



Article Release Characteristics of Potassium during Biomass Combustion

Feng Zhang ¹, Xiuqin Hou ¹, Xingchang Xue ¹, Jiyun Ren ², Lingxiao Dong ², Xumeng Wei ¹, Lin Jian ¹ and Lei Deng ²,*¹

- ¹ Engineering Technology Research Institute (Supervision Company), PetroChina Xinjiang Oilfield Company, Karamay 834000, China; zhf2009@petrochina.com.cn (F.Z.); houxiuqin@petrochina.com.cn (X.H.); xuexc@petrochina.com.cn (X.X.); wxm_xj@petrochina.com.cn (X.W.); jianlin@petrochina.com.cn (L.J.)
- ² State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China; jiyunren@stu.xjtu.edu.cn (J.R.); dlx20000128@stu.xjtu.edu.cn (L.D.)
- Correspondence: leideng@mail.xjtu.edu.cn

Abstract: To investigate the release characteristics of potassium during biomass combustion, experimental studies were conducted on three typical biomass fuels in a reactor with a fixed-bed system. The effects of fuel type, combustion temperature, exposure time, oxygen concentration, and water-washing pretreatment were evaluated. The results show that the K release ratio in corn straw increases with the increment in exposure time when the temperature is between 700 and 900 °C. When burned at 900 °C for 40 min, 17.73% of K is released in the volatile combustion stage, while only 2.62% is released in the char combustion stage. When burned at 700–900 °C, the K release ratios in both corn and wheat straw improve slightly with the elevation in oxygen concentration. Water washing significantly reduces the ratio and the amount of K release from corn straw during combustion. The effect of temperature and atmosphere on K release from the water-washed sample is similar to that for the raw sample.

Keywords: biomass combustion; potassium release; exposure time; oxygen concentration; water washing

1. Introduction

The consumption of fossil fuels is associated with a large number of greenhouse gases and harmful emissions. To reduce the environmental impact of fossil fuel resources, searching for clean and renewable energy sources has far-reaching implications. Biomass, as one of the more promising and renewable energy sources, has the potential to replace fossil fuels because of its carbon neutrality and wide distribution [1-5].

The main types of biomass utilization are thermochemical conversion, biochemical conversion, and physical conversion. Among these, thermochemical conversion is the focus of current biomass research, as it could widely be applied to almost all biomass feedstocks. At present, biomass direct-fired power generation is the main technology for large-scale commercial applications of biomass and has been widely implemented in Denmark, Sweden, Finland, the Netherlands, Brazil, and many other countries [6]. The application of biomass for heat and power generation is promising due to its ability to significantly reduce CO_2 , NO_x , and SO_x emissions [7].

Although the employment of biomass as a boiler fuel is considered to be a promising approach, many issues need to be addressed. In recent years, biomass laminar-fired furnaces have been more widely applied. However, problems such as ash fouling and slagging and high-temperature corrosion needed to be addressed [8–11]. High-temperature corrosion caused by deposits in biomass laminar-fired furnaces may result in ruptured superheater pipes, which are generally caused by the release of K in the combustion process [12,13]. K plays a crucial role in both fouling and slagging, and high-temperature



Citation: Zhang, F.; Hou, X.; Xue, X.; Ren, J.; Dong, L.; Wei, X.; Jian, L.; Deng, L. Release Characteristics of Potassium during Biomass Combustion. *Energies* **2023**, *16*, 4107. https://doi.org/10.3390/en16104107

Academic Editors: Carmen Otilia Rusănescu and Nicoleta Ungureanu

Received: 13 April 2023 Revised: 11 May 2023 Accepted: 13 May 2023 Published: 15 May 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). corrosion occurs in superheaters. This process can be divided into three steps. First, during biomass combustion, some K, chloride, and sulfur elements are released into the gas phase as gaseous HCl, Cl₂, SO₂, SO₃, KOH, KCl, and K₂SO₄ [14–17]. As the flue gas passes through the furnace and gives off heat, the gaseous K salts begin to nucleate in the gas phase or condense on the fly ash particles and the surface of the superheater. The higher temperature of the flue gas causes the condensation layer, the K-salt particles, and some of the fly ash particles to stick together [13,18,19]. Then, as the temperature decreases, the gaseous K salts form sticky particles in the gas phase and form a sticky layer on the surface of the superheater. Ash accumulation occurs when the ash particles are trapped by the viscous layer [18]. Finally, the deposited KCl, K₂SO₄, and metal matrix react together with HCl, Cl₂, SO₂, and SO₃, causing a continuous accumulation of ash and the occurrence of high-temperature corrosion [8–11,18]. Therefore, it is of great significance to study the release and conversion of K in the combustion process for the design and operation of chain grate boilers or other biomass thermal conversion devices.

