus, the yield from cotton stalk is the lowest.

The theoretical energy conversion potentials of crop residues in China in 2014 are shown in Table 3. If 100% of the 2014 outputs of the five crop residues in China were converted into HHV, ethanol, and biomethanol, then the total highest theoretical energy conversion potentials would be recovered from corn stover, which could produce 4.03×10^9 GJ HHV, 112.61 Mt ethanol, and 50.28×10^9 m³ biomethanol. The theoretical energy conversion potentials of the annual outputs of rice and wheat straws take second and third places, with rape and cotton stalks rounding out the bottom of the list (Table 3). China is rich in crop residues, however, only 18.72% of the annual output can be used for fuel and new energy utilization [65]. Then the estimated fuel equivalents for wheat straw, rice straw, corn stover, rape stalk, and cotton stalk would be approximately 17.39, 19.47, 25.71, 4.23, and 3.50 Mt standard coal, respectively, for a total conversion output of approximately 70.31 Mt standard coal, accounting for approximately 3% of China's coal consumption [28]. If 18.72% of the annual outputs of crop residues were converted into ethanol, the best conversion of wheat straw, rice straw, corn stover, rape stalk, and cotton stalk would produce approximately 14.37, 18.44, 21.08, 3.32, and 2.47 Mt ethanol, respectively, for a total theoretical ethanol conversion output of approximately 59.68 Mt,

accounting for approximately 8% of China's oil consumption [28]. The analogous conversion of 18.72% of the five crop residues into biomethanol would generate approximately 6.60×10^9 , 8.26×10^9 , 9.41×10^9 , 1.69×10^9 , and 1.12×10^9 m³ biomethanol, respectively, for a total conversion output about 27.08×10^9 m³ biomethanol, accounting for approximately 20% of China's gas consumption [28]. The annual output of crop residues increases every year in China [26], and will continue to grow to contribute highly to bioenergy supplies. Thus, converting the low cost, convenient use, and large quantities of crop residues into high-value-added energy resources is necessary, which will have long-term significance for reducing energy depletion problems and improving the environment.

4. Conclusions

The compositional characteristics of wheat straw, rice straw, corn stover, rape stalk and cotton stalk were significant different ($p < 0.05$) and highly variable. The compositions variation ranges of the five crop residues contents were cellulose (24.91–54.26%), hemicellulose (8.33–32.74%), lignin (10.40–33.36%), WSC (0.32–19.85%), CP (1.15–13.98%), Moist (1.08–8.94%), VM (55.82–80.25%), ash (1.81–19.93%), FC (8.30–27.45%), C (34.65–53.91%), H (3.17–7.94%), O (30.82–50.84%), N (0.13–2.23%), S (0.15–1.44%), P (0.04–5.38 g/kg), K (2.04–49.53 g/kg), Na (0.00–10.97 g/kg), Ca (0.03–19.63 g/kg), Mg (0.05–5.97 g/kg), Fe (0.03–2.39 g/kg), Cu (0.20–19.88 mg/kg), and Zn (0.75–93.41 mg/kg). The coefficient of variation values were negatively correlated with the means of the crop residues compositions. The 22 compositions could explain several variations and clustering rules of the five crop residues, and several significant correlations among the compositions were observed. The HHV as well as the theoretical ethanol and theoretical biomethane yields of the five crop residues were 12.97–18.58 MJ/kg, 336.69–658.25 g/kg, and 151.48–288.45 L/kg, respectively. Crop residues are considered renewable resources that have high theoretical thermal energy, ethanol and biomethane potentials.

Acknowledgements

This work was supported by the Agro-Scientific Research Project in the Public Interest (No.

201003063), we would like to thank all of the project partners, Chinese Academy of Agricultural Engineering, Nanjing Research Institute for Agricultural Mechanization Ministry of Agriculture, South China Agricultural University, Shanghai Jiao Tong University, Northwest Agricultural and Forestry University and Zhejiang University, for providing samples. We would also like to acknowledge the supports given by the Natural Science Foundation of China (Nos. 31271611 and 31201123), the Project 2662015QD009 supported by the Fundamental Research Funds for the Central Universities, the Innovation Team Project of the Ministry of Education and Department of Agriculture, the Program for New Century Excellent Talents in University (NCET-12-0524).

