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Pelletizing of hydrochar biofuels with organic binders

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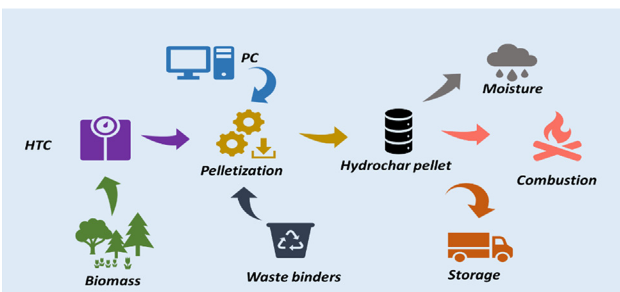
GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the effect of four organic binders (protein, starch, lignin, and molasses) on woody biomass pellets was investigated. Properties of binder based pellets were evaluated for energy consumption, tensile strength, equilibrium moisture content, and combustion performance. Results indicate that the energy consumption of all binder based pellets was less than that of hydrochar pellets (45.38 J/g). In addition, starch and protein pellets exhibited better mechanical strength when binder content is 20% (3.07 and 3.40 MPa, respectively). Scanning electron microscope results indicate that starch and protein combined closely with hydrochar. Pellets with starch as the binder (20%) exhibited the highest equilibrium moisture content. Regarding combustion performance, low ignition temperature (T_i) was observed for all binder based pellets.

1. Introduction

The efficient utilization of energy will be an urgent problem in the next several decades, and many people in developing countries lack an adequate supply of energy resources [1]. Therefore, it is imperative to find out alternative and clean fuels. Compared with fossil fuels, biomass feedstocks have a significant advantage, such as reduced greenhouse gases and sulfur dioxide [2–4]. However, it also has some disadvantages, such as high moisture content and low energy value [5]. Biomass materials, especially woody waste, are usually used as experimental materials, acquiring some positive achievements. It is reported that Canada and the United States produce several million tons of wood waste yearly [6,7]. However, unprocessed biomass cannot be used as biofuels because of their high moisture absorption capability and relatively poor storability [8,9]. Hence, indispensable pretreatment to upgrade biomass should be considered.

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Other than pyrolysis, biomass materials can be treated by thermochemistry methods, such as hydrothermal carbonization (HTC), under lower temperatures [10–12]. Biomass feedstocks treated by HTC can obtain hydrochar with advantages of decreased oxygen, moisture, and ash content, and increased energy density [13–15]. It is also an environmentally friendly technology with high thermal efficiency [16–18]. A series of decarboxylation, hydrolysis, condensation, and dehydration reactions occur during HTC [19]. Natural coalification also happens in this process, where moisture is deemed as a reaction medium [15,20]. Although modified biomass hydrochar can ease energy stress, it costs immeasurable financial resources for transportation and storage.

In comparison to hydrochar particles, pellets have advantages of enhanced quality and regular shape. The pellets maintain a certain shape due to particle integration under high pressure [21]. The bonding force between adjacent particles includes mechanical interlocking and attraction [22]. Pelletization can improve mass and energy density of pellets, and can also extend storage time for seasonal crops [23–25]. The main factors influencing pellet performance include material properties, including particle size and moisture content, and processing conditions, such as temperature, applied force, and the size of the holes in the die sleeve [26,27]. These complex conditions will decide the energy consumption (EC). Excessive EC will limit the widespread utilization of pelletization technology. Binders are still widely used in developing countries as an auxiliary substance to reduce EC during pelletization [28]. Moisture, as a frequently-used binders, can bind adjacent particles by forming an increased contact area via Van der Waals' forces [29]. It is also an indispensable lubricant and catalyst in the pelletization process [30]. Meanwhile, previous reports show that poor pellet property from palm kernel shell bio-char is due to lack of moisture, and appropriate moisture content during pelletization is from 8% to 20% [31,32]. The literature claims that soluble starch as binders has advantages of enhanced impact resistance, tensile strength (TS), and water resistance [33]. In addition, molasses based carbonized seaweed pellets have improved durability [34]. Molasses was also used in human feces char, with calorific values of 12.92 ± 0.11 MJ/kg [1].

In this study, starch, protein, molasses, and lignin are used as binders to strength pellets. Binder based pellets were prepared with low EC, better TS, and promoted combustion performance. The main objective of this study was to investigate the effect of various binders on biofuel pellets properties. The focus was on obtaining the optimum binder type. Assessing biofuel pellets with added organic binders contributes to practical application.

2. Materials and methods

2.1. Materials.

Wood sawdust (WS), China fir, was collected from a timber mill, in Changsha, China. WS hydrochar was obtained from HTC reaction equipment (a 500 mL 316 stainless steel reactor) with the addition of 10 g dried sawdust and a 100 mL deionized water per experiment. HTC temperature was 250 °C at a rate of 4 °C/min for better higher heating value (HHV) and basic performance in our previous study [35], and residence time was 1 h. The stirring speed was 150 r/min. Collected hydrochar was dried at 105 °C overnight (**Fig. S1**). The yield of hydrochar was approximately 44.2%. After drying, the hydrochar was ground until the particle size was less than 0.3 mm. The quality of protein (soybean protein isolate), starch (corn starch), molasses, and lignin (alkali lignin)) in binder based pellets were 5%, 10%, 15%, and 20%. Binders were obtained from waste resources. Proximate analysis was detected according to the Chinese standard (GB/T 28731–2012). Energy density was calculated based on former study [36]. The basic performance parameters of WS and hydrochar are summarized in Table 1.

