

Article

Analysis of Fuel Properties for Fifty Kinds of Typical Alternative Fuels

Yanpeng Guo ¹, Jinhui Yu ¹, Wenjie Rui ¹, Qiangqiang Ren ², Hao Wu ^{2,*}, Hewei Wang ¹, Yanlong Zhang ¹ and Jiajia Jiang ³

¹ Sinoma International Environmental Engineering Co., Ltd., Beijing 100102, China; guoyanpeng@sinoma.com.cn (Y.G.); yujinhui@sinoma.com.cn (J.Y.); ruiwenjie@sinoma.com.cn (W.R.); wanghewei@sinoma.com.cn (H.W.); zhangyanlong@sinoma.com.cn (Y.Z.)

² School of Energy and Mechanical Engineering, Nanjing Normal University, Nanjing 210023, China; renqiangqiang0301@163.com

³ School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China; jiang0505@whut.edu.cn

* Correspondence: wu-hao@nynu.edu.cn

Abstract

With CO₂ generation and emissions requirements, the cement industry faces huge pressure for reducing carbon emissions. Choosing alternative fuels instead of coal is a promising approach. However, the fuel properties of the alternative fuels have not been comprehensively studied. In this work, the fifty typical alternative fuels were selected based on the compositions for different classifications, and the basic fuel properties including proximate analysis, ultimate analysis, and low calorific values were analyzed. Most fuels from plastics and clothes have relatively low moisture; the values of as-received basis moisture (M_{ar}) and air-dry basis moisture (M_{ad}) of the others are all lower than 30 wt%. However, the alternative fuels of plastic and cloth all have relatively high contents of air-dry basis volatile compounds (V_{ad}) (>60 wt%), and they all have low contents of air-dry basis fixed carbon (FC_{ad}) (commonly <20 wt%) and air-dry basis ash (A_{ad}) (<30 wt%). The air-dry basis carbon contents (C_{ad}) of plastics are higher than 40 wt%, while the C_{ad} values of biomass are lower than 50 wt%. As for air-dry basis hydrogen (H_{ad}), the contents are all lower than 14 wt% and relatively stable for different kinds of alternative fuels. As for air-dry basis nitrogen (N_{ad}), the contents are all lower than 9 wt%, and most of them are lower than 3 wt%. In addition, the contents of air-dry basis sulfur (S_{ad}) of different alternative fuels are also lower than 3 wt%, while plastics, biomass, and clothes are all lower than 1 wt%. Also, the low calorific values ($Q_{net,ar}$) for the alternative fuels of plastic are commonly high, and the values for biomass are commonly between 500 and 1500 kJ/kg, while $Q_{net,ar}$ values for the alternative fuels of cloth and others vary. The fuel properties of the fifty typical alternative fuels can guide fuel selection and optimization when they are mixed for combustion with coals in cement decomposition furnaces.

Keywords: alternative fuel; fuel properties; proximate analysis; ultimate analysis; low calorific value



Academic Editor: Fabrizio Scala

Received: 29 July 2025

Revised: 27 August 2025

Accepted: 27 August 2025

Published: 29 August 2025

Citation: Guo, Y.; Yu, J.; Rui, W.; Ren, Q.; Wu, H.; Wang, H.; Zhang, Y.; Jiang, J. Analysis of Fuel Properties for Fifty Kinds of Typical Alternative Fuels. *Processes* **2025**, *13*, 2767. <https://doi.org/10.3390/pr13092767>

Copyright: © 2025 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

Nowadays, the CO₂ emission amount is continuously increasing with the development of society, and the high CO₂ emissions lead to temperature rise [1,2]. The phenomenon results in the melting of glaciers and so on, bringing devastating consequences to the living

environment of human beings [3,4]. Under the huge pressure of CO₂ emission reductions, many industries face requirements for reducing CO₂ generation and emissions [5,6]. Cement production plants are traditional and a key CO₂ emission source, where carbon-based fuels such as coals, biomass, and so on are combusted to generate CO₂; cement production plants thus also need CO₂ reduction and control [7,8].

During the production process of traditional cement, cement raw materials are mixed with coal for combustion, which leads to CO₂ emissions. Therefore, in order to reduce the CO₂ generation and emission in cement production plants, many studies focus on decreasing coal consumption by adding some other carbon-based fuels [9,10]. The carbon-based fuels used instead of coal in cement decomposition furnaces are named alternative fuels, and they are typically composed by plastics, biomass, and so on [11,12]. The specific contributions of published research on alternative fuels are shown in Table 1. As for the contributions of the alternative fuels, their use in the cement industry can also reduce energy and environmental costs, because alternative fuels are cheaper and can help reduce heavy metals emission [10]. Eugeniusz proposed the usage of alternative fuels in the cement industry and analyzed the specific economic and ecological benefits [13]. Huh studied the effect of fuel price on cement production and proposed guidance for alternative fuel selection [14]. Ali provided a comprehensive analysis of options for future cements and an up-to-date summary of the different alternative fuels and binders that can be used in cement production to mitigate carbon dioxide emissions [15]. In addition, the fuel properties are key for the selection of fuel and combustion optimization; it is thus important to study the fuel properties of alternative fuels. However, there are no comprehensive studies focusing on fuel properties for many kinds of typical alternative fuels.

Table 1. Specific contributions on alternative fuels of published works.