Extensive work [14,20-28] has been carried out to investigate the release patterns of K during the combustion of different biomass fuels. Among this, Knudsen et al. [14] investigated the release characteristics of potassium, chloride, and sulfur from annual biomass during combustion in a horizontal furnace. Keown et al. [20], Lane et al. [21], and Deng et al. [22] all investigated the effect of fuel type on K release. The results suggest that cell structure and release mechanisms may be responsible for the differences in release. Compared to wheat straw, corn straw has a lower K release and is much more sensitive to combustion temperature than oxygen concentration. Cao et al. [24] found that biomass released more than 60% of its initial K content when the combustion temperature was up to 1000 °C. Wang et al. [25] investigated dynamic K migration and transformation properties during the combustion of straw char at different O_2 concentrations. The results showed that most of the K in the rice straw char was H_2O -soluble K, while the main forms of H₂O-soluble K and insoluble K were KCl and KAlSi₃O₈, respectively. Increasing O₂ concentration stimulated the conversion of H₂O-soluble K to NH₄Ac-soluble K and HCl-soluble K and the release of K. Combustion experiments were carried out in a tube furnace with the addition of S to a maize straw/lignite fuel mix to investigate the effects of S and Al in coal on the migration conversion of potassium [28]. The results showed that an increment in S/K inhibited the release of K when S/K < 6 and an increase in S promoted the release of K when S/K > 6. When S/K = 6, the higher the temperature, the more pronounced the inhibitory effect on K release. The removal of alkali metals and chlorine by aqueous washing processes prior to the utilization of biomass for thermal conversion can fundamentally protect combustion equipment and reduce harmful emissions [29]. The transfer and recovery characteristics of inorganic nutrients inherent in Eucalyptus minor and its char were investigated by Wu et al. [30]. The results of Deng et al. [22,31,32] showed that water-washing treatment was effective in removing water-soluble K. As the washing temperature increased, the removal efficiency of the K element was also enhanced with an increment in the washing temperature. K ions were the most abundant cations in the filtrate. The increment in cation concentration was led by the elevation of the washing temperature. Chemical oxygen demand and inorganic ion charge differences indicated that some organic compounds and organic anions were also removed during the washing process. Jiang et al. [3] found that water washing increased the initial deformation temperature of biomass ash by removing alkali metals. The K₂O removal efficiencies of the six biomass fuels ranged from 69% to 90%. Recently, Huang et al. [33] revealed that the water-washing treatment reduced the heat released from biomass during combustion. However, the migration pattern of K during biomass combustion is not well studied. Exposure time and oxygen concentration can also influence K-release behavior. In addition, water-washing pretreatment may reduce the problems of sooting, slagging, and high-temperature corrosion caused by alkali metals in the thermal conversion of biomass. Until now, there have been limited reports evaluating the influence of K in the combustion process in combination with water-washing pretreatment and mixed fuel. Therefore, it is essential to consider the

influences of exposure time, oxygen concentration, and water-washing pretreatment on the migration pattern of K during combustion.

In this study, a fixed-bed reactor system was designed and constructed to simulate the combustion reaction on a biomass boiler grate. Variations in the fugitive state of biomass K at different temperatures were investigated by chemical fractionation analysis. The effects of biomass type, combustion temperature, exposure time, oxygen concentration, and water-washing pretreatment on the reaction were quantitatively evaluated. The results of this study could provide a reference on solving ash accumulation in superheaters and high-temperature corrosion.