2.2. Pelletization

Pelletization was conducted by a universal testing machine (KLC-10KN, China) at 90 °C with 0.8 g sample mixture (including 20% moisture). The machine comprised a spacer (6.5 mm in length and 13 mm in diameter), compression bar, die sleeve (with an internal diameter of 6.7 mm), and pedestal (**Fig. S2**). The integral area under the force–deformation curve represents the EC (Fig. 1). The compression process is as follows. First, the compression bar falls at a speed of 4 mm/min until the force reaches 0.5 KN, and then the speed increases to 8 mm/min until the maximum force of 4 KN is reached with a 30 s resistance time.

2.3. Pellets analysis

The thermogravimetric (TG) curves were recorded by a thermogravimetric analyzer (STA 409, Netzsch, Germany). The sample mass in each experiment was 15 mg, and the process temperature was increased from room temperature to 850 °C with a 20 °C/min heating rate and 50 mL/min air flux (N_2 = 80%, O_2 = 20%).

HHV was obtained using a Parr 6200 adiabatic oxygen-bomb calorimeter (Moline, IL). The moisture uptake test was conducted in an incubator at a temperature of 25 °C and 60% humidity. Before the test, the pellets were dried at 105 °C in an oven for 24 h. The pellet weights were measured every 15 min for the first hour and hourly for the next 8 h [15]. Mechanical strength of binder based pellets was tested by a universal testing machine. Pellets were horizontally placed between two iron plates, and applied force was put on the edge of pellets until pellets crushed. TS was calculated using the following formula [37]:

$$T_s = \frac{2F}{\pi l d} \quad (1)$$

where F is the force to break the sample pellets; d and l are the diameter and length of pellets, respectively. Impact resistance index (IRI), which is used to estimate the durability of the pellet, is calculated using the following formula [1]:

$$\mathrm{IRI} = (100 \times \mathrm{A})/\mathrm{B} \quad (2)$$

where A is the number of times that the sample is dropped, and B is the number of pieces. If the pellets are not broken after ten falls, it indicates that IRI is higher than 1000. The test method can be found in previous literature [38].

A scanning electron microscope (SEM, FEI QuANTA 200) can show the surface structure of binder based pellets. Each sample is covered in a gold film before the test to produce a conductive shell. The samples were then placed in the SEM with an accelerating voltage. The magnification was 100.

3. Results and discussion

3.1. Basic properties

The basic properties of binder based pellets and hydrochar are shown in Table 2. The fixed carbon (FC) in lignin pellets is higher than that of other binder based pellets. This is related with strong thermal stability and high density of carbon in lignin [4]. The continuous increase of volatile matter (VM) in binder based pellets is attributed to the increase in organic binders content [39]. The energy density of hydrochar pellets was 22.1 GJ/m^3, while binder based pellets increased from 17.8 to 24.1 GJ/m^3. The volume density of binder based pellets is lower than that of hydrochar pellets, suggesting that organic binders can decrease pellets volume density. A similar study indicated that the volume density of starch based biochar pellets (1080–1100 kg/m^3) was lower than that of no-binder pellets (1123 kg/m^3) [39]. The minimum value of acceptable IRI in industrial production was 50 [40]. Binder based pellets all show values much higher than the minimum. The IRI

Table 1
Proximate and element analysis of WS and hydrochar.

Sample	[a]FC (%)	[b]VM (%)	Ash (%)	C (%)	H (%)	[c]O (%)	N (%)	S (%)	HHV (MJ/kg)
WS	12.3	76.5	11.2	45.1	6.5	39.1	1.2	0.6	14.2
Hydrochar	38.4	51.8	9.8	59.9	5.3	23.5	1.5	0.4	21.1

[a] FC is fixed carbon.
[b] VM is volatile matter.
[c] Calculated by deference: O% = 100 − (C% + H% + N% + S%) − ash%.

