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Low Chlorine Fuel Pellets Production from the Mixture of Hydrothermally Treated Hospital Solid Waste, Pyrolytic Plastic Waste Residue and Biomass

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Abstract: Thirteen types of fuel pellets were prepared from hydrothermally treated hospital solid waste, hydrothermally treated rice straw, pyrolytic plastic waste residue, rice straw, and Sakhalin fir residue using a flat die pellet machine. Different pellet properties such as pellet density, pellet durability, aspect ratio, physicochemical characteristics, and gross calorific value (GCV) were evaluated as well as compared concerning the European standard specification for residential/commercial densified fuels. In addition, the quality of pellets was compared with coal. The results showed that the pellets made only with hydrothermally treated hospital solid waste, hydrothermally treated rice straw, pyrolytic plastic waste residue, and rice straw failed to meet few individual criteria (<3 wt% ash content, <10 wt% moisture content, <0.03 wt% chlorine content, >96.5 wt% pellet durability, and >600 kg/m^3 pellet density) of the European standard specifications. However, most of the mixed fuel pellets satisfied the requirement of pellet properties according to the European standard specification. In particular, up to 16.70 wt% hydrothermally treated rice straw, 1.50 wt% hydrothermally treated hospital solid waste, and 4.76 wt% of pyrolytic plastic waste residue can be blended with Shakhalin fir residue to produce low-chlorine fuel pellets. The gross calorific value of pellets made from the mixture of hydrothermally treated wastes and pyrolytic plastic waste residue (around 22 MJ/kg) showed similar results to that of coal. In the case of mixed pellets, the presence of these hydrothermally treated wastes and pyrolytic plastic waste residue valorized the fuel pellet quality. The main outcome of this study was the production of low chlorine biomass fuel pellets of high gross calorific values blended with hydrothermally treated wastes and pyrolytic waste residues, which opens a new door for utilizing waste in a better way, especially hospital solid waste.

Keywords: hydrothermal treatment; pelletization; biomass; hospital solid waste; plastic waste

1. Introduction

The progress of human civilization is heavily dependent on energy production for generating electricity, as well as for thermal applications [1]. Fossil fuels such as coal, oil, and natural gas have been used irresponsibly to produce energy over the years [2]. Therefore, the amount of greenhouse gases have sharply increased in the atmosphere. Over the past 60 years, CO_2 production has risen dramatically from 4 million tons/year to more than 28 million tons/year [3,4]. Owing to the increasing cost of fossil fuels, global warming, and rising levels of CO_2, the need to find new, clean and renewable sources of energy has become imperative.

Biomass pellets have been regarded as an environmentally sustainable and economically feasible source of renewable energy [5,6]. Fuel pellet production is viewed as superior to conventional firewood burning and fossil fuel usage [7]. Furthermore, biomass pellets are carbon neutral because they do not emit a net quantity of harmful greenhouse gases like fossil fuels during combustion [8,9]. Although the burning of biomass pellets emits carbon dioxide into the air, the amount of carbon released is the same as that generated by allowing the biomass to decompose [10]. Furthermore, when biomass decomposes, other toxic gases such as methane are emitted [11]. Based on these outcomes, the combustion of biomass pellets is more environment-friendly than biomass decomposition. The carbon produced by the former is also carbon neutral. The carbon-neutral properties of biomass pellets have increased the popularity of these materials with environmental groups [12]. The use of pellet-fueled energy systems also presents possibilities in terms of avoiding or reducing the effects of climate change because pellet-heating systems do not contribute to ozone depletion and comply with the air emission standards stipulated by the Environmental Protection Agency and Kyoto Accords [13]. Another environmentally friendly aspect of biomass pellets is that the energy needed to produce these materials is considerably lower than that required to produce other forms of energy [14]. To produce biomass fuel pellets, the loose raw materials are densified first. Later, heat, pressure, and binders are employed on these materials to produce fuel pellets [15]. Pelletizing is applied primarily to improve fuel characteristics, combustion properties, handling, transportation, and storage [16].