2. Material and Methods

2.1. Raw Material

In this study, corn straw (CS), wheat straw (WS), and rice husk (RH) were selected for investigation, all of which were obtained from rural areas in Xi'an, Shaanxi Province. The moisture contents of CS, WS, and RH were 9.75%, 7.70%, and 9.30%, respectively (asreceived base). All samples were cut and sieved to a selected particle size of 280–450 μ m [31]. The CS samples were pretreated with water washing, which is denoted by WCS. Details of the washing process can be found in our earlier studies [2,31,32,34]. In summary, a constant water bath temperature of 30 °C was chosen to ensure the repeatability of the experiment. The screened, dried CS was submerged in deionized water at 30 °C for 3 h, maintaining a solid-to-liquid ratio of 12.5 g L⁻¹. The proximate analysis and ultimate analysis of biomass are shown in Table 1; biomass was analyzed with the Organic Elemental Analyzer (EA3000) applying the National Standard of the People's Republic of China (GB/T 28731-2012 for proximate analysis, GB/T28734-2012 for C and H, GB/T30728-2014 for N, GB/T 28732-2012 for S, and GB/T3558-2014 for Cl). The contents of the main ash composition elements and molar ratio before and after the water washing pretreatment are shown in Table 2.

Table 1. I foximate analysis and altimate analysis of the biomasses (with, dry basis	Table 1. P	Proximate a	nalysis and	ultimate ana	lysis of the	biomasses	(wt%, dry	basis)
---	------------	-------------	-------------	--------------	--------------	-----------	-----------	--------

Sample	Proximate Analysis			Ultimate	Ultimate Analysis						
	Α	V	FC	С	Н	O *	Ν	S	Cl		
WS	6.80	75.29	17.91	44.11	4.97	43.67	0.20	0.25	0.183		
RH	14.23	69.67	16.10	42.17	1.86	41.30	0.37	0.06	0.076		
CS	7.09	74.89	18.02	46.18	4.89	40.50	1.09	0.25	0.055		
WCS	4.32	80.95	14.74	46.54	5.10	43.44	0.57	0.02	0.024		

(* By difference).

Table 2. Contents of the main ash-forming elements (wt%, dry basis) and molar ratio (mol/mol) in the biomasses.

Sample	Elemen	t Composit	ion	Molar Ratio					
	Si	Al	Ca	Mg	Р	K	K/Si _d	(Ca + Mg)/Si	Cl/K
WS	1.22	0.05	0.39	0.11	0.04	1.046 ± 0.016	0.615	0.328	0.193
RH	5.99	-	0.09	-	0.03	0.201 ± 0.001	0.024	0.010	0.416
CS	1.19	0.11	0.35	0.19	0.03	1.221 ± 0.016	0.737	0.387	0.050
WCS	1.20	0.07	0.31	0.14	0.02	0.185 ± 0.002	0.111	0.321	0.144

2.2. Experiment

To investigate the migration of K during the combustion of substances, a fixed-bed experimental system was built, as shown in Figure 1. The experimental system consisted of the gas supply system, the reaction system, and the cooling system. The reaction system involved a quartz tube with an inner diameter of 39 mm and a quartz cup with an inner diameter of 25 mm supported by a quartz cup holder. Before the experiment started, the mass of the quartz cup, after adding 2.0 g of biomass sample, was weighed on an electronic

balance. Next, the resistance furnace was switched on and the quartz reactor was heated to a preset temperature, then the quartz couplet and quartz cup holder were loaded into the reactor so that the dried sample was in the cooling section. Afterward, mass flow meters one and two were switched on and 500 mL min^{-1} of dispensing gas was introduced, flowing through the reactor from top to bottom. The quartz cups were then moved into the reaction zone in the middle of the resistance furnace and burned for 30 min to produce an ash sample. Finally, the quartz cup holder was withdrawn and mass flow meters one and two were switched off and three was switched on. At this point, the ash sample was cooled rapidly by both the cooling air and the water-cooling jacket. After removal and further cooling in a drying dish to room temperature, the total mass of the quartz cups and ash sample was weighed. The fixed-bed reaction system simulates the conditions of a biomass boiler grate. For each biomass sample, all combustion conditions were repeated three times to ensure the reproducibility of the experiment.



Figure 1. Schematic diagram of the vertical fixed-bed reactor.