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FIGURES

Fig. 1. Sampling locations of wheat straw, rice straw, corn stover, rape stalk, and cotton stalk in China

Fig. 2. Variations of organic chemical compositions of crop residues. The middle lines and hollow squares within the box represent the median and mean values of all data; the lower and upper edges, and bars and diamonds inside and outside the box represent 25 and 75, 5 and 95, and <5 and >95 percentiles of all data, respectively.

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630 **Fig. 3.** Variations of proximate compositions of crop residues. The middle lines and hollow squares within the
631 box represent the median and mean values of all data; the lower and upper edges, and bars and diamonds
632 inside and outside the box represent 25 and 75, 5 and 95, and <5 and >95 percentiles of all data, respectively.

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Fig. 4. Variations of ultimate compositions of crop residues. The middle lines and hollow squares within the box represent the median and mean values of all data; the lower and upper edges, and bars and diamonds inside and outside the box represent 25 and 75, 5 and 95, and <5 and >95 percentiles of all data, respectively.

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663 **Fig. 5.** Variations of mineral elements in crop residues. The middle lines and hollow squares within the box
664 represent the median and mean values of all data; the lower and upper edges, and bars and diamonds inside
665 and outside the box represent 25 and 75, 5 and 95, and <5 and >95 percentiles of all data, respectively.

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Fig. 6. Relationship between the coefficients of variation and the means of the compositions of crop residues.

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Fig. 7. Principal component analysis (PCA) of the compositions of crop residue samples

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697 **Fig. 8.** Higher heating values (HHV), theoretical ethanol conversion yields, and theoretical biogas
698 conversion yields of the five crop residues. The middle lines and hollow squares within the box represent the
699 median and mean values of all data; the lower and upper edges, and bars and diamonds inside and outside the
700 box represent 25 and 75, 5 and 95, and <5 and >95 percentiles of all data, respectively.

Table 1 Statistical analysis and differences of the compositions of crop residues in this study (n=1076) and the compositions of other biomasses and solid fossil fuels in the literatures.