Author	Objectives	Reference
Rahman	Development on the uses of alternative fuels in cement manufacturing process	[10]
Eugeniusz	The specific benefits, economic, ecological values of usage of alternative fuels in the cement industry	[13]
Huh	The effect of fuel price on the cement production and alternative fuel selection	[14]
Ali	Summary of the different alternative fuels and binders that can be used in cement production	[15]

Herein, the fifty typical alternative fuels were selected based on the compositions for different classifications, and the basic fuel properties including proximate analysis, ultimate analysis, and low calorific values were comprehensively analyzed.

2. Experimental and Analysis Methods

2.1. Alternative Fuel Sample Treatment

The alternative fuels were composed mainly of biomass, plastics, waste clothes, and other kinds. Thus, based on the alternative fuel types and production amounts, fifty different typical alternative fuels were collected from Liyang Zhongcai Environmental Protection Co., Ltd. in Changzhou located in China. The collected alternative fuels were firstly cut or ground into uniform sizes based on whether the alternative fuels can be ground, and the samples were stored and labeled as shown in Figure 1 for subsequent usage.

In addition, the specific alternative fuels are named and listed in Table 2. According to compositions of the collected alternative fuels, the fifty samples can be classified into four groups as plastic, biomass, cloth, and others, and the specific classification is also shown in Table 2. The format No.: XXX: A/B/C/D is used to show the name and classification,

where No. corresponds to the number in Figure 1, XXX is the name, and A/B/C/D is plastic/biomass/cloth/others.



Figure 1. Photos and numbers of alternative fuel samples.

Table 2. The specific names and classifications of the fifty alternative fuels in this work.

Alternative Fuels				
1: Plastic granulation residue: A	11: Chrysanthemum pollen: B	21: Wool fabric: C	31: Caragana branches: B	41: Rice husk: B
2: Sponge: C	12: Biomass briquette particle: B	22: Carbonized rock: D	32: Industrial wastewater sludge: B	42: Cotton stalk: B
3: Resin particle: A	13: Urban sludge: B	23: Coal slime: D	33: Cardboard: B	43: Pig manure: B
4: Glass fiber: D	14: White resin: A	24: Camellia oil shell: B	34: Shoe material: C	44: Plastic label: A
5: Water pipe: A	15: Plastic bag: A	25: Washing material: A	35: Landfill cloth: C	45: Furfural residue: B
6: Grey sponge: C	16: Chrysanthemum stem: B	26: Plastic residue: A	36: Biomass briquette block: B	46: Polyurethane: A
7: Automobile interior: A	17: Gasification slag: D	27: Tailings: D	37: Dry paper mud: B	47: Formed carbon: D
8: Black resin: A	18: Fermented cow dung: B	28: Waste wool: C	38: Nylon: A	48: Medicine residue: B
9: Dry mud: B	19: Hard plastic: A	29: Papermaking sludge: B	39: Fabric: C	49: Cow dung: B
10: Waste plastic molding fuel: A	20: Sawdust: B	30: Rubber: D	40: Ground film: A	50: Carbon black: D

2.2. Fuel Property Analysis and Calculation Methods of Alternative Fuels

In order to study the fuel properties, the fifty alternative fuel samples were used to conduct proximate analysis, ultimate analysis, and analysis of low calorific value. As for proximate analysis, the parameters (M_{ar} , M_{ad} , V_{ad} , FC_{ad} , A_{ad} ; wt%) were studied based on the relevant national standard GB/T 28731 [16]. Proximate analysis results for air-dry basis

were automatically determined by a proximate analyzer (Kaiyuan, China, 5E-MAG6700I). M_{ar} was analyzed by Equation (1), where M_f (wt%) was mass percent of external moisture, calculated by Equation (2).

$$M_{ar} = M_f + M_{ad} \left(\frac{100 - M_f}{100} \right) \quad (1)$$

$$M_f = \frac{m_1 - m_2}{m_1} \times 100\% \quad (2)$$

M_f was measured as follows: An appropriate amount of the sample was weighed, and the initial mass was recorded as m_1 (g). The sample was spread in a drying oven at 40 °C to dry until the mass was constant (weighed at an interval of 2 h, with a mass change $\leq 0.1\%$). The mass after drying was recorded as m_1 (g).

During ultimate analysis processes, appropriate amounts of the alternative fuel samples were, respectively, placed into an ultimate analyzer (Kaiyuan, China, 5E-CHN2200) to acquire C_{ar} , H_{ar} , N_{ar} , (wt%) and a sulfur element analyzer (Kaiyuan, China, 5E-AS3200B) to obtain S_{ar} (wt%) based on the relevant national standard GB/T 31391 [17]. In addition, O_{ar} (wt%) was calculated by difference. Low calorific values ($Q_{net,ar}$, kJ/kg) of the fifty alternative fuels were recorded and measured by a calorific value analyzer (China Lichen, LC-CV-430) based on the relevant national standard GB/T 30727 [18]. In addition, in order to compare the low calorific values of the fifty alternative fuels, $Q_{net,ar}$ was also calculated by Mendeleev's formula, which is shown in Equation (3), and the formula was based on low calorific values from coals and as shown in many books about coal properties. The error was calculated by Equation (4):

$$Q_{net,ar} = 339C_{ar} + 1030H_{ar} - 109(O_{ar} - S_{ar}) - 25M_{ar} \quad (3)$$

$$Error = \frac{Calculated\ value - Experimental\ value}{Calculated\ value} \times 100\% \quad (4)$$

3. Results and Discussion

3.1. Proximate Analysis Results of Alternative Fuels

The proximate analysis experiments of the fifty alternative fuels were measured two times to be averaged to reduce the relative errors, and the results are shown in Table 3. It can be seen that the compositions (M_{ar} , M_{ad} , V_{ad} , FC_{ad} , A_{ad}) of different alternative fuels are different, and they were further analyzed based on the classifications; the results are shown in Figure 2A–E.