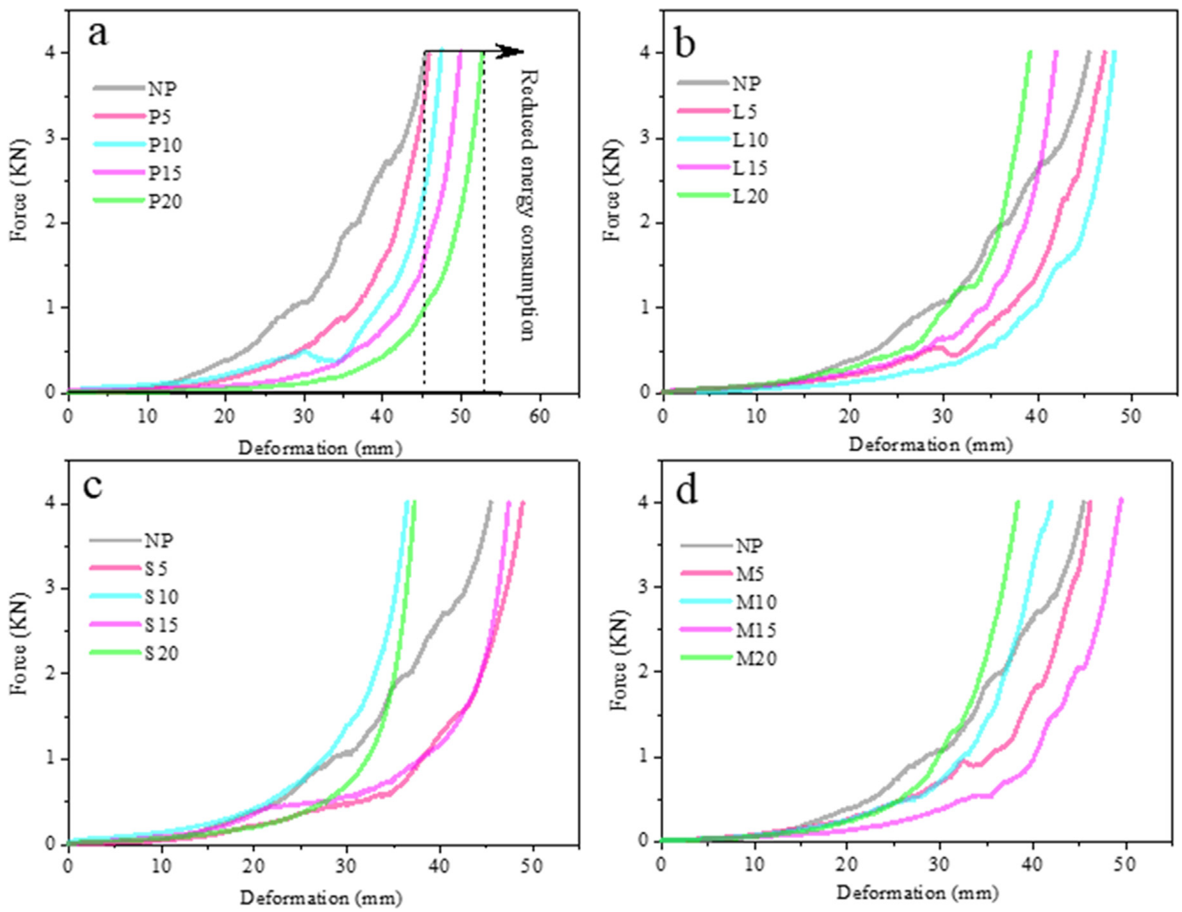

Fig. 1. Force-deformation curves of binder based pellets ((a) Protein, (b) Lignin, (c) Starch, and (d) Molasses) compared with hydrochar pellets (NP).

differed among the various pellets, relating with different lignocellulose content in binder based pellets, because more lignocellulose content could form solid bridge during pelletization [41]. And higher TS also resulted in higher IRI. It is interesting to observe that IRI of molasses and lignin pellets displayed a tremendous growth when their content exceeded 10%. The most appropriate content of starch was 5% for the highest IRI, manifesting that excess starch will not enhance pellet durability. The IRI of protein pellets is above 1000, with both 5% and 20% content.

3.2. Compression and energy consumption

The representative force–deformation curve of binder based pellets is summarized in Fig. 1. The particles combined closely with the increase in applied force. Three stages occur in this pelletization process. First, particles are rearrangement, and big particles break. Subsequently, the distance between adjacent particles is narrowed. Second, when the applied force is further increased, the particles naturally bind more tightly due to the cohesive force (Van der Waals' force and mechanical inter-lock). Lignin in biomass pellets also experiences plastic deformation during the compression process [42]. Finally, the particles continue to squeeze each other until the density remains almost unchanged [43].

In Fig. 1**a**, when the applied force is the same, deformation increased with elevated protein content, indicating that increased protein was beneficial to pelletization. In starch, lignin, and molasses pellets, deformation erratically increased when force was the same. This was possibly caused by different particle sizes and mixability between binders and hydrochar powder. Bio-oil in internal hydrochar could also influence deformation curve by reducing friction. The sunken curve around 35 mm (10% protein) was due to the above-mentioned first stage. Applied force increased slowly before 35 mm. With an increase in compression degree, deformation between adjacent particles was narrowed, and the rearrangement process occurred. Besides, added proteins could undergo denaturation under high pressure, which contributed to particle combination, causing higher pellets TS [44]. Similarly, in Fig. 1**b**, there was a transition period when lignin content was 5% (29–42 mm) and 15% (30–35 mm), respectively. It was deduced that lignin happened plastic deformation at 90 ℃ in the second densification stage [41].

Table 2
Basic properties of hydrochar and pellets.

Sample	Content (w/w)	FC (%)	VM (%)	Ash (%)	Volume density (kg/m^3)	Energy density (GJ/m^3)	IRI
hydrochar	–	38.4	51.8	9.8	–	–	–
[a]NP	–	38.0	52.4	9.6	1111	22.1	67
[b]PP	5%	36.7	53.5	9.8	879	18.6	> 1000
	10%	35.3	55.0	9.7	918	19.3	400
	15%	34.6	57.0	8.4	871	18.4	350
	20%	32.6	59.8	7.6	979	20.4	> 1000
[c]PS	5%	37.1	53.6	9.3	942	20.2	> 1000
	10%	36.6	54.6	8.8	971	20.2	100
	15%	36.0	56.1	7.9	1008	20.5	140
	20%	35.7	56.9	7.4	1180	24.1	100
[d]PM	5%	37.0	53.0	10.0	837	17.8	150
	10%	35.5	55.0	9.5	1013	21.4	66.7
	15%	34.2	57.1	8.7	940	19.6	> 1000
	20%	33.8	58.2	8.0	968	20.3	> 1000
[e]PL	5%	38.2	52.3	9.5	947	20.5	133
	10%	38.1	52.8	9.1	926	20.0	125
	15%	37.9	53.9	8.2	947	20.5	> 1000
	20%	37.8	55.0	7.2	958	21.0	> 1000

[a] NP is hydrochar pellets.
[b] PP is pellets with protein.
[c] PS is pellets with starch.
[d] PM is pellets with molasses.
[e] PL is pellets with lignin

Starch with highly polar components as soluble binders exhibited a high binding capacity for hydrogen bonds [45]. The compression curve becomes smoother with an increase in the percentage of starch (Fig. 1**c**) because starch induced gelatinization under appropriate pressure and heating conditions can make pelletization easier [28]. In this process, moisture could combine starch and soluble constituents in binder based pellets [45]. However, molasses based pellets (Fig. 1**d**) were unsmooth compared with starch pellets. A possible reason is that the sticky molasses attached to the inner wall of the die increase EC during pelletization.

