

Article

Feasibility Study of Bio-Sludge Hydrochar as Blast Furnace Injectant

Wang Liang^{1,2}, Pavlina Nanou³, Heather Wray³, Jianliang Zhang¹, Ingemar Lundstrom⁴, Stefan Lundqvist⁴ and Chuan Wang^{2,*}

¹ School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China; wang.liang@swerim.se (W.L.); zhang.jianliang@hotmail.com (J.Z.)

² Swerim AB, 97 125 Luleå, Sweden

³ TNO, Energy Transition, Biobased and Circular Technologies, Westerduinweg 3, 1755 LE Petten, The Netherlands; pavlina.nanou@tno.nl (P.N.); heather.wray@tno.nl (H.W.)

⁴ Smurfit Kappa Kraftliner Piteå Aktiebolag, 941 86 Piteå, Sweden; ingemar.lundstrom@smurfitkappa.se (I.L.); stefan.lundqvist@smurfitkappa.se (S.L.)

* Correspondence: chuan.wang@swerim.se

Abstract: Hydrothermal treatment can convert paper mill biological (bio-) sludge waste into more energy-dense hydrochar, which can achieve energy savings and fossil CO₂ emissions reduction when used for metallurgical applications. This study assesses the basic, combustion and safety performance of bio-sludge hydrochar (BSHC) to evaluate its feasibility of use in blast furnace injection processes. When compared to bituminous and anthracite coals, BSHC has high volatile matter and ash content, and low fixed carbon content, calorific value and ignition point. The T_i and T_f values of BSHC are lower and the combustion time longer compared to coal. The R_{0.5} value of BSHC is $5.27 \times 10^{-4} \text{ s}^{-1}$, indicating a better combustion performance than coal. A mixture of BSHC and anthracite reduces the ignition point and improves the ignition and combustion performance of anthracite: an equal mixture of BSHC and anthracite has a R_{0.5} of $3.35 \times 10^{-4} \text{ s}^{-1}$. The explosiveness of BSHC and bituminous coal is 800 mm, while the explosiveness of anthracite is 0 mm. A mixture of 30% BSHC in anthracite results in a maximum explosiveness value of 10 mm, contributing to safer use of BSHC. Mixing BSHC and anthracite is promising for improving combustion performance in a blast furnace while maintaining safe conditions.

Keywords: bio-sludge; TORWASH; hydrochar; combustion performance; safety performance; blast furnace ironmaking



Citation: Liang, W.; Nanou, P.; Wray, H.; Zhang, J.; Lundstrom, I.; Lundqvist, S.; Wang, C. Feasibility Study of Bio-Sludge Hydrochar as Blast Furnace Injectant. *Sustainability* **2022**, *14*, 5510. <https://doi.org/10.3390/su14095510>

Academic Editor: Rajesh Kumar Jyothi

Received: 6 April 2022

Accepted: 2 May 2022

Published: 4 May 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 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/>).

1. Introduction

The steel industry is one of the most important industrial sectors in the world, as well as one of the largest energy- and coal-consuming industries [1–3]. It has a significant impact on the global economy, but also has a significant impact on global energy consumption and CO₂ emissions. With the 2030 and 2050 targets proposed by the European Union, reducing CO₂ emissions and fossil fuel consumption is a priority for industry [4,5]. For the metallurgical industry, reducing the use of fossil fuels will also greatly improve the industry competitiveness of iron and steel enterprises [6,7]. Biomass is a carbon-neutral, renewable, green energy source with large production in Europe as well as globally [8,9]. Therefore, for the metallurgical industry, using biomass resources as an alternative energy source can greatly reduce the CO₂ emissions in the metallurgical process [10–12]. Specifically, Babich et al. [13] reported that the maximum utilization potential of biomass resources in the metallurgical industry is mainly manifested in the blast furnace injection process.

Biological (bio)-sludge from paper mills is a biomass residue with huge annual output that is produced throughout the year and contains a large amount of organic matter [14]. The discharge of this sludge to the environment can result in environmental pollution [15].

Therefore, using bio-sludge as an energy source in blast furnace injection processes allows the sludge residue to be utilized as a resource while benefiting the sustainable development of the metallurgical industry. However, as pointed out by Gerner et al. [16,17], bio-sludge has low volume and energy density, low calorific value, and high alkali metal content, which greatly limits the direct use of the sludge. Therefore, the sludge must be treated to improve its energy density for subsequent use in a blast furnace injection. Wang et al. [18] introduced the hydrothermal carbonization of sewage sludge into high value-added products or biofuels. The hydrothermal carbonization technology not only solves the problems associated with sewage sludge treatment from the perspective of resource recycling, but also contributes to greenhouse gas sequestration to mitigate climate change, as well as some additional socioeconomic benefits. Liu et al. [19] investigated the combustion characteristics of sewage sludge and found that the combustion kinetics of sewage sludge-derived hydrochar indicated a high quality of these solid fuels. He et al. [20] investigated the combustion characteristics of hydrochar produced from sewage sludge and found that hydrochar has low activation energy. At the same time, the hydrochar has higher carbon and lower volatile content, and has higher combustion quality than sewage sludge. Furthermore, Cebi et al. [21] reported that hydrochar derived from sewage sludge has lignite-like fuel properties. Experiments combining sewage sludge hydrochar with coal samples of different properties showed more stable combustion conditions, improved fuel quality, and reduced emissions. On the other hand, hydrothermal carbonization suffers from low overall conversion efficiency in relation to liquid effluent re-use and conversion [22]. In contrast, TORWASH hydrothermal treatment is performed under milder conditions than hydrothermal carbonization, enabling higher overall conversion efficiencies [23]. Although there has been extensive research on bio-sludge hydrochar, the application in the field of ironmaking is not well understood.