Figure 2A,B show M_{ar} and M_{ad} of different alternative fuels based on the classification, respectively, and it can be clearly seen that M_{ar} and M_{ad} show some obvious characteristics. For plastic, most of the fuels have relatively low moisture except for washing material, because it is obtained by washing; for biomass, the moisture is varied since the compositions are different, especially for sludges. For cloth, most of them have relatively low moisture except for wool fabric; M_{ar} and M_{ad} of the others are all lower than 30 wt%. However, the alternative fuels of plastic and cloth all have relatively high content of volatile compounds (higher than 60 wt%), and they all have low contents of fixed carbon (commonly lower than 20 wt%) and ash (lower than 30 wt%). As a whole, the A_{ad} values of clothes and plastics are lowest since there are not many additives in them. The others are composed of inorganic matter, leading to high values of A_{ad} . In addition, the fixed carbon contents of the alternative fuels except for carbon black are all lower than 30 wt%, and they are similar, which can determine the burnout characteristics.

Table 3. Proximate analysis results (wt%) of alternative fuels.

No.	Fuels	M_{ar}	M_{ad}	V_{ad}	FC_{ad}	A_{ad}
1	Plastic granulation residue	2.04	1.55	70.05	1.65	26.75
2	Sponge	2.93	1.95	88.91	6.19	2.95
3	Resin particle	0.40	0.30	97.70	0.35	1.65
4	Glass fiber	4.38	3.90	23.46	1.62	71.02
5	Water pipe	1.69	1.20	67.23	21.71	9.86
6	Grey sponge	1.88	1.58	88.60	9.05	0.77
7	Automobile interior	0.42	0.32	70.94	2.26	26.48
8	Black resin	4.45	3.97	78.47	7.08	10.48
9	Dry mud	48.10	42.33	25.27	22.67	9.73
10	Waste plastic molding fuel	4.03	3.55	70.37	5.73	20.35
11	Chrysanthemum pollen	16.32	10.98	63.22	14.56	11.24
12	Biomass briquette particle	12.72	8.13	71.40	16.82	3.65
13	Urban sludge	66.88	61.03	14.41	5.99	18.57
14	White resin	2.31	2.02	71.69	2.02	24.27
15	Plastic bag	1.76	1.27	94.86	3.13	0.74
16	Chrysanthemum stem	13.84	9.30	70.16	17.23	3.31
17	Gasification slag	12.80	10.10	0.00	22.42	67.48
18	Fermented cow dung	48.11	36.72	41.30	10.47	11.51
19	Hard plastic	0.45	0.35	87.16	0.16	12.33
20	Sawdust	14.17	9.65	67.32	15.88	7.15
21	Wool fabric	64.93	58.74	28.72	3.42	9.12
22	Carbonized rock	0.69	0.49	22.80	13.94	62.77
23	Coal slime	27.33	19.25	16.75	23.88	40.12
24	Camellia oil shell	15.79	10.41	65.76	21.60	2.23
25	Washing material	31.62	25.67	64.80	7.21	2.32
26	Plastic residue	0.76	0.56	84.17	4.44	10.83
27	Tailings	9.39	7.54	19.22	4.67	68.57
28	Waste wool	0.95	0.75	88.96	7.74	2.55
29	Papermaking sludge	56.15	51.28	34.62	2.70	11.40
30	Rubber	2.02	1.53	61.83	19.97	16.67
31	Caragana branches	13.81	8.31	76.25	13.76	1.68
32	Industrial wastewater sludge	7.41	4.55	74.83	5.79	14.83
33	Cardboard	8.40	5.57	72.67	17.33	4.43
34	Shoe material	0.65	0.45	85.47	13.61	0.47
35	Landfill cloth	1.58	1.28	81.18	10.88	6.66
36	Biomass briquette block	12.38	8.73	50.40	13.01	27.86
37	Dry paper mud	9.74	5.98	45.33	5.47	43.22
38	Nylon	1.77	1.47	95.57	2.99	0.00
39	Fabric	7.84	5.96	83.03	10.03	0.98
40	Ground film	4.00	2.54	78.09	1.39	17.98
41	Rice husk	17.73	11.54	62.28	14.63	11.55
42	Cotton stalk	17.85	10.71	66.46	18.81	4.02
43	Pig manure	73.88	67.35	22.72	4.22	5.71
44	Plastic label	0.86	0.66	90.69	7.34	1.31
45	Furfural residue	37.06	28.48	50.21	17.26	4.05
46	Polyurethane	3.67	3.19	80.98	11.86	3.97
47	Formed carbon	13.45	11.68	29.72	14.72	43.88
48	Medicine residue	45.54	38.11	45.87	8.95	7.07
49	Cow dung	44.28	32.05	34.60	10.93	22.42
50	Carbon black	1.37	1.07	2.40	89.94	6.59