The above-mentioned processes including particles rearrangement, crushing the large one, and narrowing the gap are the reason for EC (Fig. 2) [30,42]. As shown in Fig. 2, EC of lignin pellets sharply decreased when content was 5% and 10%. However, EC was maintained at approximately 25 J/g when lignin content exceeded 10%, indicating that increased lignin was not beneficial to energy reduction. Moreover, with binder content at the same level, the viscosity of molasses resulted in higher EC by increasing friction between the compression bar and the inner wall during pelletization. EC of starch and protein pellets show a continuously decreasing trend with the increase of binder content. The largest energy reduction of the starch pellet was 60%, whereas molasses, protein, and lignin had a reduction of 45%, 51%, and 44%, respectively, demonstrating that starch had better bonding performance comparing with other binders.

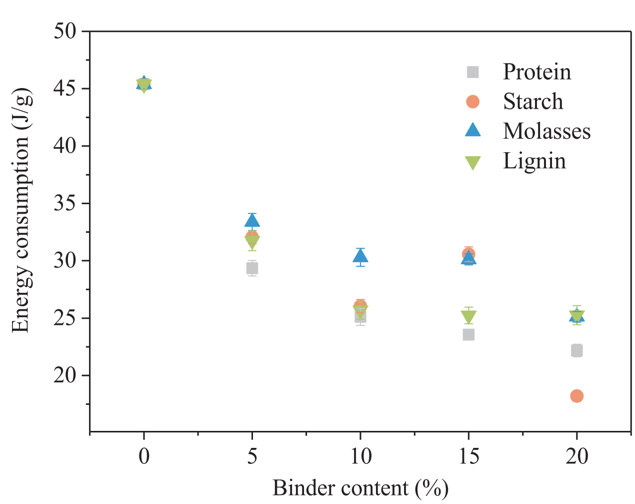

Fig. 2. EC of hydrochar pellets and binder based pellet.

3.3. Mechanical strength, SEM and EMC

The mechanical strength of binder based pellets is shown in Fig. 3**a**. Low mechanical strength causes a potential risk of pellets' quality loss during the handling and transportation process, which further affects the combustion efficiency and storage performance. In Fig. 3, TS increased with the increase of lignin and protein content. The raised TS of the lignin pellet was ascribed to a cohesive and attractive force. The generation of a solid bridge by softening the lignin contributed to strengthening the pellets [39]. The binder type was more important since binder based pellets have higher TS than that of hydrochar pellets. For instance, protein and starch pellets showed higher TS than that of molasses and lignin pellets when binder content was at the same level. The maximal TS value of the starch pellet was 3.4 MPa, whereas that of the hydrochar pellets (NP) was only 1.4 MPa, indicating that starch could improve pellet TS. However, TS of molasses pellets was less than that of hydrochar pellets until binder content exceeded 15%. In this paper, TS of various biomass pellets from former studies and three selected pellets from this study (hydrochar pellets, 20% starch, and protein pellet) are compared in Fig. 3**b**. From the figure, wood sawdust hydrochar pellet only reached 0.90 MPa, while 20% protein and starch pellet could reach 3.07 and 3.40 MPa, respectively, indicating that starch and protein could increase the contact area between particles. Besides, pinewood sawdust pellets and hydrochar pellets could reach 3.91 and 7.10 MPa, respectively [15], which was higher than that of the rice husk pellet [37,39]. In order to compare properties of binder based pellets with other materials, **Table S1** was summarized [15,33,37].

Various binders show different effects on the morphological structure of pellets. Fig. 4 is the SEM images of binder based pellets (20% binders). As shown in Fig. 4, there was a crack on the surface of nobinder pellets. The crack could weaken the resistance to shape change, causing the movement between adjacent particles during the transportation process [15]. For molasses pellets, noticeable gaps are also observed due to the existence of excessive moisture. In addition, the morphological structure of lignin and molasses pellet was rougher than