Therefore, the purpose of this study was to investigate the metallurgical properties of bio-sludge hydrochar produced under relatively mild hydrothermal conditions and to assess the feasibility of bio-sludge hydrochar as an injectant in blast furnace processes. Firstly, two commonly used blast furnace injectants (bituminous coal and anthracite coal) were selected as control samples for the performance test of bio-sludge hydrochar. Then, the differences between bio-sludge hydrochar and the other two fuels were evaluated based on three aspects: basic performance, combustion performance and safety performance. Further, the effect of the addition ratio of bio-sludge hydrochar on the properties of anthracite mixtures was explored. Finally, the feasibility of bio-sludge hydrochar application in a blast furnace smelting process was assessed to provide useful information for expanding the application of sludge resources.

2. Materials and Methods

2.1. Experimental Raw Materials

In this study, bio-sludge (BS) was used as the feedstock for the TORWASH hydrothermal treatment process. The bio-sludge is the residue stream produced by the aerobic wastewater treatment plant on location of the Smurfit Kappa paper mill in Piteå, Sweden. The bio-sludge used for the experiments described here contained 1.5–1.8 wt.% dry matter. Selected analysis results of the bio-sludge are given in Table 1.

Table 1. Selected analysis results of the raw bio-sludge residue stream.

Sample	Proximate Analysis (%)			Ultimate Analysis (%)					HHV (MJ/kg)
	FC _d ^a	V _d	A _d	C	H	O	N	S	
BS	11.0	70.0	19.0	41.3	5.8	32.7	6.3	2.2	18.1

Note: ^a, calculated by difference. FC, fixed carbon; A, ash; V, volatile matter. _d, dry basis.

The bio-sludge was used as a feedstock for long duration tests at pilot scale on location of the paper mill of Smurfit Kappa. These tests were performed during the months August-

September in 2021 at an average of 26.6 kg/h inlet flow for 410 h of operation. In total, 10,893 kg of TORWASH effluent was produced after treatment at 200 °C at an average residence time of 30 min. The TORWASH product was pumped through a pilot scale membrane filter press also installed on location of the paper mill. By applying a final membrane squeeze at a maximum pressure of 15 bar, the solids could be dewatered to press cakes containing 40–50% dry matter. These were subsequently dried in an oven and transported to Swerim to perform the analyses and experiments for the metallurgical application as described in this paper. This solid fraction resulting from TORWASH hydrothermal treatment and subsequent dewatering is called bio-sludge hydrochar (BSHC).

In addition to the BSHC, two pulverized coals typically used in steel enterprises were selected as control samples, namely bituminous coal (BC) and anthracite coal (AC). A series of pretreatments were performed on the BSHC and two types of coal, including crushing and screening to achieve prepared samples with a particle size up to 0.074 mm. These materials were dried at 105 °C for 8 h and used as raw materials for subsequent experiments.

2.2. Experimental Method

Proximate analysis and ultimate analysis were performed on the BSHC, BC and AC. The proximate analysis of the samples was measured at 815 °C and 915 °C using a muffle furnace. The ultimate analysis was determined using an elemental analyzer (Flash 2000, Thermo Electron Corporation, Waltham, MA, USA). The K and Na contents were determined by chemical analysis, and the P content was determined by X-ray fluorescence spectroscopic analysis.

The calorific value of the three samples was measured using a bomb calorimeter. The ignition point and explosiveness of the fuels were the two main evaluation parameters for the safety performance. The ignition point and explosiveness were measured with the commonly used blast furnace coal safety performance measurement device in China. The explosiveness of the samples was measured by a fuel safety performance measurement device, a schematic diagram of which was included in our previous research [24]. Inject 1 g of fuel into a pipe with a heat source of 1050 °C and observe the return flame length of the fuel to determine the explosive characteristics of the sample.

The combustion performance of the samples was carried out by a thermogravimetric analyzer (HCT-4, Henven, Beijing, China) to assess the combustibility of the fuels. The combustion performance of the fuels was measured by a thermogravimetric analyzer in an air atmosphere. Before the thermogravimetric experiment, 5 mg (± 0.1 mg) of sample was weighed and placed in a crucible which was then placed in the thermogravimetric analyzer. The heating rate of the thermogravimetric experiment was controlled at 20 °C/min, and the temperature was raised from room temperature to 800 °C.

3. Results

3.1. Basic Performance of Fuel

To clarify the differences between the basic properties of BSHC and BC and AC as blast furnace injection fuel, the basic performance of the three fuels was tested, including proximate analysis, ultimate analysis and calorific value analysis. The experimental results are shown in Table 2.

Table 2. Basic performance analysis results of BSHC, BC and AC.

Sample	Proximate Analysis (%)			Ultimate Analysis (%)					HHV (MJ/kg)
	FC _d ^a	V _d	A _d	C	H	O ^a	N	S	
BSHC	15.87	61.09	23.04	46.50	6.04	19.45	4.22	0.74	23.45
BC	59.10	34.95	5.95	65.02	3.82	23.77	0.99	0.45	27.46
AC	82.49	8.85	8.66	85.26	3.40	0.40	1.08	1.09	30.65

Note: ^a, calculated by difference. FC, fixed carbon; A, ash; V, volatile matter. _d, dry basis.