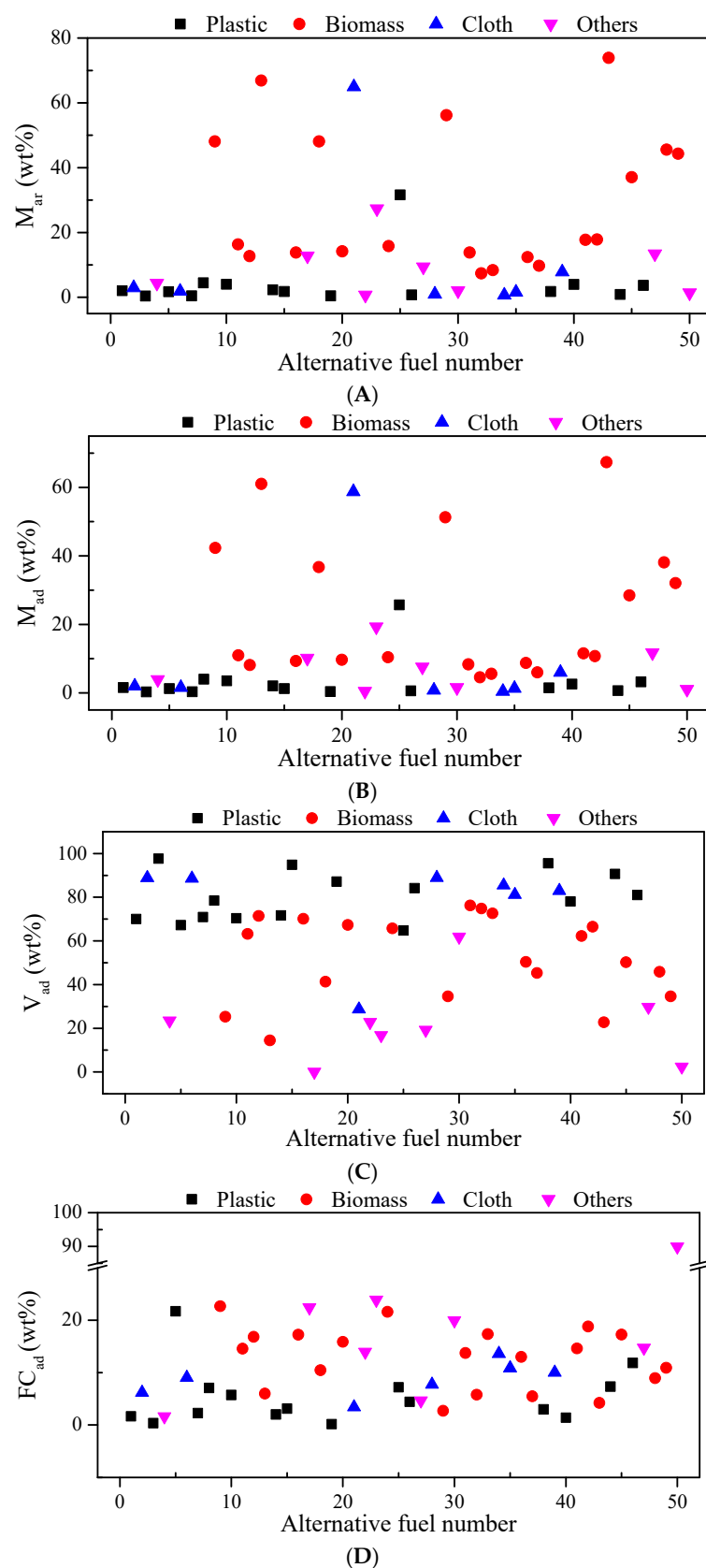


Figure 2. Cont.

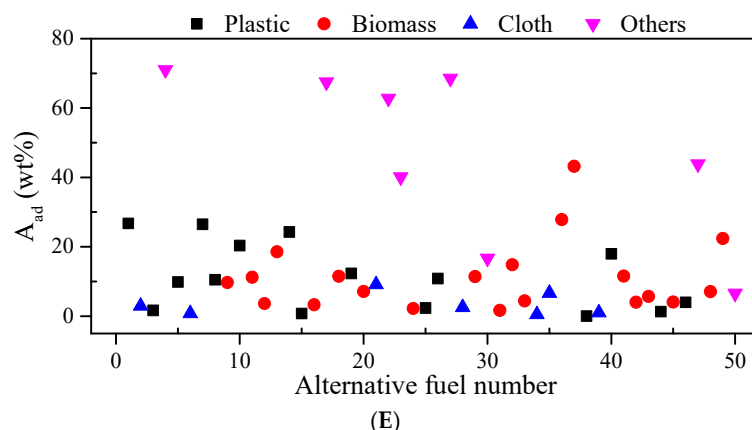


Figure 2. (A) M_{ar} of different alternative fuels. (B) M_{ad} of different alternative fuels. (C) V_{ad} of different alternative fuels. (D) FC_{ad} of different alternative fuels. (E) A_{ad} of different alternative fuels.

3.2. Ultimate Analysis Results of Alternative Fuels

The ultimate analysis experiments of the fifty alternative fuels were also analyzed two times and averaged to reduce the relative errors, the results of which are listed in Table 4. C_{ad} , H_{ad} , N_{ad} , and S_{ad} were analyzed by an experimental instrument, and O_{ad} was calculated by the differences. It can be found that the element compositions for the alternative fuels are different. Furthermore, they are also analyzed based on the classification, and the results are shown in Figure 3A–D. The figure for O_{ar} of different alternative fuels is not shown, because the parameter was calculated, rather than measured.

Figure 3A shows the C_{ad} of different alternative fuels, and it can be clearly seen that carbon contents of plastics are higher than 40 wt%, while the carbon contents of biomass are lower than 50 wt%. In addition, the alternative fuels for cloth and others varied in carbon content. Hydrogen content values are all lower than 14 wt% and are relatively stable for different kinds of alternative fuels: H_{ad} of plastics is commonly higher since they are composed by organic polymers, while H_{ad} of the others is lowest since their main component is inorganic matter. As for nitrogen content, the values are all lower than 9 wt%, and most of them are lower than 3 wt% which is lower than most coals, suggesting the alternative fuels can produce fewer nitrogen oxides when they are reasonably blended for combustion. In addition, S_{ad} of different alternative fuels are also lower than 3 wt%, while plastics, biomass, and clothes are all lower than 1 wt%. The results of sulfur contents also directly show that the alternative fuels can be blended before the combustion process to reduce sulfur when the sulfur content of coal is high, which is beneficial for gas pollutant control.