2.3. Analysis

The total K content of raw, charred, ash, and water-washed samples of biomass is essential for the study of the migration pattern of K during the combustion process, which is obtained by reducing the sample to a liquid state with a microwave digester and measuring it with an inductively coupled plasma optical emission spectrometer (ICP-OES, Multiwave 3000 by Anton Paar, Graz, Austria). Each measurement was carried out three times to ensure reproducibility. According to Equation (1), the K release ratio can be calculated.

$$R_{\rm K} = 100 \left[1 - \left(\frac{m_{\rm res}}{m_{\rm raw}} \right) \left(\frac{C_{\rm res}}{C_{\rm raw}} \right) \right] \tag{1}$$

where $R_{\rm K}$ denotes the K release ratio (%), $m_{\rm res}$ is the mass of the residue (g), $m_{\rm raw}$ represents the mass of the raw sample (g), $C_{\rm res}$ is the K amount in the residue (μ g g⁻¹), and $C_{\rm raw}$ denotes the K amount in the raw sample (μ g g⁻¹). $C_{\rm res}$ and $C_{\rm raw}$ are calculated as follows:

$$C_i = \frac{CV}{m_i} \tag{2}$$

where C_i is the K content in the raw sample or residue (µg g⁻¹), C denotes the K concentration in the digesting solution after fixing (µg mL⁻¹), V represents the volume of the digesting solution after fixing (mL), and m_i is the mass of the raw sample or residue (g).

3. Results and Discussion

3.1. Effect of Exposure Time on K Release

To investigate the effect of exposure time on the release and conversion of K from biomass, four exposure times were selected at an oxygen concentration of 20%. Dev time is the time to burn out the command hair fraction. The effect of exposure time on K release ratio during biomass straw combustion is shown in Figure 2, while the K release rates in each reaction zone are given in Figure 3. Focusing on the data for the two biomass straws' combustion for Dev and 40 min, it is easy to see that the increment in K release ratio in the reaction zone between Dev and ~40 min at 800 and 900 $^\circ C$ is smaller than the K release ratio when the volatile fraction is burnt out. This indicates that K release at temperatures above 700 °C for 40 min occurs mainly prior to the combustion of the volatile fraction, while the char combustion phase from Dev to 40 min contributes slightly. This is attributed to the fact that the fuel K can react with Si and Al to form aluminum silicate [15] or enter the silicate network [14,15,17], thereby reducing the volatility of K. At 900 °C, 17.73% of the K is released when the volatile fraction of CS is burnt out, while 35.82% is released at 180 min. This means that 18.09% is considered to be released during the char combustion phase, which is even more than the amount during volatile fraction combustion. WS releases 32.9% of K at the end of volatile fraction combustion and 24.8% at the char combustion stage, which is close to the amount at the end of volatile fraction combustion.





When comparing the burning of CS at 800 and 900 °C, it can be seen that the K release ratio decreases with increasing temperature for Dev, 30, 40, and 180 min are 7.35%, 2.92%, 2.29%, and 1.3%, respectively. This indicates that the effect of temperature on K release is more prominent in the early stages of combustion. It can be concluded that the effect of exposure time on the K release ratio from CS during combustion is more critical than that of temperature. The WS, conversely, shows increments in release ratio of 6.70%, 5.67%, 5.13%, and 9.77% when the combustion temperature rises from 800 °C to 900 °C at the same time. However, the values are close to the first three time points, all of which are smaller than the values at 180 min. This indicates that the effect of temperature is already present in the first 40 min of combustion during the devolatilization fraction stage, although its effect diminishes as combustion continues. Ultimately, combustion temperature determines the

K release ratio from WS. It can be concluded that combustion temperature plays a decisive role in the release ratio of K from WS.



Figure 3. K release rates in each zone of the combustion experiment ($\% \min^{-1}$).

As can be seen in Figure 3, the K release rate is greatest in the volatile analysis out of the combustion phase under all conditions except for the CS at 700 °C, while K release is slow in the char combustion phase and becomes smaller as the combustion proceeds. This reveals that the release rate of K is greater before the volatile fraction is burnt out during biomass combustion, but the magnitude of the release also needs to be integrated over time, as shown in Figure 2. The Cl in the biomass acts as a shuttle to facilitate the transport of K from the biomass matrix to the surface. Thus, higher Cl/K values in WS (Table 2) promote the release rate of fuel K from the biomass matrix to the flue gas.