Hydrothermal treatment (HT) is a novel thermal conversion technique that serves as an environmentally beneficial waste/biomass treatment process [17]. During HT, a feedstock is heated in subcritical water temperatures at autogenous pressure. As a result, the feedstock is decomposed by a series of simultaneous reactions including hydrolysis, dehydration, decarboxylation, aromatization, and recondensation [18]. Due to these reactions, the solid product, hydrochar, generally had an improved calorific value, hydrophobicity, and homogeneity [19]. Usually, the hydrochar shows excellent potential to be an alternative form of solid fuel. Furthermore, the pelletization process in combination with HT is considered to be an alternative way to improve the fuel properties of biomass [20]. Considering the above-mentioned benefits, HT technology was used in this study to valorize hospital solid waste and biomass properties.

Biomass pellets have been extensively studied in recent years, and these studies have mainly focused on woody biomass pellets [20–22]. The co-pelletization process using biomass has become a well-known technology, as it improves the characteristics of pellets by enhancing pellet density and strength, improving combustion characteristics, and decreasing energy consumption. The main advantage of co-pelletization is that it eradicates the harmful properties of pellets with the help of additives [23]. However, few works have been done on the co-pelletization of biomass with wastes [24–27]. Furthermore, only a handful of them have been on the co-pelletization of biomass with hydrothermally treated wastes [28,29]. Thus, in this study, efforts were made to produce fuel pellets by co-pelletizing hydrothermally treated wastes with biomass. In addition, attempts were made to produce fuel pellets from the pyrolytic plastic waste residue obtained from the oilification of plastic waste by the pyrolysis process. In this study, HT was used to treat hospital solid waste and rice straw to make them suitable for blending with Sakhalin fir residue for clean fuel pellet production. As far as the authors are aware, no work has been done on the co-pelletization of biomass with hydrothermally treated hospital waste to date. It is the first time that hospital waste has been treated to make low-chlorine fuel pellets with a high gross calorific value (GCV) similar to coal. The mixing of pyrolytic plastic waste residue, hydrothermally treated hospital waste, hydrothermally treated and untreated rice straw, and untreated Sakhalin fir residue (obtained during the furniture making process from Sakhalin fir) in different ratios to make clean and cost-effective fuel pellets is one of the key differentiators of this research. After preparing the fuel pellets, the properties of these pellets were assessed in terms of pellet strength, pellet density, pellet durability, aspect ratio, ash content, gross calorific value, and physicochemical characteristics, and compared. Furthermore, fuel pellet qualities were compared with the European standard specification and coal. The ultimate goal of this study was to promote the development of eco-friendly waste-based fuel pellets.

2. Materials and Methods

2.1. Experimental Procedure of HT and Pyrolysis

HT was performed in a 200-L pilot-scale hydrothermal reactor. Figure 1 shows a schematic diagram of the pilot-scale HT facility. To begin with, about 6 kg feedstock (in dry weight) was supplied to the reactor. Later, saturated steam was injected into the reactor from the boiler until the temperature and pressure of the reactor reached 180 °C and 1.0 MPa, respectively. Then, the feedstocks were mixed for around 30 min inside the reactor using blades installed within. The reason for selecting this condition is that, in this condition, water behaves like subcritical water, which is an excellent medium for a fast, homogenous, and efficient reaction. Also, in this condition water shows low viscosity and high organic solubility [30]. When the treatment was completed, steam was flashed through the condenser by decompressing the reactor. Later, the condensed liquid was collected in a pot and sent to the wastewater treatment facility, as it contained chlorine and organics that might have been harmful. Finally, the treated feedstock was released by using rotating blades installed inside the reactor. In the end, the treated product was cooled down, mixed, and preserved at 10 °C.