Table 4. Ultimate analysis results (wt%) of alternative fuels.

No.	Fuels	C_{ad}	H_{ad}	O_{ad}	N_{ad}	S_{ad}
1	Plastic granulation residue	57.03	8.87	5.48	0.24	0.08
2	Sponge	58.20	7.29	23.24	6.28	0.09
3	Resin particle	83.84	11.68	2.32	0.14	0.07
4	Glass fiber	11.45	2.71	3.83	7.08	0.01
5	Water pipe	76.88	9.24	2.06	0.20	0.56
6	Grey sponge	59.76	7.63	22.87	7.38	0.01
7	Automobile interior	47.68	5.42	19.83	0.26	0.01
8	Black resin	50.75	7.29	23.19	4.14	0.18
9	Dry mud	29.80	7.04	10.14	0.31	0.65
10	Waste plastic molding fuel	56.44	7.29	11.13	1.02	0.22
11	Chrysanthemum pollen	43.71	7.26	24.72	1.86	0.23

Table 4. Cont.

No.	Fuels	C_{ad}	H_{ad}	O_{ad}	N_{ad}	S_{ad}
12	Biomass briquette particle	46.18	7.19	32.26	2.51	0.08
13	Urban sludge	7.95	8.63	2.10	1.48	0.24
14	White resin	53.09	8.53	6.80	5.18	0.11
15	Plastic bag	72.70	12.86	10.18	2.23	0.02
16	Chrysanthemum stem	46.82	6.17	33.84	0.48	0.08
17	Gasification slag	19.74	1.00	1.50	0.09	0.09
18	Fermented cow dung	26.49	5.31	18.92	0.90	0.15
19	Hard plastic	77.34	9.31	0.60	0.00	0.07
20	Sawdust	47.54	5.72	29.87	0.05	0.02
21	Wool fabric	19.47	6.24	6.42	0.00	0.01
22	Carbonized rock	11.08	1.47	24.14	0.00	0.05
23	Coal slime	34.66	3.04	1.27	0.43	1.23
24	Camellia oil shell	46.44	6.91	33.74	0.20	0.07
25	Washing material	42.60	3.41	25.84	0.13	0.03
26	Plastic residue	57.21	6.76	24.61	0.00	0.03
27	Tailings	6.74	0.91	13.62	0.00	2.62
28	Waste wool	65.83	5.80	24.55	0.47	0.05
29	Papermaking sludge	22.14	8.95	5.95	0.16	0.12
30	Rubber	71.79	7.14	2.27	0.14	0.46
31	Caragana branches	47.95	7.12	32.94	1.88	0.12
32	Industrial wastewater sludge	18.38	7.62	53.64	0.78	0.20
33	Cardboard	40.51	6.85	34.34	8.27	0.03
34	Shoe material	49.98	7.60	36.74	4.73	0.03
35	Landfill cloth	61.38	4.91	25.26	0.38	0.13
36	Biomass briquette block	33.34	4.41	22.68	2.51	0.47
37	Dry paper mud	21.50	2.63	24.52	1.90	0.25
38	Nylon	80.97	11.53	5.81	0.21	0.01
39	Fabric	64.68	5.93	21.34	1.04	0.07
40	Ground film	65.23	10.05	3.22	0.06	0.92
41	Rice husk	42.20	5.64	26.27	2.57	0.23
42	Cotton stalk	41.97	7.44	34.52	1.16	0.18
43	Pig manure	13.64	9.29	3.35	0.52	0.14
44	Plastic label	45.97	5.79	46.23	0.00	0.04
45	Furfural residue	36.85	6.39	23.18	0.31	0.74
46	Polyurethane	62.65	5.90	17.70	6.50	0.09
47	Formed carbon	23.15	3.15	16.43	1.45	0.26
48	Medicine residue	28.92	5.79	18.98	1.03	0.10
49	Cow dung	24.28	6.55	12.58	1.74	0.38
50	Carbon black	89.26	1.03	0.45	0.86	0.74

Note: O_{ad} was calculated by difference.

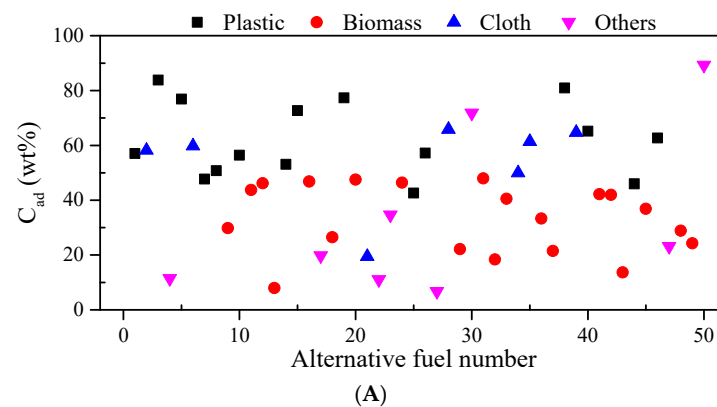


Figure 3. Cont.