3.2. Effect of Oxygen Concentration on K Release

The effect of oxygen concentration on the K release ratio from CS and WS is displayed in Figure 4. Five oxygen concentrations of 5%, 10%, 15%, 21%, and 25% were selected for the combustion experiments. An oxygen concentration of 5% is insufficient compared to the sample volume, while oxygen concentrations of 10% to 25% are excessive. An increment in combustion temperature of 100 °C has a more significant effect on the promotion of the K release ratio compared to that of 5%. The ratio of K release increases with increasing oxygen concentration when the same straw is burnt at the same temperature. On the one hand, this can be attributed to destruction of the organic structure of the char by oxygen [14], which to some extent lifts the constraints on K and promotes its release. On the other hand, an improvement in oxygen concentration increases the temperature at the beginning of biomass combustion, thus promoting K release. This can be explained by the fact that some of the water-soluble potassium in biomass can be found in more stable forms, such as K_2CO_3 and organic K [15,17]. For the same type of straw burned at the same oxygen concentration, it is found that the release ratio increases with rising temperature. The increase in the temperature range of 700–800 °C is greater than that of 800–900 °C, which is probably due to the fact that a large amount of K is released in the form of KCl in the gaseous state starting at 800 °C.

3.3. Effect of Co-Combustion on K Release

Figure 5 presents K release from CS after mixing with different mass fractions of RH under combustion conditions. All data in the figure have been converted into K release per unit of raw biomass. The data are not available for the combustion of CS alone at

1000 °C, nor for mixing 20% RH, as the ash samples are not available due to adhesion to the crucible. As previous studies [16,17,24] have shown, temperature remains a crucial factor influencing K release, which is also reflected in the co-combustion temperatures for this study. However, after 800 °C, the release of K shows a modest incremental variation with temperature. The K release ratio decreases versus the RH mixing ratio increasing in terms of general trends, which is not evident at 700 °C or 800 °C. The data for each mixing point fall in the vicinity of the line connecting the K releases from single burning of CS and RH, from which it can be assumed that co-combustion does not affect K release.



Figure 4. Effect of oxygen concentration on K release ratio.



Figure 5. Effects of co-combustion of CS and RH on K release.

3.4. Combined Effect of Water Washing and Co-Combustion

Table 3 shows the effects of reaction temperature and water washing on K release under an oxidizing atmosphere, indicating that the oxidizing atmosphere can also promote the release of K from the water-washed samples. The promotion effect of the oxidizing atmosphere is more significant at temperatures below 700 °C compared with the raw sample. This may be because the water-washing process removes some organic matter and some inorganic salts (including potassium, calcium, and magnesium salts) [35,36], which increases the porosity of the biogenic samples and disrupts the organic structure of the carbon chains, resulting in an incremental release pathway for organic K. From 700 °C onwards, the gaseous release of inorganic K dominates, and temperature becomes the main factor influencing the release of K. The high temperature can also destroy the organic structure of the carbon chains to a certain extent, compensating for the effect of the washing on the carbon chains, so that the oxidizing atmosphere has a similar effect on the release of K from the samples before and after water washing.

Table 3. The effects of reaction temperature and water washing on the K release of CS.

Reaction Temperature (°C)	400	500	600	700	800	900	1000	
CS	0.08	0.07	0.08	0.53	0.65	0.45	0.18	
WCS	6.46	2.99	3.43	0.55	0.52	0.39	0.55	

The effect of water washing and mixing of RH on the release of K from CS is given in Figure 6. Considering matter conservation and energy conservation, biomass mixtures should also satisfy these conclusions. The grey plane at the top of the graph characterizes the amount of K release per unit of heat when mixing different mass fractions of RH into the CS at 700–1000 °C, while the bottom plane of mixed colors characterizes the combustion of CS and RH after water-washing pretreatment. It is clear from the figure that water-washing pretreatment significantly reduces the released amount of K at each operating point. This may be due to the fact that the water-washing process removes some organic matter and some inorganic salts (including potassium, calcium, and magnesium salts) [35,36], which enhances the porosity of the biogenic samples and disrupts the organic structure of the carbon chains, resulting in an incremental release pathway of organic K. When the CS mixes with 40% RH and burns at 800 °C, the release is reduced from 0.27 mg kJ⁻¹ in the CS to 0.03 mg kJ⁻¹ in the water-washed sample. The situation is similar for the other working points. As can be seen in Table 2, the amount of K in the CS after water-washing pretreatment decreases from 12.21 mg g^{-1} in the CS to 1.85 mg g^{-1} in the water-washed sample, a reduction of 15.15% of the CS, while the RH reduces to 20.03% of the CS after water washing.