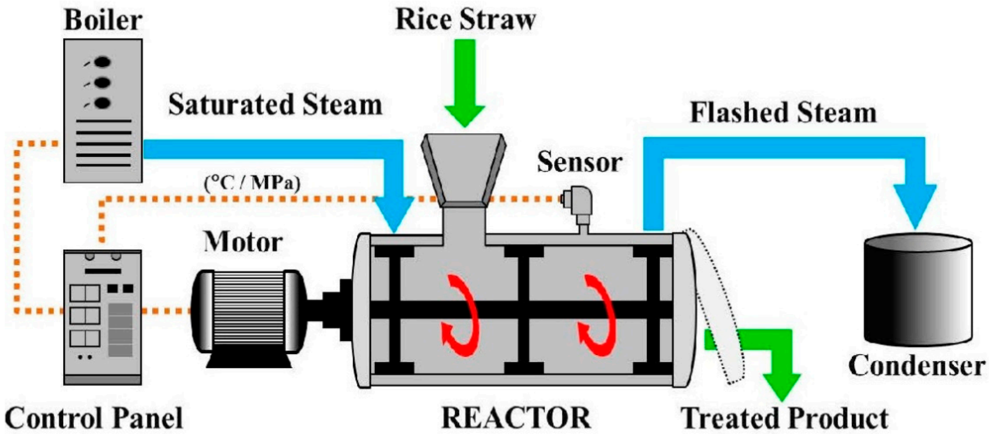

Figure 1. Schematic diagram of the pilot-scale hydrothermal treatment facility.

Pyrolysis plastic waste residue was obtained from the oilification of municipal plastic waste via the pyrolysis process. The municipal plastic waste contained polyethylene bags and high-density polyethylene. This pyrolysis experiment was conducted using a batch system pilot-scale reactor. The reactor was made of stainless steel, had a 200-mm inner diameter and 400-mm height, and was covered with an electric heater. The experiments were conducted at a 450 °C temperature, and each time about 2 kg feedstock was fed into the reactor. Further details of the experimental procedure can be found in [31].

2.2. Feedstock Characterization and Preparation

The feedstocks used in this study were hydrothermally treated hospital solid waste products, hydrothermally treated rice straw, pyrolytic plastic waste residue, untreated rice straw, and untreated Sakhalin fir residue. The physicochemical characteristics of these feedstocks were analyzed based on the recommendation of the American Society of Testing Materials (ASTM). The ultimate analysis was done by using an EA 1112 (Thermo Fisher Scientific, Waltham, MA, USA) instrument and following the ASTM D5373 method. The proximate analysis was done by using a TGA-701 (LECO Co., St. Joseph, MI, USA) instrument and following the ASTM D3172 method. Table 1 shows the physicochemical characteristics of these feedstocks. The effect of hydrothermal treatment on rice straw and hospital solid waste can be described from the results shown in Table 1. The result shows that after using hydrothermal treatment, fixed carbon content, carbon content, volatile content, and hydrogen had increased in the case of rice straw, whereas ash content and chlorine content had decreased. Due to the strict regulation of the Japanese government, the hospital solid waste boxes could not be opened before treatment; thus, we were unable to measure the physicochemical characteristics of untreated hospital waste. However, the general composition of hospital waste is known. The main constituents of hospital solid waste are transfusion tubes, sample collectors for urine, one-off medical gloves, operating gloves, catheters, cotton swabs, toilet paper, gauze, absorbent cotton, absorbable catgut sutures, and fillings of dressing. The typical physicochemical characteristics of these components can be found in Table A1 (Appendix A). It is widely known that due to hydrothermal treatment dechlorination, a chemical dehydration reaction and decarboxylation reaction take place; as a result, a carbon and fixed carbon enriched product with a much lower chlorine content can be obtained [32]. Based on this well-established fact, we assumed that similar chemical reactions took place during the hydrothermal treatment of hospital solid waste, and that the obtained product was rich in carbon and fixed carbon contents and lean in chlorine content compared to the untreated feedstock.

Table 1. Physicochemical characteristics of the feedstocks used in this study.

Feedstock	Proximate Analysis (wt%)				Ultimate Analysis (wt%)					
	MC	VM	FC	AC	C	H	N	O	Cl	S
URS	15.20	63.44	5.06	16.30	43.80	4.61	0.82	50.13	0.02	0.04
HRS	6.80	73.68	6.62	12.90	44.91	5.24	0.14	48.94	0.01	0.04
HHW	3.20	86.99	5.21	4.60	56.77	7.07	0.64	35.09	0.40	0.01
PPR	4.80	80.10	9.35	5.30	76.30	11.50	0.26	11.47	0.33	0.02
USR	10.90	81.17	7.63	0.30	47.40	6.30	0.31	45.32	0.02	0.03

To maintain homogeneity during the experiment, the preparation of feedstock is crucial. Feedstock preparation requires particle size reduction to achieve a consistent small grind. In this study, a C.S. Bell No. 1 Modern Hammer Mill equipped with a 16-inch screen was used for particle size reduction. Different sieve sizes (1.18 mm, 500 µm, 160 µm, and 125 µm) were used to characterize the particle sizes of the untreated rice straw residue, hydrothermally treated rice straw residue, hydrothermally treated hospital solid waste, pyrolytic plastic waste residue, and untreated Sakhalin fir residue. After sieve analysis, the different raw materials in different proportions and varying homogeneity and fine particle sizes were used to produce pellets.