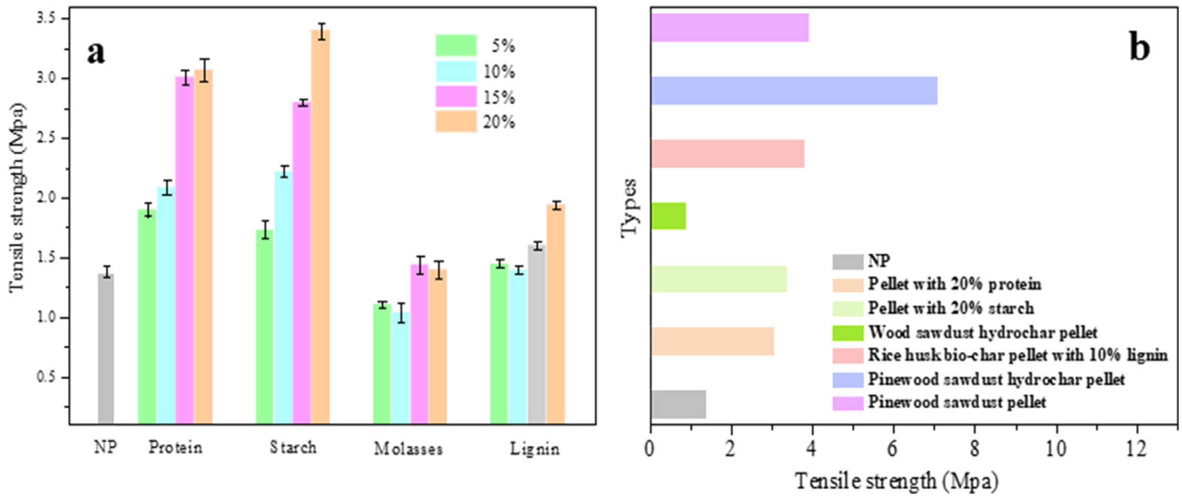

Fig. 3. Comparing TS of **(a)** binder based and hydrochar pellets (NP) and **(b)** NP, 20% starch pellets and 20% protein pellets from this study with wood sawdust hydrochar pellets [37], rice husk bio-char pellets with 10% lignin [39], and pinewood sawdust (hydrochar) pellets [15].

that of starch and protein pellets, indicating that these two binders exhibited unattractive bond property, resulting in lower TS (Fig. 3**a**).

The equilibrium moisture content (EMC) of binder based pellets is summarized in Fig. 5. As showed in the figure, the EMC of hydrochar pellets was 1.7 wt%, which was lower than that of binder based pellets. A reasonable explanation was that organic binders could absorb moisture for the existence of oxygen-containing functional groups [46]. The increase of EMC in protein pellets was related to its hydrotropic

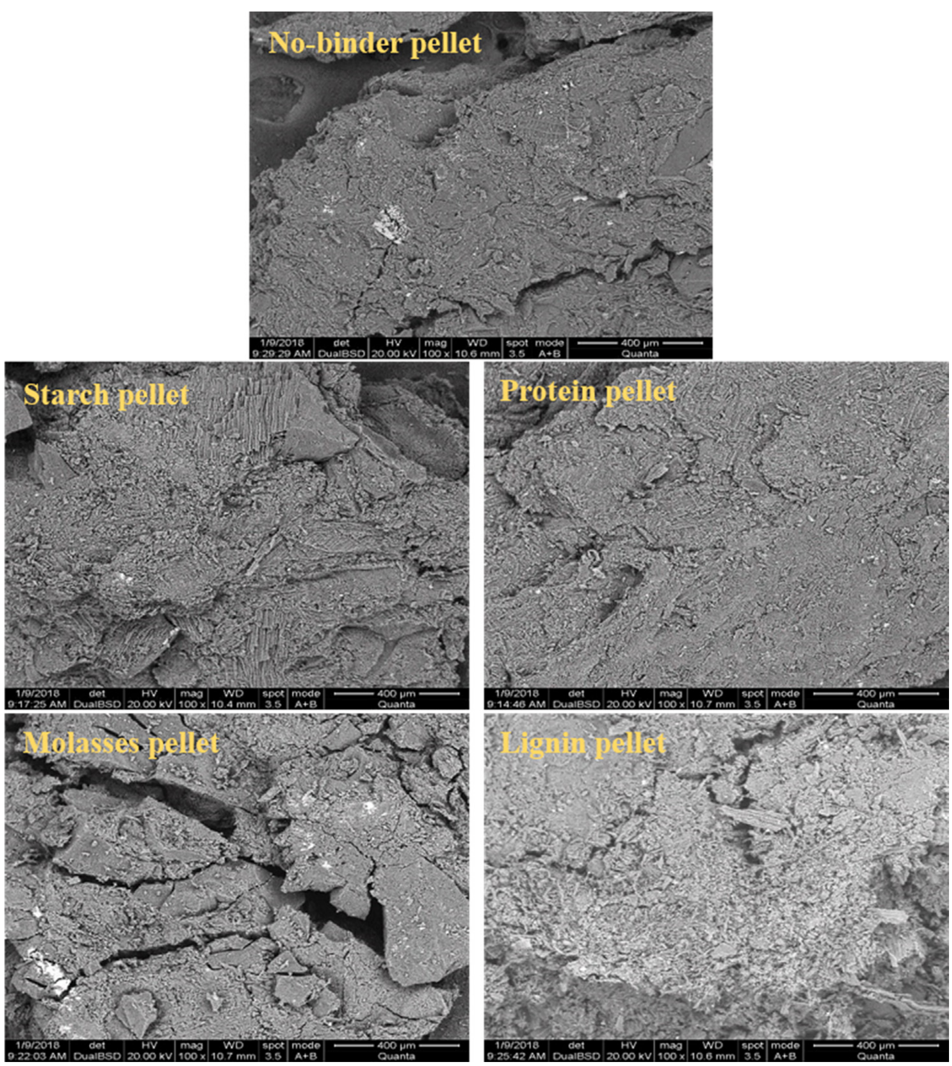

Fig. 4. Scanning electron microscope of hydrochar and binder based pellets with 20% binders.

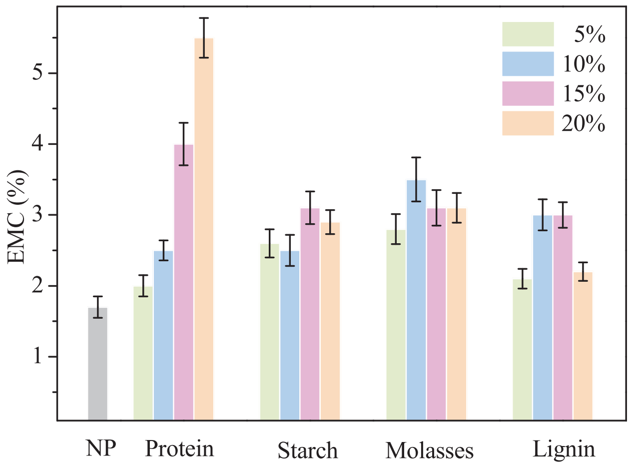

Fig. 5. Equilibrium moisture content of hydrochar pellets (NP) and binder based pellets.

properties [47]. Lignin pellets, as a hydrophilic substance, exhibited higher EMC than that of hydrochar pellets because the low HTC temperature could not degrade lignin. Furthermore, starch and molasses pellets reached the maximum EMC at 15% and 10%, respectively.