Figure 6. Effect of water-washing and mixed ratios of RH on K release for CS.

To understand the effect of water washing, the amount of K released per unit of heat at each operating point of the WCS is divided by that in the CS, which is collated in Table 4. The amount of K released after water washing is only 3.97% to 19.10% of that for the CS, which is a significant reduction. This demonstrates that water washing can significantly reduce the amount of K released from the biomass [35,36], thus alleviating the problems of ash buildup and slagging in the biomass boiler.

Table 4. The effects of water washing and mixed ratios on K release during combustion (%).

RH Mixed Ratio (%)	0	20	40	60	80	100
700 °C	5.94	10.19	13.12	11.82	3.97	7.24
800 °C	13.28	12.47	11.21	18.45	18.92	19.10
900 °C	13.68	14.89	14.76	12.10	16.34	19.10
1000 °C	-	-	12.38	13.77	12.14	15.71

4. Conclusions

In this study, a combustion experiment was carried out on CS, WS, and RH in a fixed-bed system to investigate the migration pattern of K in biomass. The effects of fuel type, combustion temperature, exposure time, oxygen concentration, and water-washing pretreatment on K-migration characteristics were examined. The main conclusions are as follows.

- (1) When burning at 700–900 °C, the K release ratio in both CS and WS increases as exposure time rises. However, when the exposure time is long enough, the K release ratio of CS is close to the same value at different temperatures. For WS, the upper limit of the release ratio is different at different temperatures. After the volatile fraction burns out, 700 °C is not sufficient to convert water-soluble K to other fugitive forms in the solid phase. The production of insoluble K is significantly promoted above 800 °C.
- (2) With augmentation of the oxygen concentration, the K release ratio increases. The enhancement of the K release ratio is more significant when increasing the combustion temperature by 100 °C than with an increment in the oxygen concentration of 5%. The K release ratio decreases overall versus the RH mixing ratio, which improves and becomes more pronounced up to higher temperatures.
- (3) The oxidizing atmosphere facilitates K release from the water-washed samples. RH mixing has essentially no effect on K release from CS. Water-washing pretreatment significantly reduces K release in the samples with different mixing ratios at different combustion temperatures. In addition, water-washing pretreatment not only reduces the K content in the samples but also removes the K with release potential.

Author Contributions: F.Z.: investigation, data curation, writing—original draft. X.H.: conceptualization, writing—review and editing. X.X.: conceptualization, writing—review and editing. J.R.: investigation, data curation, writing—original draft. L.D. (Lingxiao Dong): investigation, data curation, writing—original draft. X.W.: conceptualization, data curation, investigation, writing—original draft. L.J.: conceptualization, supervision, resources, writing—review & editing. L.D. (Lei Deng): conceptualization, supervision, data curation, investigation, writing—original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the [Key Technology Research and Field Test of Renewable Energy] under grant number [210099992002032].

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: This work acknowledges financial support from the Key Technology Research and Field Test of Renewable Energy. The authors also thank the staff at the Instrument Analysis Center of Xi'an Jiaotong University for their assistance with sample analysis. **Conflicts of Interest:** The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References