2.3. Mixing Ratios of Different Samples

In this study, hydrothermally treated rice straw, hydrothermally treated hospital waste, pyrolytic plastic waste residue, untreated rice straw, and untreated Sakhalin fir residue were used as feedstocks for pellet production; their bulk densities were 608, 340, 457, 540, and 740 kg/m^3 respectively. The bulk density of pellets profoundly influences transportation and handling efficiency, as well as storage space requirements [16]. According to the European standard specification for residentially and commercially densified fuel pellets, the bulk density of the pellet should be more than 600 kg/m^3 [33]. Except for hydrothermally treated rice straw and Sakhalin fir residue, all other feedstocks used in this experiment had a bulk density less than 600 kg/m^3; hence, mixing ratios were selected in such manner that the bulk density of the produced pellets became more than 600 kg/m^3. Therefore, feedstocks were mixed in different ratios, considering the fulfillment of the basic requirement of pellet production. Different proportions of feedstocks were mixed to produce fuel pellets, after which the effects of varying proportions on the hydrothermally treated hospital solid waste product, hydrothermally treated rice straw, pyrolytic plastic waste residue, untreated Sakhalin fir residue, and untreated rice straw were determined. Table 2 shows the composition of different fuel pellets used in this study.

Table 2. Composition of different pellets.

Pellet Type	Composition
URP	100 wt% URS
HRP	100 wt% HRS
HRP1	28.60 wt% HRS and 71.40 wt% USR
HRP2	16.70 wt% HRS and 83.30 wt% USR
HRP3	10.50 wt% HRS and 89.50 wt% USR
HWP	100 wt% HHW
HWP1	16.70 wt% HHW and 83.30 wt% USR
HWP2	12.20 wt% HHW and 87.80 wt% USR
HWP3	1.50 wt% HHW and 98.50 wt% USR
HWP4	1.00 wt% HHW and 99.00 wt% USR
PRP	100 wt% PPR
PRP1	4.76 wt% PPR and 95.24 wt% USR
USP	100 wt% USR

2.4. Pellet Production Process

The pilot-scale flat die pellet machine (AMSPLM 300 Electric Flat Die) used in this experiment is shown in Figure 2. At first, the feedstock was supplied in the pellet machine. After that, it was compressed using a roller against a warm metal plate called a die., The feedstocks were squeezed through the tiny holes of the die at 180 °C temperature and 200 MPa pressure. Next, pellets were sliced into predefined lengths as they exited the die, using a blade. The pellets that exited the die were hot (around 150 °C) and relatively soft. Therefore, before using these materials, cooling and drying were required and achieved by blowing air through the pellets. Later, to enable uniform moisture distribution in fuel pellets, pellets were kept in a conditioning room for 72 h with a temperature of 28 °C and a humidity of 65%.

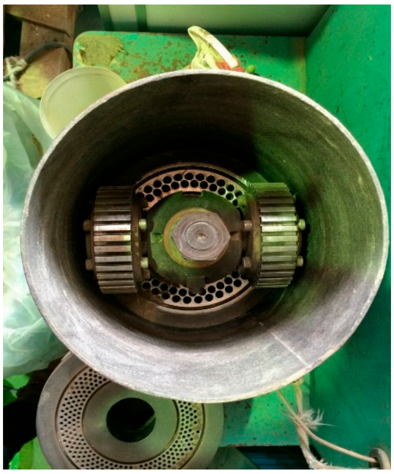

Figure 2. Flat die pellet machine.

2.5. Tests for Pellet Properties

The selected pellet properties were ascertained and evaluated based on the European standard specification for residential/commercial densified fuel [33]. Table 3 shows the threshold values of the most crucial pellet parameters according to the European standard specifications.

Table 3. Threshold values of the most important pellet parameters [33].