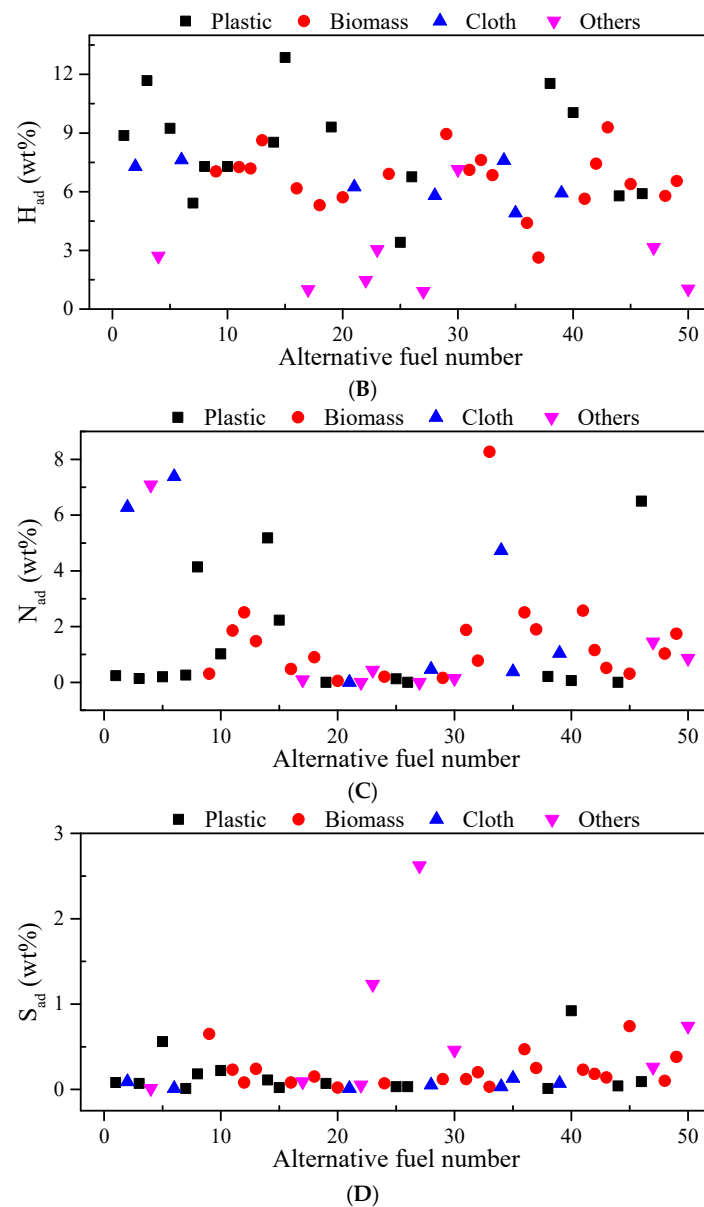


Figure 3. (A) C_{ad} of different alternative fuels. (B) H_{ad} of different alternative fuels. (C) N_{ad} of different alternative fuels. (D) S_{ad} of different alternative fuels.

3.3. Low Calorific Value Results of Alternative Fuels

The low calorific value ($Q_{net,ar}$) experiments of the fifty alternative fuels were still repeatedly analyzed two times, and the results were averaged to reduce relative errors. The experimental values of $Q_{net,ar}$ are shown in Table 5. In addition, the calculated values of $Q_{net,ar}$ were calculated based on Equation (3), where the proximate and ultimate analysis results were transformed to as-received basis. Moreover, the errors were calculated by Equation (4), and the results are listed in Table 5.

Figure 4 shows the relationship of low calorific values by experimental and calculated methods, and it can be seen that the as-received basis low calorific values calculated by Mendeleev's formula are generally close to the experimental values, which also verifies the rationality of the experimental detection results. Furthermore, the deviation rates of the low calorific value of the 50 alternative fuels are mostly below 10%, and the rest are mainly between 10% and 20%. This is primarily due to the following reasons: (1) the complexity and non-uniformity of the components of the alternative fuel samples; (2) Mendeleev's formula is mainly derived from coals and is relatively less adaptable to alternative fuels.

The average deviation rate of the 50 samples was calculated to be 6.1%, which was relatively small, indicating the reliability of the experimental results.

Table 5. Low calorific value results ($Q_{net,ar}$, kJ/kg) and errors of alternative fuels.

No.	1	2	3	4	5	6	7	8	9	10
Exp.	24,370	25,519	37,516	6457	32,591	23,256	17,602	21,715	11,394	20,460
Cal.	27,691	24,395	40,157	6116	35,198	25,501	19,556	21,983	13,484	25,225
Error	11.99%	−4.61%	6.58%	−5.58%	7.41%	8.80%	9.99%	1.22%	15.50%	18.89%
No.	11	12	13	14	15	16	17	18	19	20
Exp.	15,019	15,126	9843	22,073	36,955	13,782	8738	7275	33,861	16,097
Cal.	18,041	18,258	8001	25,919	36,557	17,273	7021	8968	35,703	17,462
Error	16.75%	17.15%	−23.03%	14.84%	−1.09%	20.21%	−24.46%	18.88%	5.16%	7.81%
No.	21	22	23	24	25	26	27	28	29	30
Exp.	7525	2538	10,359	15,393	16,641	26,081	1962	26,304	10,992	33,660
Cal.	8856	2622	12,705	17,643	13,138	23,611	1748	25,544	13,077	31,287
Error	15.03%	3.20%	18.46%	12.75%	−26.66%	−10.46%	−12.25%	−2.97%	15.94%	−7.59%
No.	31	32	33	34	35	36	37	38	39	40
Exp.	15,632	6198	14,458	23,157	20,562	11,827	5498	36,532	23,560	31,634
Cal.	18,466	7822	16,328	20,712	23,016	12,577	6814	38,530	25,006	31,631
Error	15.35%	20.76%	11.45%	−11.81%	10.66%	5.97%	19.32%	5.19%	5.78%	−0.01%
No.	41	42	43	44	45	46	47	48	49	50
Exp.	14,596	13,787	7633	19,053	12,105	23,881	8814	8848	8419	25,382
Cal.	15,624	16,251	9227	16,458	13,707	25,178	8807	10,925	10,084	31,222
Error	6.58%	15.16%	17.82%	−15.77%	11.68%	5.15%	−0.08%	19.01%	16.51%	18.71%

Note: Exp. means experimental value; Cal. means calculated value.