- Ahmed, I.I.; Gupta, A.K. Sugarcane bagasse gasification: Global reaction mechanism of syngas evolution. *Appl. Energy* 2012, 91, 75–81. [CrossRef]
- Long, J.; Deng, L.; Che, D. Analysis on organic compounds in water leachate from biomass. *Renew. Energy* 2020, 155, 1070–1078. [CrossRef]
- Jiang, J.; Tie, Y.; Deng, L.; Che, D. Influence of water-washing pretreatment on ash fusibility of biomass. *Renew. Energy* 2022, 200, 125–135. [CrossRef]
- 4. Jun, L. Strategy for building a digital management system of carbon assets in group enterprises. Xinjiang Oil Gas 2022, 18, 10–15.
- Cheng, Y.; Tiemei, L.; Xiang, L.; Kecheng, L.; Xuyang, Y.; Jiaqin, G. Ecological utilization and development trend of environmentfriendly drilling fluid. Xinjiang Oil Gas 2021, 17, 25–29.
- 6. Liao, Y.; Wu, S.; Chen, T.; Cao, Y.; Ma, X. The Alkali Metal Characteristic during Biomass Combustion with Additives. *Energy Procedia* **2015**, 75, 124–129. [CrossRef]
- 7. Demirbas, A. Combustion characteristics of different biomass fuels. Prog. Energy Combust. 2004, 30, 219–230. [CrossRef]
- 8. Karatas, H.; Akgun, F. Experimental results of gasification of walnut shell and pistachio shell in a bubbling fluidized bed gasifier under air and steam atmospheres. *Fuel* **2018**, *214*, 285–292. [CrossRef]
- 9. Alipour Moghadam Esfahani, R.; Osmieri, L.; Specchia, S.; Yusup, S.; Tavasoli, A.; Zamaniyan, A. H2-rich syngas production through mixed residual biomass and HDPE waste via integrated catalytic gasification and tar cracking plus bio-char upgrading. *Chem. Eng. J.* **2017**, *308*, 578–587. [CrossRef]
- Deng, L.; Jin, X.; Zhang, K.; Jiang, J.; Zhu, Z.; Che, D. Catalytic conversion of toluene by modified biochar from oak. J. Energy Inst. 2022, 102, 374–383. [CrossRef]
- 11. Deng, L.; Ma, S.; Jiang, J.; Tie, Y.; Zhang, Y.; Zhu, Z.; Belošević, S.; Tomanović, I.; Che, D. Numerical Investigation on Cofiring Characteristics of Biomass Syngas and Coal in a 660-MW Tower Boiler. *J. Energy Eng.* **2022**, *148*, 04022014. [CrossRef]
- 12. Song, H.; Zhen, H. Study on mechanism of high temperature superheater corrosion of biomass fired boiler. *Boiler. Manufacturing* **2010**, *5*, 14–18.
- 13. Jensen, P.A.; Frandsen, F.J.; Hansen, J.; Dam-Johansen, K.; Henriksen, N.; Hörlyck, S. SEM Investigation of Superheater Deposits from Biomass-Fired Boilers. *Energy Fuel* **2004**, *18*, 378–384. [CrossRef]
- 14. Knudsen, J.N.; Jensen, P.A.; Dam-Johansen, K. Transformation and Release to the Gas Phase of Cl, K, and S during Combustion of Annual Biomass. *Energy Fuel* **2004**, *18*, 1385–1399. [CrossRef]
- 15. Jensen, P.A.; Frandsen, F.J.; Dam-Johansen, K.; Sander, B. Experimental Investigation of the Transformation and Release to Gas Phase of Potassium and Chlorine during Straw Pyrolysis. *Energy Fuel* **2000**, *14*, 1280–1285. [CrossRef]
- 16. Johansen, J.M.; Jakobsen, J.G.; Frandsen, F.J.; Glarborg, P. Release of K, Cl, and S during Pyrolysis and Combustion of High-Chlorine Biomass. *Energy Fuel* **2011**, 25, 4961–4971. [CrossRef]
- 17. Zhao, H.; Song, Q.; Wu, X.; Yao, Q. Study on the Transformation of Inherent Potassium during the Fast-Pyrolysis Process of Rice Straw. *Energy Fuel* **2015**, *29*, 6404–6411. [CrossRef]
- 18. Michelsen, H.P.; Frandsen, F.; Dam-Johansen, K.; Larsen, O.H. Deposition and high temperature corrosion in a 10 MW straw fired boiler. *Fuel Process. Technol.* **1998**, *54*, 95–108. [CrossRef]
- 19. Jin, X.; Ye, J.; Deng, L.; Che, D. Condensation Behaviors of Potassium during Biomass Combustion. *Energy Fuel* **2017**, *31*, 2951–2958. [CrossRef]
- Keown, D.M.; Favas, G.; Hayashi, J.; Li, C.Z. Volatilisation of alkali and alkaline earth metallic species during the pyrolysis of biomass: Differences between sugar cane bagasse and cane trash. *Bioresource Technol.* 2005, 96, 1570–1577. [CrossRef]
- 21. Lane, D.J.; van Eyk, P.J.; Ashman, P.J.; Kwong, C.W.; de Nys, R.; Roberts, D.A.; Cole, A.J.; Lewis, D.M. Release of Cl, S, P, K, and Na during Thermal Conversion of Algal Biomass. *Energy Fuel* **2015**, *29*, 2542–2554. [CrossRef]
- 22. Deng, L.; Jiang, J.; Tie, Y.; Ma, S.; Fan, G.; Zhu, T.; Che, D. Potassium transformation and release during biomass combustion. *Can. J. Chem. Eng.* **2023**, *101*, 337–346. [CrossRef]
- 23. Ng, J.; DeMartini, N. Effect of Steam on the Release of K and Cl during Biomass and Black Liquor Combustion. *Energy Fuel* **2022**, 36, 7733–7743. [CrossRef]
- 24. Cao, W.H.; Li, J.; Li, L.; Zhang, X. Release of potassium in association with structural evolution during biomass combustion. *Fuel* **2021**, *287*, 119524. [CrossRef]
- Wang, M.; Xu, D.; Bai, Y.; Yu, G.; Zhang, J.; Zhang, S.; Xu, J.; Zhang, H.; Zhang, S.; Wei, J. Dynamic investigation on potassium migration and transformation during biochar combustion and its correlation with combustion reactivity. *Fuel* 2023, 340, 127540. [CrossRef]
- 26. Davidsson, K.O.; Korsgren, J.G.; Pettersson, J.B.C.; Jäglid, U. The effects of fuel washing techniques on alkali release from biomass. *Fuel* **2002**, *81*, 137–142. [CrossRef]
- 27. Zhang, Z.; Song, Q.; Yao, Q.; Yang, R. Influence of the Atmosphere on the Transformation of Alkali and Alkaline Earth Metallic Species during Rice Straw Thermal Conversion. *Energy Fuel* **2012**, *26*, 1892–1899. [CrossRef]