Property	Unit	ENplus-A1	ENplus-A2	EN-B
Diameter	mm		6 or 8	
Length	mm		$3.15 \leq L \leq 40$ [(3)]	
Moisture content	wt% [(1)]		≤ 10	
Ash content	wt% [(2)]	≤0.7	≤1.5	≤ 3.0
Mechanical durability	wt% [(1)]	≥97.5 [(4)]		≥96.5 [(4)]
Fine particles (<3.15 mm)	wt% [(1)]		<1	
Net calorific value	MJ/kg [(1)]	$16.5 \leq Q \leq 19$	$16.3 \leq Q \leq 19$	$16.0 \leq Q \leq 19$
Bulk density	kg/m^3		≥600	
Nitrogen content	wt% [(2)]	≤0.3	≤0.5	≤1.0
Sulfur content	wt% [(2)]	≤0.03		≤0.04
Chlorine content	wt% [(2)]	≤0.02		≤0.03

[(1)] As received; [(2)] dry basis; [(3)] a maximum of 1 wt% of the pellets may be longer than 40 mm, no pellets > 45 mm are allowed; [(4)] deformation temperature, sample preparation at 815 °C.

2.5.1. Pellet Dimensions

Ten pellets were randomly selected from each pellet type to determine the unit mass and dimension of the pellets. The shape of the produced pellets was cylindrical; thus, a digital Vernier caliper was used to measure the length (L) and diameter (d) of each sample. For measuring the mass (m) of fuel pellets, a precision digital balance was used. The diameter of fuel pellets was the same for all the pellets (8 mm); however, the length differed from pellet to pellet. Using the results of length and diameter obtained from the above process, the aspect ratio (A_r) = L/d was calculated. Similar repetitions were conducted for every type of pellet.

Unit density (ρ_u) was calculated by weighing a single pellet and calculating its volume based on its length and diameter [34,35]. The equations that were used are as follows:

$$V_u = (\pi d^2/4)\ L \tag{1}$$

$$\rho_u = m_u/V_u \tag{2}$$

where V_u represents the volume of a pellet (m^3), d denotes the diameter of a pellet (m), L is the length of a pellet (m), ρ_u refers to the density of a pellet (kg/m^3), and m_u denotes the mass of a pellet (kg).

2.5.2. Bulk Density

Bulk density (ρ_b) was calculated as the ratio of material mass to container volume [35,36]. At first, the volume of the container was calculated by measuring the diameter and length of the container. Later, the container was filled with pellets to the surface and weighed using a digital scale. Finally, the bulk density was calculated using the formula as follows:

$$\rho_b = m_b/V_b \tag{3}$$

where ρ_b refers to the bulk density (kg/m^3), V_b denotes the volume of the container (m^3), and m_b represents the total mass of the pellets (kg).

2.5.3. Fine Particle Content

Fine particle content (P_f) of pellets was determined by screening a pellet directly from the pellet mill [37], after which the percentage mass of the fine particles passing through the sieve was calculated from the total pellet mass based on the European standard specification for fuel pellets.

2.5.4. Pellet Durability

Pellet durability (P_d) was measured based on the mass loss of the samples [38]. The evaluation was conducted in accordance with ASAE Standard S269.4. Firstly, a few pellets from the same pellet groups were selected randomly. Later, selected pellets were weighed using a high-precision digital scale and the primary mass was noted. After that, the pellets were placed in a vibrating sieve for 15 min; the screen size of the sieve was 3.17 mm. After 15 min, the pellets were taken out of the sieve and re-weighed. The final mass was noted down and, using the following equation, the pellet durability was calculated:

$$P_d = 100 - [(m_i - m_f)/m_i \times 100] \quad (4)$$

where P_d denotes the pellet durability (wt%), m_i refers to the initial mass of the samples (g), and m_f is the final mass of the samples (g).

2.5.5. Ash Content

On the basis of the ASTM D1857 standard test method for fusibility of coal and coke ash, the ash content (AC) of the pellets was determined.

2.5.6. Gross Calorific Value

The amount of energy released upon the complete combustion of per unit mass is called gross calorific value (GCV) [39]. In this study, the GCV of the fuel pellets were measured using a PARR 1266 Bomb Calorimeter. A benzoic acid tablet with a calorific value 26,465 J/g was used to calibrate the calorimeter before testing. Around 1 g of the pellet sample was placed in the bomb for the experiment, and the bomb was charged with high-purity oxygen (>99.5% pure) at a pressure of 3 MPa. Combustion was not aided in any way, and five samples were tested from each pellet type.