3.4. Combustion characteristics

TG curves are used to analyze the combustion behavior of binder based pellets (Fig. 6). The selected binder content is 20% for higher TS. Differential thermal gravimetric (DTG) curves describe the process of constituent changes. T_i is ignition temperature. T_m is the temperature of the maximum weight loss rate (R_m). The residue is used to estimate the combustion characteristic of pellets (Table 3). The method used to calculate T_i is reported in previous literature [48].

Different properties of samples result in different devolatilization and hydrochar combustion stages [37]. From Fig. 6, the DTG curve could be divided into two or three stages according to composition combustion. In Fig. 6**a**, the first small peak (at approximately 80 °C) was related to the evaporation of moisture. FC combustion and constituent devolatilization resulted in the second peak. In contrast, there are three peaks in starch pellets. The first peak was also ascribed to evaporation of moisture, but the wider second peak, around 300 °C, was due to the release and combustion of volatile substances from the adhesive. Furthermore, an imperceptible variation, around 665 °C, resulted from the hydrochar degradation. The same variation could be observed in the molasses based pellets (Fig. 6**c**). In Fig. 6**d**, the second peak was due to the release of volatiles and the combustion of lignin and FC. The residue of molasses and protein pellets was less than that in hydrochar pellets, indicating that pellets could burn efficiently with the addition of these two binders. In addition, protein pellets had a wider second peak, manifesting as the combustion process continued much longer. Regarding the slagging problem, previous researches reported that alkali metals as binders could cause obvious mass loss at temperatures higher than 600 °C [38,39]. From Fig. 6**b** and Fig. 6**c**, it was clear that there was an imperceptible peak between 600 and 700 °C, but it did not appear in protein and lignin pellets, indicating that in starch and molasses pellets, a slight slagging could occur.

Table 3 shows the combustion parameters of binder based pellets. In the table, T_i of binder based pellets was lower than that of hydrochar pellets for the high VM content in binders, indicating that the addition of binders contributed to the decrease in T_i. Lower T_i and higher volatiles content (Table 2) caused better combustion performance of binder based pellet [48]. T_m and R_m changed with the type of binder. The D_i represented ignition index, and higher D_i value indicated better ignition performance [49]. Starch pellet showed the highest D_i, demonstrating it had the best combustion performance.

3.5. Pyrolysis characteristics

The pyrolysis temperature was from room temperature to 950 °C with a 20 °C/min heating rate. The carrier gas was nitrogen, and the gas flow rate was 50 mL/min. From Fig. 7, all pellets had a small peak before 100 °C, indicating that moisture was released during this process. In Fig. 7**a**, the DTG curve of hydrochar pellet reached the peak at around 400 °C, which was caused by the release of volatile matter in the hydrochar pellet. In starch, molasses, and protein pellets, two peaks appeared in the DTG curve between 200 and 400 °C. It is speculated that the first peak before 400 °C is caused by the liberation of the volatile matter in the organic binders. However, lignin based pellets only had one peak in this temperature interval. A reasonable explanation was that woody biomass materials contained abundant lignin. Meanwhile, in protein, molasses, and starch pellets, the temperature during the weight loss at the beginning of pyrolysis process (after 100 °C) is 15–35 °C higher than that in the hydrochar pellets, indicating that the three binders give rise to a more complex pellet structure. Therefore, higher pyrolysis temperature was required for breaking the functional group of pellets. The initial pyrolysis temperature of lignin pellets was almost consistent with hydrochar pellet. In addition, the residue in hydrochar pellets was about 20%, while that in all binder based pellets were between 45 and 55%. The temperature of maximal mass loss rate of hydrochar, protein, molasses, and lignin was between 400 and 500 °C, while that of starch pellets was about 300 °C, demonstrating that the addition of starch contributed to the mass loss of pellets.

3.6. Economic analysis

The feasibility of 20% binder fuel pellets was evaluated by economic analysis. The improved TS and reduced energy consumption make the 20% content binders an ideal choice for long-distance transportation and a wide range of commercial applications. In the following discussion, we only considered operating and management costs and not the cost of equipment purchase. The cost calculation was based on price in Changsha, China. Moreover, the operational wear and tear of the equipment were not taken into account for cost calculation. The HTC equipment referred to an 8 m^3 reactor from a previous study [50]. According to the HTC experiment design conditions, 1548.8 ton/year of hydrochar and 23827.2 ton/year of wastewater can be produced. In addition, power usage was required during three processes in HTC, desiccation, and pelletization. Of the total electricity consumption, 11.3% goes into the drying process [38]. Considering the cost of electricity (0.888 Yuan/ kWh), 1.5 Yuan/ton waste water treatment price, and other forms of expenses, we obtain the data in Table 4.

From the Table, it is seen that the cost of binder based pellets mainly depend on binders and woody sawdust cost. The management expenditure is approximately 20% of labor costs [38]. The unit price is obtained by dividing the total cost with the hydrochar yield. The unit price of protein, starch, molasses, and lignin based pellets was respectively 2037.7, 877.2, 809.6, and 879.6 Yuan/ton. Except for protein pellets, the price of binder based pellets is all lower than that of grape marc hydrochar [50]. Starch is considered as the optimum binder for its low price and better pellet performance.