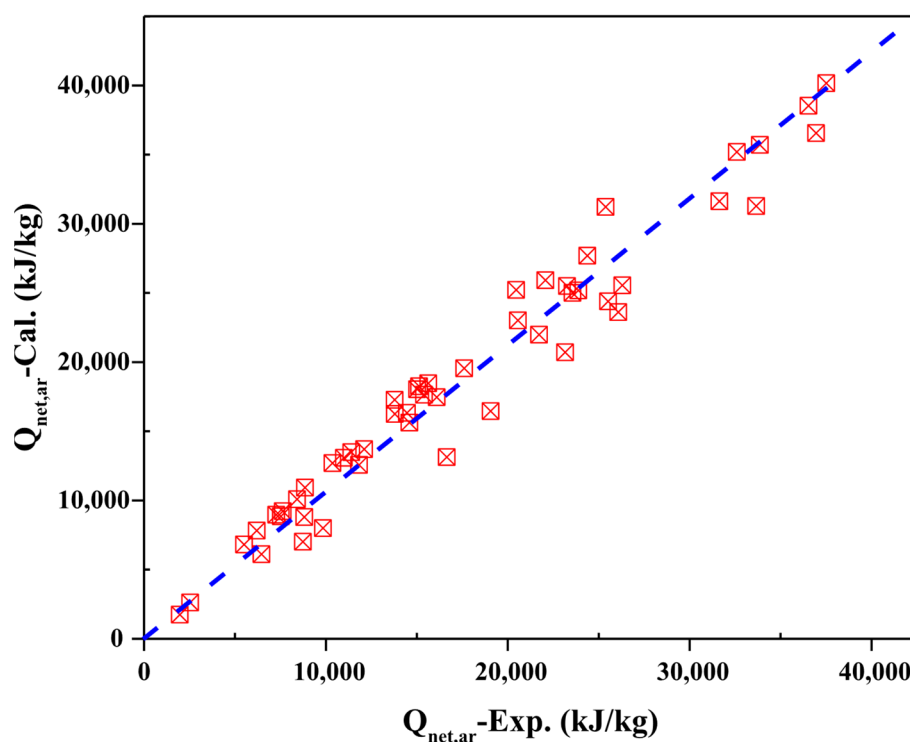


Figure 4. The correlation between $Q_{net,ar}$ -Exp. and $Q_{net,ar}$ -Cal.

Also, $Q_{net,ar}$ values of different alternative fuels for the specific classification are shown in Figure 5. It can be found that the alternative fuels of plastic commonly have high values,

and biomass has commonly low values between 500 and 1500 kJ/kg, while the alternative fuels for cloth and others have varied values as for different alternative fuels. The low calorific values of the fifty alternative fuels can guide fuel selection and optimization when they are mixed for combustion with coals in cement decomposition furnaces.

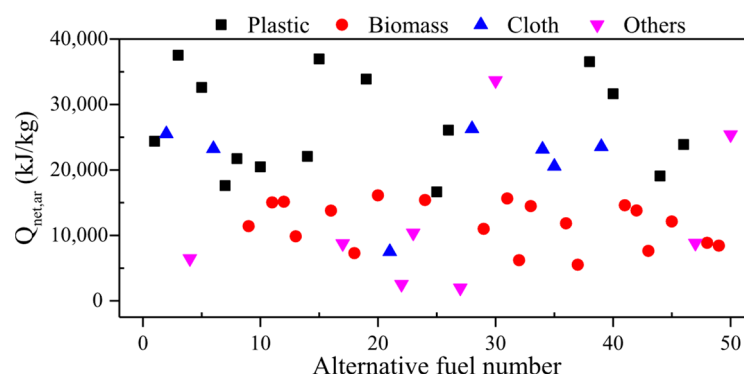


Figure 5. $Q_{net,ar}$ of different alternative fuels.

4. Conclusions

The fifty typical alternative fuels were selected based on the compositions for different classifications, and the basic fuel properties including proximate analysis, ultimate analysis, and low calorific values were comprehensively analyzed.

Most alternative fuels from plastics and clothes have relatively low moisture; M_{ar} and M_{ad} of the others are all lower than 30 wt%. However, the alternative fuels of plastic and cloth all have relatively high contents of volatile compounds (>60 wt%), and they all have low contents of fixed carbon (commonly <20 wt%) and ash (<30 wt%). The carbon contents of plastics are higher than 40 wt%, while the carbon contents of biomass are lower than 50 wt%. As for hydrogen content, they are all lower than 14 wt% and relatively stable for different kinds of alternative fuels. As for nitrogen content, they are all lower than 9 wt%, and most of them are lower than 3 wt%. In addition, S_{ad} values of different alternative fuels are also lower than 3 wt%, while plastics, biomass, and clothes are all lower than 1 wt%. Also, $Q_{net,ar}$ values for the alternative fuels of plastic are commonly high, and biomass commonly shows values between 500 and 1500 kJ/kg, while $Q_{net,ar}$ values for the alternative fuels for cloth and others are varied.