2.5.7. Physicochemical Characteristics

To investigate the basic characteristics of the pellet, proximate analysis and ultimate analysis were conducted. The ultimate analysis was conducted using EA 1112 (Thermo Fisher Scientific) in accordance with ASTM D5373. Proximate analysis was conducted using TGA-701 (LECO Co., St. Joseph, MI, USA) based on ASTM D3172.

3. Results and Discussion

3.1. Particle Size Reduction and Distribution

The most significant factors affecting overall pellet quality are particle size and moisture content. According to MacBain, finer particle sizes shows conformity with greater pellet strength and durability, as large particles serve as fissure points [40]. Generally, the quality of the pellets is inversely proportional to particle size. Several studies have reported that smaller particle sizes will produce higher-density pellets [41]. However, according to Payne, a proportion of fine-to-medium particles is required for achieving good pellet quality, but the pellet quality and efficiency of commercial pellets will suffer if coarse material is missing [42]. Payne further reported that to produce high-quality pellets the particle size distribution should be <0.25 mm (≥20 wt%), 0.25–2.00 mm (≈75 wt%), and >2 mm (≤5 wt%) [43]. In conclusion, the best pellet quality could be attained with a mixture of different particle sizes because such a combination increases inter-particle bonding and eliminates inter-particle spaces [41–44]. In this work, the authors used raw materials with heterogeneously distributed particles and particle size (less than 3 mm). Figure 3 depicts the particle size distributions of five kinds of raw material used in this research. Figure 3 also illustrates that hydrothermally treated rice straw, hydrothermally treated clean hospital solid waste, and pyrolytic waste plastic residue exhibited more homogeneously distributed and finer-sized particles than did untreated rice straw and Sakhalin fir residue. The major particle fractions in the untreated rice straw and Sakhalin fir residue were larger than 1.18 mm, whereas those in the hydrothermally treated rice straw, hospital solid waste, and pyrolytic plastic waste residue were less than 1.18 mm. These findings indicate that hydrothermally treated products have higher amounts of fine particles from which high-quality fine-particle fuel pellets can be produced. The major reason behind this phenomenon is the mechanical action of the blades. A minor reason could also be the effect of hydrothermal treatment, as subcritical water shows properties such as low viscosity and high organic solubility during hydrothermal treatment, and due to this, the physical structure of the particles break down into smaller and simpler molecules [32].

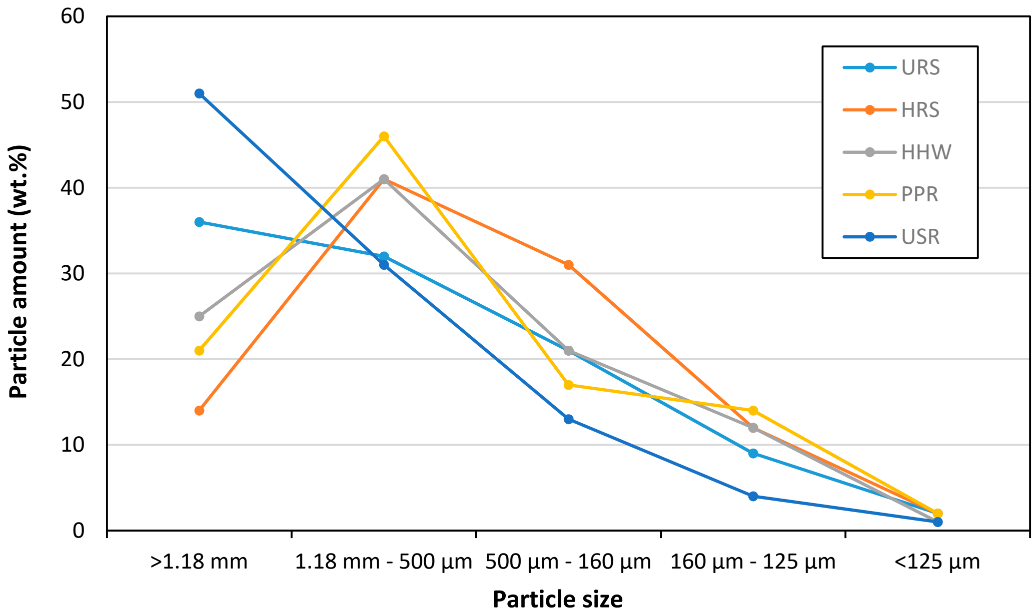

Figure 3. The particle size distribution of feedstocks for pellet production.