Compositions	Crop residues in this study						Other biomasses in the literatures			Solid fossil fuels in the literatures
	Wheat straw	Rice straw	Corn stover	Rape stalk	Cotton stalk	Total samples	Grasses [6, 7, 47, 52]	Animal manure [44]	Wood [7, 33, 45, 51]	Coal [46, 47, 55, 56]
Cellulose (%·DM)	38.42±3.66 ^b	41.30±3.31 ^c	37.24±3.38 ^a	41.91±5.12 ^c	38.37±4.15 ^b	38.81±4.10	25.00-45.00	/	40.00–65.00	/
Hemicellulose (%·DM)	21.82±3.69 ^e	18.21±3.18 ^d	17.04±2.96 ^c	14.24±3.00 ^b	13.01±3.03 ^a	17.88±4.30	30.00-50.00	/	25.00–40.00	/
Lignin (%·DM)	21.13±2.53 ^c	18.11±3.09 ^a	22.87±3.03 ^d	19.99±2.41 ^b	27.53±2.87 ^e	22.02±3.78	12.00-24.00	/	20.00–60.00	/
WSC (%·DM)	1.56±1.09 ^a	4.84±3.71 ^d	6.32±3.72 ^c	0.99±0.42 ^a	2.23±1.09 ^b	3.61±3.49	8.00-8.75	/	/	/
CP (%·DM)	3.58±1.08 ^a	5.23±1.42 ^b	5.81±1.77 ^c	4.93±2.17 ^b	6.41±1.35 ^d	4.99±1.86	3.81-6.44	/	0.63-3.13	/
Moist (%·DM)	5.01±1.08 ^c	3.78±1.30 ^a	4.38±1.03 ^b	4.59±1.17 ^b	3.92±1.10 ^a	4.46±1.19	4.56-5.00	/	/	2.36-8.71
VM (%·DM)	68.72±2.74 ^a	69.19±2.75 ^a	71.53±2.47 ^b	73.48±3.54 ^d	72.46±2.38 ^c	70.74±3.23	74.95-77.90	73.60-74.30	74.70–87.10	7.03–37.80
Ash (%·DM)	9.28±2.07 ^c	11.99±2.20 ^d	7.14±1.93 ^b	6.83±1.98 ^b	4.96±1.29 ^a	8.09±2.81	1.10-3.50	16.90-20.90	0.29–1.53	4.87–56.09
FC (%·DM)	17.01±2.21 ^b	14.80±2.45 ^a	17.00±1.97 ^b	15.07±3.27 ^a	18.58±2.17 ^c	16.65±2.57	16.0-16.99	5.60-8.80	12.40–22.50	40.97–82.20
C (%·DM)	42.46±1.22 ^b	40.65±1.93 ^a	44.11±1.73 ^d	43.17±1.96 ^c	45.84±1.86 ^e	43.25±2.21	42.40-46.03	40.45-47.42	45.00–55.41	64.37–92.23
H (%·DM)	5.44±0.56 ^a	5.35±0.60 ^a	5.65±0.59 ^b	5.80±0.42 ^c	5.89±0.64 ^c	5.59±0.59	5.90-7.76	5.04-6.01	5.50–7.70	3.61–5.21
O (%·DM)	41.75±1.93 ^b	40.49±2.28 ^a	41.66±2.74 ^b	42.39±2.46 ^c	41.67±2.65 ^b	41.63±2.46	41.60-50.4	26.07-34.80	41.30–47.70	1.82–24.73
N (%·DM)	0.63±0.19 ^a	0.85±0.27 ^b	1.03±0.29 ^c	0.79±0.34 ^b	1.13±0.26 ^d	0.86±0.32	0.61-1.09	3.43-4.11,	<0.10–0.50	0.87–2.94
S (%·DM)	0.39±0.15 ^{ab}	0.37±0.13 ^a	0.43±0.26 ^{bc}	0.63±0.18 ^d	0.45±0.26 ^c	0.44±0.22	0.06-0.47	0.48-0.94	<0.01–0.45	0.30–9.99
P (g/kg·DM)	0.50±0.34 ^a	1.38±0.78 ^d	0.99±0.53 ^c	0.82±0.48 ^b	1.45±0.56 ^d	0.93±0.62	0.24-0.96	13.90-24.70	0.00–2.07	0.04–0.20
K (g/kg·DM)	23.31±7.62 ^d	17.16±6.11 ^c	17.72±7.53 ^c	15.06±6.00 ^b	13.20±4.25 ^a	18.50±7.73	7.84-13.28	10.90-30.50	0.09–9.83	0.10–2.16
Na (g/kg·DM)	0.77±1.02 ^b	1.77±2.05 ^d	0.15±0.23 ^a	3.47±2.35 ^e	2.21±1.27 ^c	1.19±1.70	0.37-0.62	3.62-9.20	0.01–0.97	0.30–2.60
Ca (g/kg·DM)	2.91±1.95 ^b	3.23±2.38 ^b	2.03±1.12 ^a	9.22±3.96 ^d	3.93±2.04 ^c	3.54±3.04	0.52-1.72	18.00-24.10	0.00–4.75	5.00–29.90
Mg (g/kg·DM)	1.16±0.63 ^a	1.95±0.89 ^b	2.50±0.96 ^c	1.24±0.70 ^a	1.80±0.77 ^b	1.78±0.98	0.71-2.48	5.27-15.00	0.00–1.62	1.02–4.00
Fe (g/kg·DM)	0.45±0.26 ^b	0.59±0.57 ^c	0.41±0.36 ^b	0.23±0.12 ^a	0.19±0.18 ^a	0.39±0.35	0.02-0.42	0.68-3.15	0.00–1.46	4.30–33.95
Cu (mg/kg·DM)	3.08±1.55 ^b	3.42±2.39 ^b	5.91±2.24 ^d	2.47±1.48 ^a	5.17±1.59 ^c	4.24±2.25	1.80-2.52	146-918	0.14-1.23	5.60-15.00
Zn (mg/kg·DM)	7.99±6.08 ^a	25.69±13.38 ^d	13.96±11.29 ^c	14.42±8.11 ^c	10.31±5.95 ^b	13.09±10.68	4.93-9.00	424-1961	1.00-96.60	13.70-53.60