It can be seen from Table 2 that the volatile content, H content and O content of the BSHC is higher than for coal. Anthracite coal has the lowest volatile matter content (8.85%) of the three fuels tested. In general, fuels with higher volatile content (H and O elements) have better combustion performance [25]. Therefore, the use of BSHC may improve the combustion efficiency of fuel in the blast furnace, but the higher volatile content may also result in safety issues. BSHC has a high ash content, and its use in blast furnaces will produce more by-products, such as slag. The content of fixed carbon and C of BSHC is lower than for coal, resulting in a lower calorific value. BC has some similar characteristics as BSHC, for instance higher O element content when compared to AC. However, the fixed carbon content of AC is much higher than that of BC and BSHC, and the ash content is lower, which also explains the higher calorific value of AC. Therefore, BSHC and AC each have advantages and disadvantages. To balance the advantages and disadvantages of the two, a mixture of BSHC and anthracite is proposed.

3.2. Hazardous Element Analysis of Fuel

The alkali metal content in the fuel has a very important influence on blast furnace smelting [26]. After the fuel is burned in the tuyere zone of the blast furnace, the alkali metals in the fuel will volatilize and move to the upper part of the blast furnace, and will be adsorbed on the surface of the coke. Since alkali metals have a catalytic effect on the gasification reaction of coke, the presence of alkali metals will accelerate the gasification reaction of coke and reduce the strength of the coke, thus affecting the production of molten iron in a blast furnace. Phosphorus is also an important element that is detrimental in steelmaking [27]. However, in the blast furnace ironmaking process, since desulfurization cannot be performed, all phosphorus elements will directly enter the molten iron, which will seriously affect the quality of the molten iron [27]. Therefore, the alkali metal content and phosphorus content in the injection fuel need to be controlled at a low level. The test results of the K, Na, and P element contents of the three fuels are shown in Table 3.

Table 3. Quantities (%) of critical contaminants in bio-sludge hydrochar (BSHC), bituminous coal (BC) and anthracite coal (AC).

Sample	K	Na	P
BSHC	0.077	0.110	2.489
BC	≤0.010	0.060	0.079
AC	0.155	0.790	0.006

The K and Na contents in BSHC are 0.077% and 0.110%, respectively, which are higher than those of BC, but lower than those of AC. Therefore, compared with AC, the use of BSHC in a blast furnace may be advantageous. However, the P content of the BSHC is 32 times that of BC and 415 times that of AC. Therefore, from the perspective of P content, the use of BSHC will have a serious negative impact [28]. The higher P content in the BSHC is an important factor limiting the use of the BSHC, indicating that the BSHC should be mixed with other fuels.

3.3. Combustion Performance of Fuel

The combustion performance of the sample is also an important performance indicator. Figure 1 shows that the combustion properties of the three fuels are significantly different, but the shapes of the combustion curves are very similar. The combustion conversion curve of BSHC is located in the low temperature region, the combustion conversion curve of BC is in the middle region, and the conversion curve of AC is in the high temperature region. Through the shape of the combustion conversion curve, the combustion process of the fuel can be divided into three main stages: (1) the initial heating stage, in which mainly the volatilization of water occurs and the ignition of the sample. In this stage, the weight loss of the sample is not obvious; (2) the combustion reaction stage, which mainly includes the decomposition of volatile matter in the sample and the combustion of char. The weight

loss of the sample mainly occurs at this stage; and (3) the combustion completion stage, in which the volatile matter and char are basically completely burned, and the remaining ash undergoes a combustion reaction, and the weight loss of the sample is also not obvious. The combustion conversion process of BSHC is significantly earlier than that of BC and AC, indicating that the combustion performance of BSHC is better.

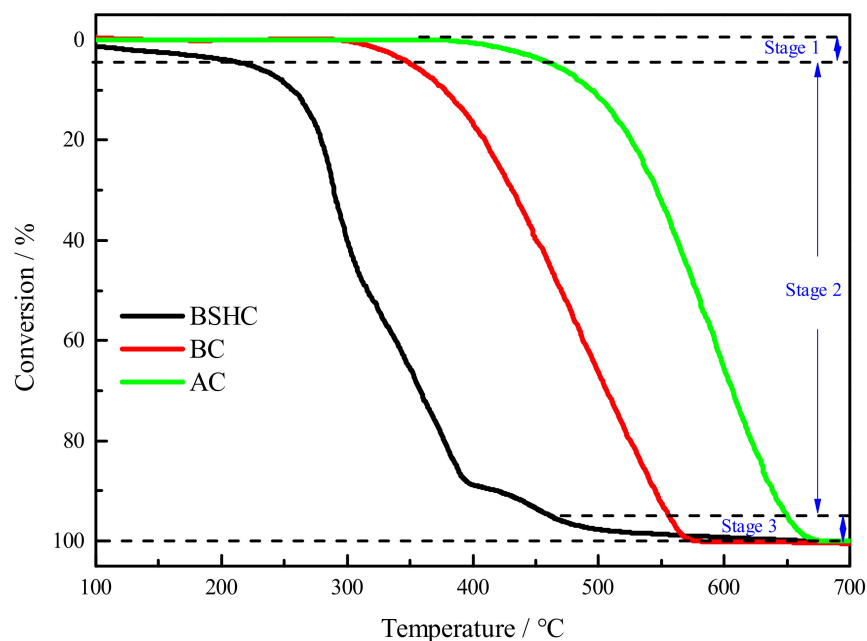


Figure 1. Combustion conversion curves of Bio-sludge hydrochar (BSHC), bituminous coal (BC) and anthracite coal (AC).