- Liu, Q.; Zhong, W.; Zhou, J.; Yu, Z. Effects of S and Al on K Migration and Transformation during Coal and Biomass Co-Combustion. ACS Omega 2022, 7, 15880–15891. [CrossRef]
- 29. Patel, B.; Gami, B.; Patel, P. The Leaching of Soluble Chloride from Terrestrial and Water-Based Biomass. Energy sources. *Part A Recovery Util. Environ. Eff.* 2012, 34, 2280–2286.
- Wu, H.; Yip, K.; Kong, Z.; Li, C.; Liu, D.; Yu, Y.; Gao, X. Removal and Recycling of Inherent Inorganic Nutrient Species in Mallee Biomass and Derived Biochars by Water Leaching. *Ind. Eng. Chem. Res.* 2011, 50, 12143–12151. [CrossRef]
- 31. Deng, L.; Zhang, T.; Che, D. Effect of water washing on fuel properties, pyrolysis and combustion characteristics, and ash fusibility of biomass. *Fuel Process. Technol.* **2013**, *106*, 712–720. [CrossRef]
- Deng, L.; Che, D. Chemical, Electrochemical and Spectral Characterization of Water Leachates from Biomass. Ind. Eng. Chem. Res. 2012, 51, 15710–15719. [CrossRef]
- Huang, X.; Tie, Y.; Jiang, J.; Deng, L.; Che, D. Water washing of biomass and biochar. Sustain. Energy Techn. 2023, 56, 103066. [CrossRef]
- Deng, L.; Long, J.; Wu, Y.; Che, D. A study on benzene release during water washing of biomass. *Asia-Pac. J. Chem. Eng.* 2020, 15, e2536. [CrossRef]
- 35. Jenkins, B.M.; Wei, R.R.B.A. On the properties of washed straw. *Biomass Bioenergy* **1996**, *10*, 177–200. [CrossRef]
- 36. He, Z.; Mao, J.; Honeycutt, C.W.; Ohno, T.; Hunt, J.F.; Cade-Menun, B.J. Characterization of plant-derived water extractable organic matter by multiple spectroscopic techniques. *Biol. Fert. Soils* **2009**, *45*, 609–616. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.