^{a, b, c, d, e} Different lowercase letter superscripts represent significant differences among different crop residues ($p < 0.05$).

Table 2 Correlation analysis results (Pearson) among the compositions and higher heating value (HHV) of crop residues (n=1076)

Compositions	Cell- ucose	Hemic- ellulose	Lignin	WSC	CP	Moist	VM	Ash	FC	C	H	O	N	S	P	K	Na	Ca	Mg	Fe	Cu	Zn
Cellulose	1.00																					
Hemicellulose	-0.11 ^b	1.00																				
Lignin	-0.16 ^b	-0.53 ^b	1.00																			
WSC	-0.06	-0.20 ^b	0.12 ^b	1.00																		
CP	-0.31 ^b	-0.44 ^b	0.19 ^b	0.19 ^b	1.00																	
Moist	0.02	0.25 ^b	-0.11 ^b	-0.20 ^b	-0.25 ^b	1.00																
VM	0.37 ^b	-0.27 ^b	0.17 ^b	0.10 ^b	0.01	-0.23 ^b	1.00															
Ash	-0.10 ^b	0.24 ^b	-0.46 ^b	-0.16 ^b	-0.06	-0.02	-0.60 ^b	1.00														
FC	-0.39 ^b	-0.04	0.36 ^b	0.13 ^b	0.18 ^b	-0.13 ^b	-0.51 ^b	-0.50 ^b	1.00													
C	-0.13 ^b	-0.29 ^b	0.55 ^b	0.16 ^b	0.23 ^b	-0.13 ^b	0.34 ^b	-0.62 ^b	0.33 ^b	1.00												
H	-0.07 ^a	-0.08 ^a	0.07 ^a	0.00	0.15 ^b	0.01	0.17 ^b	-0.50 ^b	0.10 ^b	0.34 ^b	1.00											
O	0.25 ^b	0.12 ^b	0.00	0.03	-0.28 ^b	0.20 ^b	0.35 ^b	-0.51 ^b	0.01	-0.31 ^b	-0.22 ^b	1.00										
N	-0.35 ^b	-0.47 ^b	0.30 ^b	0.20 ^b	0.82 ^b	-0.24 ^b	0.03	-0.06	0.21 ^b	0.31 ^b	0.18 ^b	-0.37 ^b	1.00									
S	0.04	-0.26 ^b	0.05	-0.02	0.16 ^b	-0.09 ^a	0.14 ^b	0.08	-0.13 ^b	0.25 ^b	0.08 ^a	-0.36 ^b	0.20 ^b	1.00								
P	-0.10 ^b	-0.51 ^b	0.23 ^b	0.15 ^b	0.58 ^b	-0.25 ^b	0.02	-0.02	0.06	0.08 ^a	0.05	-0.18 ^b	0.52 ^b	0.07 ^a	1.00							
K	-0.14 ^b	0.16 ^b	-0.10 ^b	-0.13 ^b	-0.15 ^b	0.16 ^b	-0.42 ^b	0.53 ^b	-0.11 ^b	-0.28 ^b	-0.30 ^b	-0.26 ^b	-0.10 ^b	0.05	-0.10 ^b	1.00						
Na	0.23 ^b	-0.30 ^b	0.00	-0.21 ^b	0.10 ^b	-0.05	0.15 ^b	-0.06 ^a	-0.08 ^a	0.01	0.02	-0.01	0.06	0.17 ^a	0.11 ^b	-0.19 ^b	1.00					
Ca	0.14 ^b	-0.26 ^b	-0.16 ^b	-0.34 ^b	0.08 ^a	0.01	0.16 ^b	0.01	-0.20 ^b	-0.07 ^a	0.11 ^b	-0.05	-0.00	0.30 ^b	0.16 ^b	-0.10 ^b	0.40 ^b	1.00				
Mg	-0.13 ^b	-0.24 ^b	0.12 ^a	0.37 ^b	0.50 ^b	-0.10 ^b	0.09 ^b	-0.10 ^a	0.04	0.11 ^b	0.05	-0.10 ^a	0.52 ^b	-0.03	0.32 ^b	-0.13 ^b	-0.10 ^b	-0.14 ^b	1.00			
Fe	0.02	0.17 ^b	-0.22 ^b	-0.06	-0.02	0.13 ^b	-0.23 ^b	0.30 ^b	-0.12 ^b	-0.25 ^b	-0.18 ^b	-0.06	-0.05	-0.06	0.17 ^b	0.14 ^b	-0.11 ^b	-0.06	0.20 ^b	1.00		
Cu	-0.20 ^b	-0.20 ^b	0.23 ^b	0.25 ^b	0.51 ^b	-0.02	0.07 ^a	-0.14 ^b	0.10 ^b	0.20 ^b	0.04	-0.15 ^b	0.52 ^b	0.08 ^a	0.33 ^b	-0.06	-0.15 ^b	-0.18 ^b	0.47 ^b	0.11 ^b	1.00	
Zn	0.00	0.12 ^b	-0.20 ^b	0.12 ^b	0.26 ^b	-0.18 ^b	-0.03	0.26 ^b	-0.20 ^b	-0.23 ^b	0.01	-0.15 ^b	0.17 ^b	-0.01	0.30 ^b	-0.12 ^b	0.03	0.15 ^b	0.15 ^b	0.18 ^b	0.20 ^b	1.00
HHV	-0.11 ^b	-0.22 ^b	0.52 ^a	0.07 ^a	0.13 ^b	-0.11 ^b	0.30 ^b	-0.62 ^b	0.35 ^a	0.58 ^a	0.20 ^b	0.26 ^a	-0.16 ^b	0.01	0.29 ^b	-0.30 ^b	-0.02	0.08 ^a	0.07 ^a	-0.22 ^a	0.20 ^a	-0.24 ^b