The initial combustion temperature (T_i), the final combustion temperature (T_f), and the combustion reaction characteristic parameter ($R_{0.5}$) were used to quantitatively characterize the combustion performance of the three samples [29]. The $R_{0.5}$ of the combustion reaction was calculated according to formula (1) [30]. The results of the combustion reaction characteristic parameters of different samples are listed in Table 4. The initial combustion temperatures of the BSHC, BC and AC were 221 °C, 351 °C, and 465 °C, respectively, and the final combustion temperatures were 462 °C, 556 °C, and 650 °C, respectively. Among them, the initial combustion temperature of AC is close to the final combustion temperature of the BSHC, indicating that the AC has a higher conversion temperature during the combustion process. Also, the combustion process of AC is shorter than that of BSHC and BC, and the temperature difference is only 185 °C. Smaller temperature differences indicate shorter conversion times, possibly due to the higher initial temperature of the anthracite. At the same time, it can also be seen that the $R_{0.5}$ value of BSHC is the largest, and the $R_{0.5}$ value of AC is the smallest. These results show that the BSHC has better combustibility, while AC has the worst combustibility, and the combustibility of BC is in between. Therefore, the addition of BSHC may have a promoting effect on the combustion performance of AC, which is beneficial to the combustion and application of the sample.

$$R_{0.5} = \frac{0.5}{t_{0.5}} \quad (1)$$

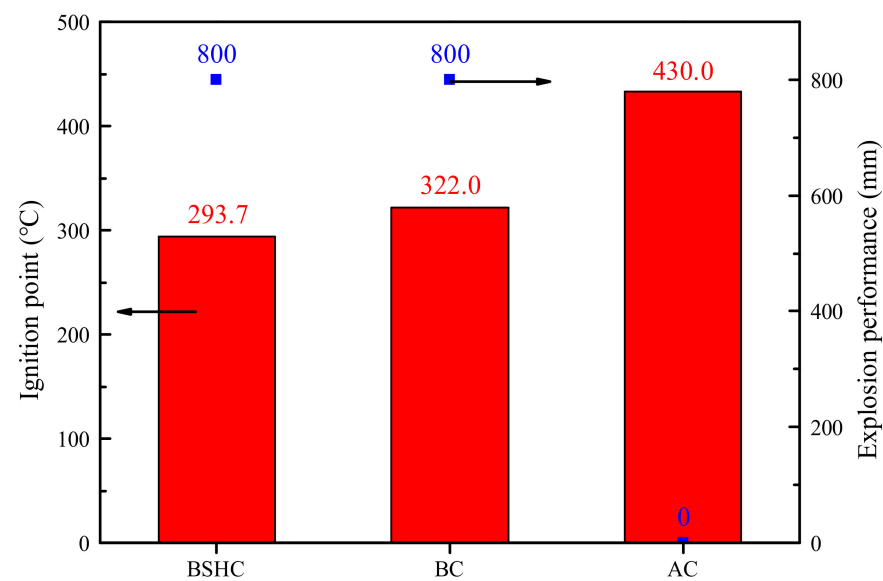
where, $t_{0.5}$ is the time required for the conversion of 50% of the sample, s.

Table 4. Combustion reaction characteristic parameters of the three fuels.

Sample	T_i (°C)	T_f (°C)	$T_f - T_i$ (°C)	$R_{0.5} \times 10^{-4}$ (s ⁻¹)
BSHC	221	462	241	5.27
BC	351	556	205	3.55
AC	465	650	185	2.88

3.4. Safety Performance of Fuel

The ignition point and explosion performance of fuel are important indicators to evaluate its safety performance [24,31]. In order to ensure the safety performance of blast furnace injection fuel in the pulverization and injection process, it is necessary to clarify the ignition point and explosion performance of the fuel. The experimental results of ignition point and explosion performance are shown in Figure 2.

**Figure 2.** Ignition point and explosion performance of fuel.

The ignition point of the BSHC is 293.7 °C, which is lower than that of BC, which is 322.0 °C. The ignition point of AC is 430.0 °C, which is much higher than that of BC and BSHC. Generally speaking, the volatile content is the main factor affecting the ignition point of the fuel [32]. Due to the high volatile content of the BSHC, the ignition point of the BSHC is low. Therefore, the use of BSHC is more beneficial to ignition and combustion in the blast furnace. However, the lower ignition point of BSHC is a safety issue during storage and transport, a major disadvantage of BSHC. Therefore, the BSHC and AC could be mixed to balance the ignition points of the two samples. Figure 2 also shows that the explosiveness of BSHC and BC is strong, reaching 800 mm, which is also mainly due to the high volatile content of BSHC and BC [31]. The volatile content of AC is low, so the explosiveness of AC is 0. Therefore, considering the safety of BSHC application, it is necessary to reduce the volatile content of the sample by adding AC, so as to improve the safety performance of the sample.

3.5. Study on the Properties of Mixtures

3.5.1. Determination of Mixture Ratio

According to the analysis results of the three samples, the volatile matter is the most important factor affecting the safety performance of the fuel. The volatile content of BC is 34.95%, but BC still has a high explosiveness. Therefore, in order to ensure the BSHC can be used safely, the volatile content of the mixed sample should be lower than 34.95%.