3.7. Selection

Protein and starch pellets exhibited better performance, including higher TS and lower EC compared with molasses and lignin pellets, facilitating biofuels production and transportation. Furthermore, these two pellets showed good combustion and basic property. EC could reduce by 60% (starch pellets) and 51% (protein pellets). However, protein based pellets were more expensive, making starch pellets the first choice for practical application.

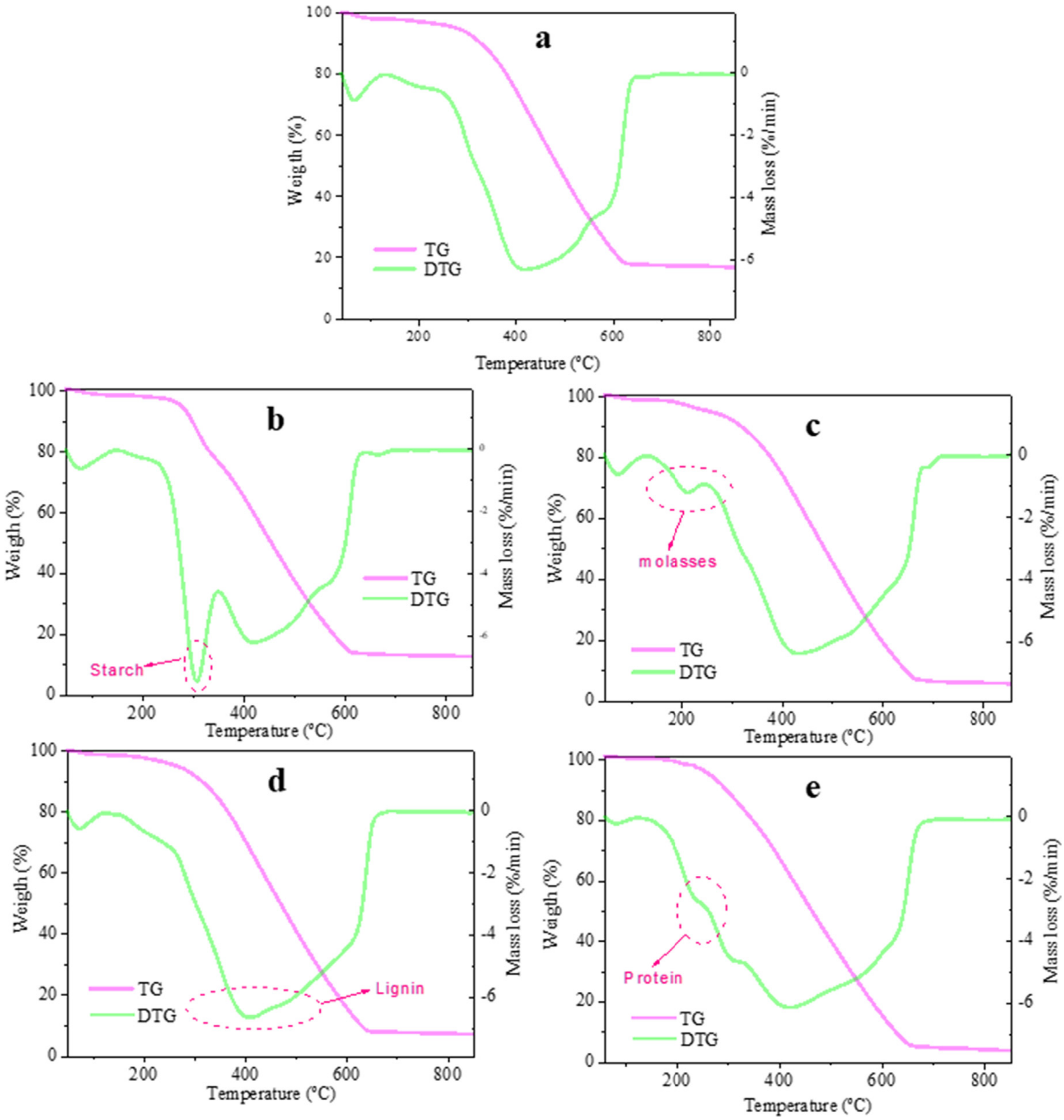

Fig. 6. TG-DTG curves of (a) hydrochar, (b) starch, (c) molasses, (d) lignin, and (e) protein pellets.

Table 3
Combustion parameters of hydrochar and binder based pellets with 20% content.

Sample	T_i (°C)	T_m (°C)	R_m (%/°C)	D_i ($\times 10^{-3}$)
Hydrochar pellets	320	421	6.35	23.0
Starch pellets	273	309	7.49	24.2
Molasses pellets	292	431	6.40	15.4
Protein pellets	260	420	6.17	17.5
Lignin pellets	285	410	6.67	17.5

4. Conclusion

This study discussed effect of binder type and content on pellets properties, but pellets had not been produced on a large scale. The emission of gaseous products during the thermochemical process needed further investigation. Results indicated that binders were found to contribute to increasing pellet performance. EC of all binder based pellets decreased by 26–51% compared with hydrochar pellets. Furthermore, EC decreased with increasing binder content, and the 20% starch pellets had the lowest EC (18.20 J/g). Starch and protein pellets obtained better TS than lignin and molasses pellets. When protein content exceeded 15%, EMC was higher than that with other organic binders (2–3.5%). T_i of binder based pellets reduced by 28–60 ℃ compared with hydrochar pellets. The addition of starch contributed to improved combustion performance for lower T_i and higher D_i. For preparing the pellets, even though protein and starch based pellets offer similar performances, the high cost of protein based pellets make starch based pellet more preferable. In addition, this work provides a reference for future research possibilities.