^a Correlation is significant at the 0.01 level (2-tailed).

^b Correlation is significant at the 0.05 level (2-tailed).

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Table 3 The theoretical energy conversion potentials of the five crop residues in China in 2014

Theoretical energy conversion potentials	Wheat straw	Rice straw	Corn stover	Rape stalk	Cotton stalk
Theoretical thermal energy conversion potential of 100% crop residues (10^9 GJ)	2.72±0.12	3.05±0.16	4.03±0.13	0.66±0.03	0.55±0.01
Theoretical thermal energy conversion potential of 18.72% crop residues for energy use (10^9 GJ)	0.51±0.02	0.57±0.03	0.75±0.02	0.12±0.00	0.10±0.00
Theoretical ethanol conversion potential of 100% crop residues (Mt)	76.76±6.04	98.48±9.36	112.61±11.74	17.74±2.26	13.19±1.52
Theoretical ethanol conversion potential of 18.72% crop residues for energy use (Mt)	14.37±1.07	18.44±1.67	21.08±2.09	3.32±0.40	2.47±0.27
Theoretical biomethanol conversion potential of 100% crop residues (10^9 m ³)	35.26±1.88	44.11±3.35	50.28±4.22	9.04±0.51	5.98±0.49
Theoretical biomethanol conversion potential of 18.72% crop residues for energy use (10^9 m ³)	6.60±0.33	8.26±0.60	9.41±0.75	1.69±0.09	1.12±0.09

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