Accordingly, the maximum value of BSHC in a mixture with anthracite was determined to be 50%. In addition to a 50% mixture of BSHC and AC, mixtures of 40%, 30%, 20% and 10% BSHC in anthracite were also prepared and tested. The mixed samples were labeled as xBSHC/yAC according to their content, where x and y are the percentages in the samples, respectively. The specific mixing scheme and the proximate analysis results of the mixed samples are shown in Table 5. As the amount of AC in the mixed samples increases, the fixed carbon content of the mixed samples also increases, while the volatile content and ash content decreases. The volatile content of the mixed samples ranges from 14.07–34.94%. In addition, as the proportion of AC increases, P content decreases linearly.

Table 5. Proximate analysis results of blended fuels.

Sample	FC _d ^a (%)	V _d (%)	A _d (%)	P (%)
50%BSHC/50%AC	49.18	34.97	15.86	1.25
40%BSHC/60%AC	55.84	29.75	14.41	1.00
30%BSHC/70%AC	62.50	24.52	12.98	0.75
20%BSHC/80%AC	69.17	19.30	11.53	0.50
10%BSHC/90%AC	75.83	14.07	10.10	0.25

Note: ^a, calculated by difference. FC, fixed carbon; A, ash; V, volatile matter. _d, dry basis.

3.5.2. The Combustion Performance of Mixed Samples

In order to clarify the change of the combustion performance of the samples after mixing, the combustion conversion curves of different mixed fuels were measured by a thermogravimetric analyzer. The experimental results are shown in Figure 3. The combustion conversion curves of different mixtures show obvious differences, indicating that the amount of BSHC added is an important factor affecting the combustion of the mixtures. The combustion characteristics of the mixed fuel depend on the combustion characteristics of the individual fuels, so the combustion curve of the mixtures is between the combustion curves of the two individual fuels [33,34]. And with the increasing proportion of BSHC, the combustion process of the mixed fuel gradually moves to the low temperature region, and the combustibility is improved. Ye et al. [35] also noted that the mixing of biomass hydrochar with anthracite can significantly improve the combustion performance of anthracite, so that the combustion of the mixtures moves to the lower temperature region.

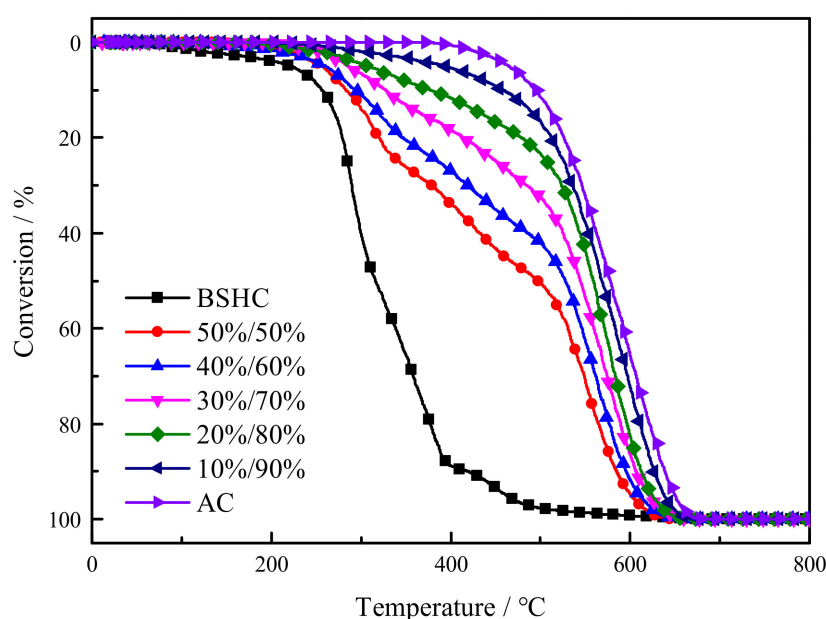


Figure 3. Combustion conversion curves of different mixtures.

To quantitatively analysis the change of the combustion performance of the mixed fuels, the combustion characteristic parameters of the mixtures were also calculated (Table 6). As the proportion of BSHC in the mixture increases, the T_i value decreases. This indicates that the addition of BSHC can significantly reduce the initial temperature of anthracite, which is beneficial to the conversion of anthracite. The T_f value also showed the same trend as T_i , but the change of T_f values was relatively small. The T_f value of the 50%BSHC/50%AC sample was 600 °C, which is 50 °C lower and 138 °C higher than that of 100% anthracite and 100% BSHC, respectively, indicating that the addition of the BSHC has little effect on the final combustion temperature of AC. Therefore, as the BSHC addition increases, the combustion time gradually increases. The $R_{0.5}$ value of the mixed sample also shows a gradually increasing trend. This also shows that the addition of BSHC has an obvious promoting effect on the combustion reaction of AC. Therefore, the addition of BSHC will promote the combustion performance of anthracite, which is beneficial to the combustion and application of the sample.

Table 6. Combustion characteristic parameters of mixed fuel.