CRediT authorship contribution statement

Zhexian Wang: Writing - original draft, Methodology, Writing - review & editing. **Yunbo Zhai:** Supervision, Validation. **Tengfei Wang:** Writing - review & editing, Supervision. **Bei Wang:** Investigation, Visualization, Investigation. **Chuan Peng:** Data curation, Conceptualization, Investigation. **Caiting Li:** Software, Supervision.

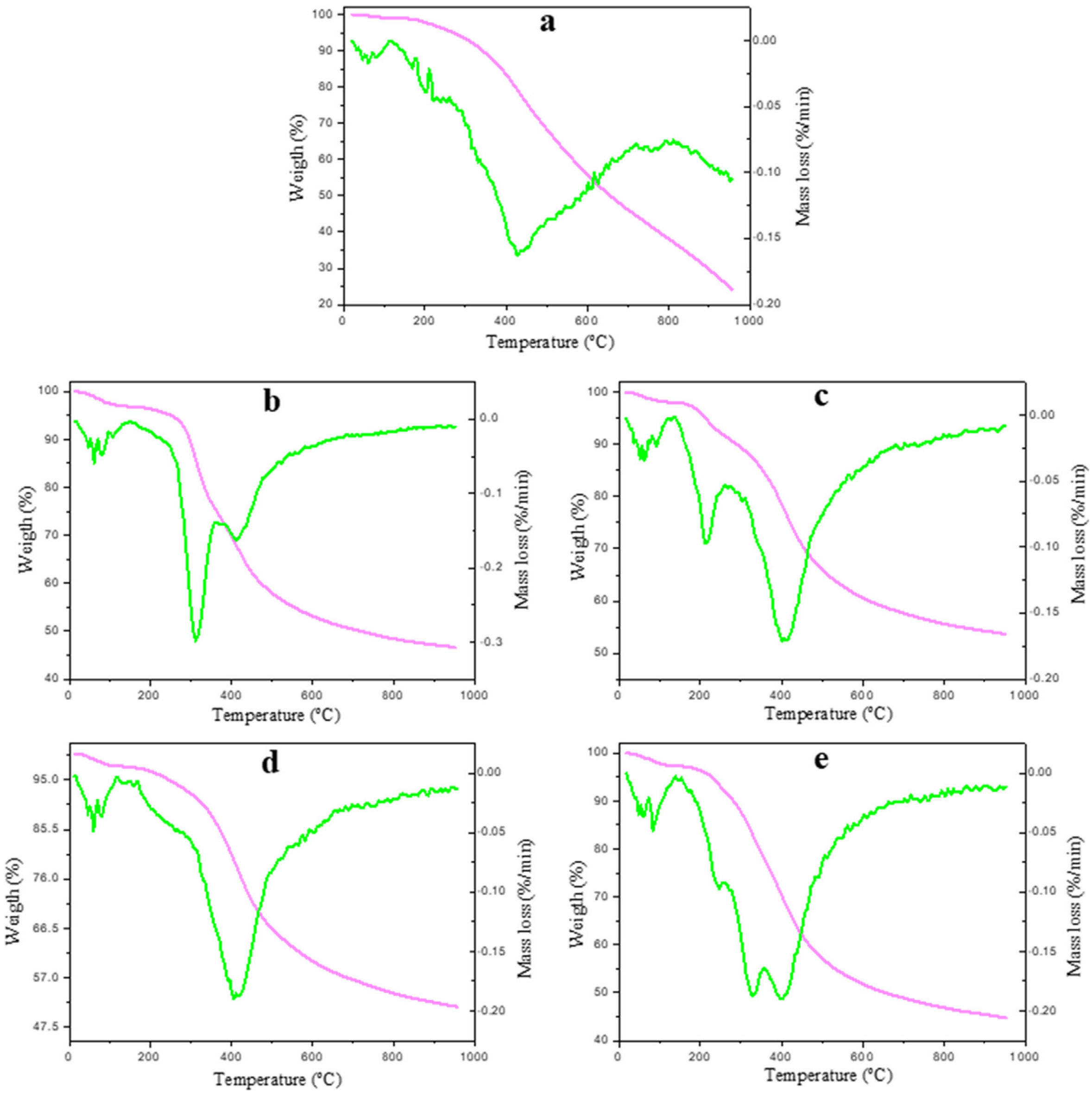

Fig. 7. TG-DTG curves of pyrolysis (a. hydrochar, b. 20% starch, c. 20% molasses, d. 20% lignin, and e. 20% protein pellets).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 4
Cost of 20% binder pellets production in a year. (Yuan/year).

	Starch pellet	Protein pellet	Molasses pellet	Lignin pellet
HTC	20068.5	20068.5	20068.5	20068.5
Desiccation	2267.9	2267.9	2267.9	2267.9
Pelletization	12234.4	13234.0	16886.2	16973.6
Binder	387200	2632960	251680	387000
Labor	93768	93768	93768	93768
Management	18753.6	18753.6	18753.6	18753.6
Water treatment	35740.8	35740.8	35740.8	35740.8
Water	77087.1	77087.1	77087.1	77087.1
Woody sawdust	1051221.7	1051221.7	1051221.7	1051221.7
Total (Yuan/year)	1698324	3945101.6	1567473.8	1702881.2

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2020.118659.

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