The work provided abundant basic fuel properties of typical alternative fuels, which can be used to analyze actual applications by coupling with AI.

Author Contributions: Conceptualization, J.Y. and H.W. (Hao Wu); data curation, Q.R.; formal analysis, Y.G.; funding acquisition, H.W. (Hao Wu); investigation, Y.G., J.Y., W.R. and Q.R.; project administration, H.W. (Hao Wu); supervision, H.W. (Hao Wu); validation, H.W. (Hewei Wang); visualization, Y.Z. and J.J.; writing—original draft, J.Y. and Q.R.; writing—review and editing, Y.G. and H.W. (Hao Wu). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because they are part of an ongoing study.

Acknowledgments: The assistance from School of Energy and Mechanical Engineering of Nanjing Normal University is acknowledged. Also, the authors would like to acknowledge the ultimate analysis provided by zkec (www.zkec.cc, accessed on 1 August 2025).

Conflicts of Interest: Authors Yanpeng Guo, Jinhui Yu, Wenjie Rui, Hewei Wang and Yanlong Zhang were employed by the company Sinoma International Environmental Engineering Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or

financial relationships that could be construed as a potential conflict of interest. The companies had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Ali, M.; Jha, N.K.; Pal, N.; Keshavarz, A.; Hoteit, H.; Sarmadivaleh, M. Recent advances in carbon dioxide geological storage, experimental procedures, influencing parameters, and future outlook. *Earth Sci. Rev.* **2022**, *225*, 103895. [\[CrossRef\]](#)
2. Wang, J.; Feng, L.; Palmer, P.I.; Liu, Y.; Fang, S.; Bosch, H. Large Chinese land carbon sink estimated from atmospheric carbon dioxide data. *Nature* **2020**, *586*, 720–723. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Raza, S.; Ghasali, E.; Raza, M.; Chen, C.; Li, B.; Orooji, Y. Advances in technology and utilization of natural resources for achieving carbon neutrality and a sustainable solution to neutral environment. *Environ. Res.* **2023**, *220*, 115135. [\[CrossRef\]](#)
4. Yang, Y.; Tilman, D.; Jin, Z.; Smith, P.; Barrett, C.B.; Zhu, Y.G. Climate change exacerbates the environmental impacts of agriculture. *Science* **2024**, *385*, 1068. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Olabi, A.G.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Maghrabie, H.M.; Abdelkareem, M.A. Large scale application of carbon capture to process industries—A review. *J. Clean. Prod.* **2022**, *362*, 132300. [\[CrossRef\]](#)
6. Ouyang, X.; Fang, X.; Cao, Y.; Sun, C. Factors behind CO₂ emission reduction in Chinese heavy industries: Do environmental regulations matter? *Energy Policy* **2020**, *145*, 111765. [\[CrossRef\]](#)
7. Shen, W.; Cao, L.; Li, Q.; Zhang, W.; Wang, G.; Li, C. Quantifying CO₂ emissions from China’s cement industry. *Renew. Sust. Energy Rev.* **2015**, *50*, 1004–1012. [\[CrossRef\]](#)
8. Supriya; Chaudhury, R.; Sharma, U.; Thapliyal, P.C.; Singh, L.P. Low-CO₂ emission strategies to achieve net zero target in cement sector. *J. Clean. Prod.* **2023**, *417*, 137466. [\[CrossRef\]](#)
9. Rychter, K.W.; Kucharski, P.; Smolinski, A. Conventional and Alternative Sources of Thermal Energy in the Production of Cement—An Impact on CO₂ Emission. *Energies* **2021**, *14*, 1539. [\[CrossRef\]](#)
10. Rahman, A.; Rasul, M.G.; Khan, M.M.K.; Sharma, S. Recent development on the uses of alternative fuels in cement manufacturing process. *Fuel* **2015**, *145*, 84–99. [\[CrossRef\]](#)
11. Luo, Z.; Song, H.; Huang, Y.; Jin, B. Recent Advances on the Uses of Biomass Alternative Fuels in Cement Manufacturing Process: A Review. *Energy Fuels* **2024**, *38*, 7454–7479. [\[CrossRef\]](#)
12. Mancini, V.; Verdone, N.; Trinca, A.; Vilardi, G. Economic, environmental and exergy analysis of the decarbonisation of cement production cycle. *Energy Convers. Manag.* **2022**, *260*, 115577. [\[CrossRef\]](#)
13. Mokrzycki, E.; Uliasz-Bocheńczyk, A.; Sarna, M. Use of alternative fuels in the Polish cement industry. *Appl. Energy* **2003**, *74*, 101–111. [\[CrossRef\]](#)
14. Huh, S.; Lee, H.; Shin, J.; Lee, D.; Jang, J. Inter-fuel substitution path analysis of the Korea cement industry. *Renew. Sustain. Energy Rev.* **2018**, *82*, 4091–4099. [\[CrossRef\]](#)
15. Naqi, A.; Jang, J.G. Recent Progress in Green Cement Technology Utilizing Low-Carbon Emission Fuels and Raw Materials: A Review. *Sustainability* **2019**, *11*, 537. [\[CrossRef\]](#)
16. GB/T 28731; Proximate Analysis of Solid Biofuels. State Administration for Market Regulation & Standardization Administration of the People’s Republic of China: Beijing, China, 2012.
17. GB/T 31391; Ultimate Analysis of Coal. General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China & Standardization Administration of the People’s Republic of China: Beijing, China, 2015.
18. GB/T 30727; Determination of Calorific Value for Solid Biofuels. General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China & Standardization Administration of the People’s Republic of China: Beijing, China, 2014.

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.