Sample	T_i (°C)	T_f (°C)	$T_f - T_i$ (°C)	$R_{0.5} \times 10^{-4}$ (s ⁻¹)
BSHC	221	462	241	5.27
50%BSHC/50%AC	256	600	344	3.35
40%BSHC/60%AC	260	610	350	3.16
30%BSHC/70%AC	285	621	336	3.06
20%BSHC/80%AC	307	625	318	2.98
10%BSHC/90%AC	393	637	244	2.93
AC	465	650	185	2.88

3.5.3. The Safety Performance of Mixed Samples

In order to clarify the safety performance of the mixed fuel of BSHC and AC, the ignition point and explosiveness tests were carried out on the mixed fuel. The test results of the safety performance of the mixture are shown in Table 7. The ignition point temperature decreases as the proportion of BSHC in the mixture increases, and the ignition temperature ranges from 323.33–413.00 °C. When the addition of BSHC is 10%, the ignition point of the sample is 413 °C, which is still higher than 400 °C, which is not conducive to ignition and combustion in the blast furnace. When the fuel is injected into the blast furnace, if the fuel has a lower ignition temperature, it is beneficial to improve the combustion efficiency of the fuel. The ignition points of these mixtures are within the normal range and close to the ignition points of injection fuels commonly used by steel companies. It can be seen from the explosiveness test results that when the ratio of BSHC does not exceed 30%, all the mixing schemes are non-explosive. Therefore, the proportion of BSHC should be appropriately increased according to the actual situation of the mill in the steel enterprise. When the ratio of BSHC is 30%, the volatile content of the mixture is 24.52%. This also provides a reference for other fuels in terms of safety performance. Therefore, under the premise of ensuring the safe production of the mill, the proportion of BSHC in the mixed fuel should not exceed 30%.

Table 7. Safety performance of mixed fuels.

Sample	Ignition Point (°C)				Explosion Performance (mm)			
	1st	2nd	3rd	Average Value	1st	2nd	3rd	Max Value
50%BSHC/50%AC322	326	322	322	323.33	800	800	800	800
40%BSHC/60%AC341	320	327	327	329.33	200	210	200	210
30%BSHC/70%AC341	343	339	339	341.00	10	0	0	10
20%BSHC/80%AC380	400	388	388	389.33	0	0	0	0
10%BSHC/90%AC421	405	413	413	413.00	0	0	0	0

4. Discussion

It was found that bio-sludge hydrochar has significantly lower fixed carbon content and HHV than bituminous and anthracite. Therefore, when BSHC is used as a fuel for blast furnace ironmaking, more bio-sludge hydrochar may be required to ensure normal blast furnace production [36]. In this study, it was reported that BSHC has a high explosiveness, and the direct use of sludge hydrochar would negatively impact the safety of the ironmaking process. However, based on experience, the particle size of biomass can be enlarged to make it more difficult to contact with air, so as to ensure safer use. In a study by Sundqvist et al., it was also reported that due to the differences in grindability of different biomasses, use of high quantities of biomass may lead to additional wear on the pipes, negatively affect the performance of blast furnaces [37]. Moreover, due to the high P content in the BSHC, it is also quite difficult to directly use the BSHC in the blast furnace ironmaking process. Therefore, the blend experiment to balance the advantages and disadvantages of both BSHC and AC was carried out.

Ye et al. [35] reported the feasibility of using a mixture of biomass hydrochar and anthracite as a blast furnace fuel, and determined that the optimum ratio of biomass hydrochar is 60% by combustion kinetics. Better combustibility is beneficial to the combustion reaction and heat release of fuel in the blast furnace, which is beneficial to the progress of blast furnace smelting. In our study, experiments on co-combustion of bio-sludge hydrochar and anthracite were also carried out, and it was found that when the addition of bio-sludge hydrochar increased from 10% to 50%, the combustion performance of the mixture was enhanced. At the same time, it was also reported in our research that the maximum addition amount of bio-sludge hydrochar should not exceed 30% based on safety (explosiveness). Moreover, the P content in the mixture showed a linear downward trend with the increase in the AC ratio, which was also a very favorable factor for the use of BSHC. Therefore, it is necessary to comprehensively take into account these influencing factors to determine the optimal addition ratio of BSHC in fuel mixtures.

In addition, Ng et al. [38] showed that the use of biomass resources could greatly benefit the cost and CO₂ emissions of the blast furnace ironmaking process. However, due to the variety of available biomass feedstocks, the impacts must be calculated based on specific biomass sources. Based on this study, biomass has theoretical feasibility for use in creating hydrochars for use in blast furnace injection, in terms of technology, economics and emissions. Generally speaking, it is theoretically feasible to use BSHC in the blast furnace injection process, but the performance of BSHC must be improved if the usage of BSHC is to be increased above 50% in a blend with AC.

5. Conclusions

Compared with bituminous coal and anthracite coal, bio-sludge hydrochar has higher volatile and ash content, lower fixed carbon content and lower calorific value. The content of K and Na elements in the BSHC is considered acceptable, but the P content of the bio-sludge hydrochar was 415 times that of the anthracite coal, which has negative impacts on its use in a blast furnace. The T_i and T_f values of the BSHC are lower than for coal, the $R_{0.5}$ value is $5.27 \times 10^{-4} \text{ s}^{-1}$, and the combustion performance is better. However, the higher T_i and T_f values of anthracite make the burning time of anthracite shorter. Among the three samples, BSHC has the lowest ignition point, AC has the highest ignition point, and BC has an ignition point in between. The explosiveness of BSHC and BC is 800 mm, while the explosiveness of anthracite is 0 mm. Therefore, the use of BSHC and BC is dangerous and should be mixed with AC. The combustion performance of the mixed samples was gradually enhanced with the increase of the BSHC addition ratio. When the addition ratio of BSHC is 50%, the $R_{0.5}$ of the sample reaches $3.35 \times 10^{-4} \text{ s}^{-1}$. The addition of BSHC to anthracite coal can significantly reduce the ignition point of AC and improve the ignition and combustion performance of AC. When the addition ratio of BSHC is 30%, the maximum value of the explosion performance is 10 mm, which is beneficial to the safer use of BSHC, indicating that the addition amount of BSHC should not exceed 30%. In general,

the mixture of BSHC and AC can neutralize the advantages and disadvantages of both. Therefore, using a mixture of BSHC and AC in the blast furnace injection process achieves utilization of a residue stream (bio-sludge), leading to add-on environmental and economic benefits in the overall value chain.

Author Contributions: Conceptualization, J.Z. and C.W.; methodology, W.L., J.Z. and C.W.; validation, P.N. and H.W.; investigation, H.W. and S.L.; resources, I.L. and S.L.; data curation, W.L.; writing—original draft preparation, W.L.; writing—review and editing, P.N., H.W. and C.W.; supervision, P.N., I.L. and C.W.; project administration, C.W.; funding acquisition, W.L. and C.W. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 884226. This achievement was also funded by the China Scholarship Council.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Liang, W.; Wang, G.; Jiao, K.; Ning, X.; Zhang, J.; Guo, X.; Li, J.; Wang, C. Conversion mechanism and gasification kinetics of biomass char during hydrothermal carbonization. *Renew. Energy* **2021**, *173*, 318–328. [CrossRef]
2. Song, M.; Wang, J.; Zhao, J. Coal endowment, resource curse, and high coal-consuming industries location: Analysis based on large-scale data. *Resour. Conserv. Recycl.* **2018**, *129*, 333–344. [CrossRef]
3. Ren, Y.-S.; Apergis, N.; Ma, C.; Baltas, K.; Jiang, Y.; Liu, J.-L. FDI, economic growth, and carbon emissions of the Chinese steel industry: New evidence from a 3SLS model. *Environ. Sci. Pollut. Res.* **2021**, *28*, 52547–52564. [CrossRef] [PubMed]
4. Krenek, A. How to implement a WTO-compatible full border carbon adjustment as an important part of the European Green Deal. Österreichische Gesellschaft für Europapolitik (ÖGfE) Policy Brief 2020. Available online: https://www.oegfe.at/wp-content/uploads/2020/01/OEGfE_Policy_Brief-2020.02-2.pdf (accessed on 3 May 2022).
5. Chiamonti, D.; Talluri, G.; Scarlat, N.; Prussi, M. The challenge of forecasting the role of biofuel in EU transport decarbonisation at 2050: A meta-analysis review of published scenarios. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110715. [CrossRef]
6. Holappa, L. A general vision for reduction of energy consumption and CO₂ emissions from the steel industry. *Metals* **2020**, *10*, 1117. [CrossRef]
7. Wu, R.; Lin, B. Does industrial agglomeration improve effective energy service: An empirical study of China’s iron and steel industry. *Appl. Energy* **2021**, *295*, 117066. [CrossRef]
8. Mandova, H.; Leduc, S.; Wang, C.; Wetterlund, E.; Patrizio, P.; Gale, W.; Kraxner, F. Possibilities for CO₂ emission reduction using biomass in European integrated steel plants. *Biomass Bioenergy* **2018**, *115*, 231–243. [CrossRef]
9. Malico, I.; Pereira, R.N.; Gonçalves, A.C.; Sousa, A.M. Current status and future perspectives for energy production from solid biomass in the European industry. *Renew. Sustain. Energy Rev.* **2019**, *112*, 960–977. [CrossRef]
10. Xu, Z.; Qi, R.; Xiong, M.; Zhang, D.; Gu, H.; Chen, W. Conversion of cotton textile waste to clean solid fuel via surfactant-assisted hydrothermal carbonization: Mechanisms and combustion behaviors. *Bioresour. Technol.* **2021**, *321*, 124450. [CrossRef]
11. Alper, K.; Tekin, K.; Karagöz, S.; Ragauskas, A.J. Sustainable energy and fuels from biomass: A review focusing on hydrothermal biomass processing. *Sustain. Energy Fuels* **2020**, *4*, 4390–4414. [CrossRef]
12. Guan, Y.; Tai, L.; Cheng, Z.; Chen, G.; Yan, B. Biomass molded fuel in China: Current status, policies and suggestions. *Sci. Total Environ.* **2020**, *724*, 138345. [CrossRef]
13. Babich, A.; Senk, D.; Solar, J.; de Marco, I. Efficiency of biomass use for blast furnace injection. *ISIJ Int.* **2019**, *59*, 2212–2219. [CrossRef]
14. Antonkiewicz, J.; Popławska, A.; Kołodziej, B.; Ciarkowska, K.; Gambuś, F.; Bryk, M.; Babula, J. Application of ash and municipal sewage sludge as macronutrient sources in sustainable plant biomass production. *J. Environ. Manag.* **2020**, *264*, 110450. [CrossRef]
15. Wolejko, E.; Wydro, U.; Jabłońska-Trypuć, A.; Butarewicz, A.; Łoboda, T. The effect of sewage sludge fertilization on the concentration of PAHs in urban soils. *Environ. Pollut.* **2018**, *232*, 347–357. [CrossRef]
16. Gerner, G.; Meyer, L.; Wanner, R.; Keller, T.; Krebs, R. Sewage sludge treatment by hydrothermal carbonization: Feasibility study for sustainable nutrient recovery and fuel production. *Energies* **2021**, *14*, 2697. [CrossRef]
17. Zhang, L.; Xie, Y.; Liu, J.; Zhong, S.; Qian, Y.; Gao, P. An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. *Environ. Sci. Technol.* **2020**, *54*, 4248–4255. [CrossRef]
18. Wang, L.; Chang, Y.; Li, A. Hydrothermal carbonization for energy-efficient processing of sewage sludge: A review. *Renew. Sustain. Energy Rev.* **2019**, *108*, 423–440. [CrossRef]

19. Liu, T.; Lang, Q.; Xia, Y.; Chen, Z.; Li, D.; Ma, J.; Gai, C.; Liu, Z. Combination of hydrothermal carbonization and oxy-fuel combustion process for sewage sludge treatment: Combustion characteristics and kinetics analysis. *Fuel* **2019**, *242*, 265–276. [[CrossRef](#)]
20. He, C.; Giannis, A.; Wang, J.-Y. Conversion of sewage sludge to clean solid fuel using hydrothermal carbonization: Hydrochar fuel characteristics and combustion behavior. *Appl. Energy* **2013**, *111*, 257–266. [[CrossRef](#)]
21. Çebi, D.; Celiktaş, M.S.; Sarptas, H. A Review on Sewage Sludge Valorization via Hydrothermal Carbonization and Applications for Circular Economy. *Circ. Econ. Sustain.* **2022**, 1–23. [[CrossRef](#)]
22. Nyktari, E.; Danso-Boateng, E.; Wheatley, A.D.; Holdich, R. Anaerobic digestion of liquid products following hydrothermal carbonisation of faecal sludge at different reaction conditions. *Desalination Water Treat.* **2017**, *91*, 245–251. [[CrossRef](#)]
23. Pels, J.; Cieplik, M.; Bleijendaal, L.; Nijman, M.; Zandvoort, M. Conversion of water plants to biomass fuel using torwash. 2014. Available online: <https://repository.tudelft.nl/islandora/object/uuid:ea383ee8-2c42-4cbc-9654-099a78e4ddd2> (accessed on 3 May 2022).
24. Song, T.; Zhang, J.; Wang, G.; Wang, H.; Xu, R. Influencing factors of the explosion characteristics of modified coal used for blast furnace injection. *Powder Technol.* **2019**, *353*, 171–177. [[CrossRef](#)]
25. Aich, S.; Nandi, B.K.; Bhattacharya, S. Utilization of sal leaves and sal leaves char to improve the combustion performance of reject coal. *Energy Sources Part A Recovery Util. Environ. Eff.* **2019**, *41*, 2299–2312. [[CrossRef](#)]
26. Dastidar, M.G.; Bhattacharyya, A.; Sarkar, B.K.; Dey, R.; Mitra, M.K.; Schenk, J. The effect of alkali on the reaction kinetics and strength of blast furnace coke. *Fuel* **2020**, *268*, 117388. [[CrossRef](#)]
27. Liu, Y.; Zhang, H.; Li, Z.; Zhang, A.; Zhang, X.; Qing, S. Impact of slag composition activity on the behavior of phosphorus in the smelting reduction process of high-phosphorus iron ores. *Int. J. Hydrogen Energy* **2017**, *42*, 24487–24494. [[CrossRef](#)]
28. Xie, J.; Zhou, P. Robust stochastic configuration network multi-output modeling of molten iron quality in blast furnace ironmaking. *Neurocomputing* **2020**, *387*, 139–149. [[CrossRef](#)]
29. Wang, P.; Wang, G.; Zhang, J.; Lee, J.-Y.; Li, Y.; Wang, C. Co-combustion characteristics and kinetic study of anthracite coal and palm kernel shell char. *Appl. Therm. Eng.* **2018**, *143*, 736–745. [[CrossRef](#)]
30. Takarada, T.; Tamai, Y.; Tomita, A. Reactivities of 34 coals under steam gasification. *Fuel* **1985**, *64*, 1438–1442. [[CrossRef](#)]
31. Jin, L.-Z.; Niu, X.-M. Micromorphology and safety properties of meager and meager-lean coal for blast furnace injection. *Int. J. Miner. Metall. Mater.* **2021**, *28*, 774–781. [[CrossRef](#)]
32. Rybak, W.; Moroń, W.; Ferens, W. Dust ignition characteristics of different coal ranks, biomass and solid waste. *Fuel* **2019**, *237*, 606–618. [[CrossRef](#)]
33. Tong, W.; Liu, Q.; Ran, G.; Liu, L.; Ren, S.; Chen, L.; Jiang, L. Experiment and expectation: Co-combustion behavior of anthracite and biomass char. *Bioresour. Technol.* **2019**, *280*, 412–420. [[CrossRef](#)]
34. Guo, F.; Zhong, Z. Co-combustion of anthracite coal and wood pellets: Thermodynamic analysis, combustion efficiency, pollutant emissions and ash slagging. *Environ. Pollut.* **2018**, *239*, 21. [[CrossRef](#)]
35. Ye, L.; Zhang, J.; Xu, R.; Ning, X.; Zhang, N.; Wang, C.; Mao, X.; Li, J.; Wang, G.; Wang, C. Co-combustion kinetic analysis of biomass hydrochar and anthracite in blast furnace injection. *Fuel* **2022**, *316*, 123299. [[CrossRef](#)]
36. Orre, J.; Ökvist, L.S.; Bodén, A.; Björkman, B. Understanding of Blast Furnace Performance with Biomass Introduction. *Minerals* **2021**, *11*, 157. [[CrossRef](#)]
37. Sundqvist Ökvist, L.; Lundgren, M. Experiences of bio-coal applications in the blast furnace process—Opportunities and limitations. *Minerals* **2021**, *11*, 863. [[CrossRef](#)]
38. Ng, K.W.; Giroux, L.; Todoschuk, T. Value-in-use of biocarbon fuel for direct injection in blast furnace ironmaking. *Ironmak. Steelmak.* **2018**, *45*, 406–411. [[CrossRef](#)]