3.2. *Analyses of Pellet Properties*

Thirteen types of pellets were used in this research work.Table 4 shows the pellet properties exhibited by various fuel pellets.

Table 4. Properties of different fuel pellets.

Pellet Type	A_r	ρ_u (kg/m^3)	ρ_b (kg/m^3)	P_f (wt%)	P_d (wt%)
URP	2.67	1150	540	0.27	91.10
HRP	2.31	1250	608	0.37	93.40
HRP1	2.26	1271	702	0.26	96.50
HRP2	2.39	1275	718	0.24	96.60
HRP3	2.41	1177	726	0.30	96.80
HWP	3.28	1030	340	0.36	92.50
HWP1	3.21	1238	673	0.22	98.20
HWP2	3.19	1250	692	0.21	97.90
HWP3	2.31	1276	734	0.21	98.10
HWP4	2.24	1279	737	0.20	97.90
PRP	4.17	1090	457	0.23	96.20
PRP1	3.67	1271	727	0.19	98.30
USP	2.18	1280	740	0.18	97.60

3.2.1. Pellet Density

In evaluating the pellet properties, pellet density plays a significant role. It is known as a quality indicator of pellets, according to several national standards [45]. Further, storage space requirements, handling efficiency, and transportation costs are highly dependent on the bulk density of pellets.

Fasina reported that greater bulk density leads to higher transport efficiency and lower storage space requirements [46]. The mean values of unit density and bulk density of various pellets used in the present research are listed in Table 4. The pellets made of untreated Sakhalin fir residue or containing a mixture of untreated Sakhalin fir residues such as HRP1, HRP2, HRP3, HWP1, HWP2, HWP3, HWP4, PRP1, and USP showed very high bulk and unit density. The reason behind this phenomenon is the high bulk density of the Sakhalin fir residue feedstock, which is the major component of these pellets. On the other hand, pellets made only with untreated rice straw (URP), hydrothermally treated hospital waste (HWP), and pyrolytic plastic waste residue (PRP) showed comparatively lower bulk and unit density. This happened because of the low bulk density of the feedstocks used in these pellets.

3.2.2. Aspect Ratio of Pellets

The aspect ratios (A_r) of different fuel pellets are shown in Table 4. The fuel feeding properties depend on the lengths of the pellets. For easier arrangement and continuous flow, shorter pellets are preferred [47]. In addition, the thickness of a pellet is important for a uniform combustion rate. According to Demirbas, when combustion is carried out in a small furnace, thinner pellets show better combustion rates than thicker ones [47]. In this study, the pellet diameter (8 mm) was the same for all the types of fuel pellets. The dimensions of all the pellets satisfied the requirements stipulated in the European standard specification for residential/commercial densified fuels. For all kinds of pellets, the aspect ratio was more than 2.

3.2.3. Pellet Strength

In this experiment, pellet durability and fine particle content were used as a parameter to evaluate the strength of pellets. The values of durability and fine particle content for different types of pellets are shown in Table 4. In the pellet industry, durability is considered to be a critical factor of pellet quality. High durability is important for high-quality pellets [48]. The results in our study showed that all mixed pellets (HRP1, HRP2, HRP3, HWP1, HWP2, HWP3, HWP4, and PRP1) had high durability, which successfully satisfied European standard specifications (≥96.5 wt%). All of these mixed pellets contained a high amount of untreated Sakhalin fir residue, which is the reason for the high durability of the pellets. Even the pellet made only with untreated Sakhalin fir residue (USP) showed high durability, whereas the pellets without Sakhalin fir residue (URP, HRP, HWP, PRP) failed to meet the European standard specification. Again, according to the European standards for testing fuel pellet quality, the amount of fine particle content should be <1 wt%. From the experimental results, it was found that every pellet sample had a fine particle content <1 wt%.

3.2.4. Ash Content

Table 5 shows the ash content of the different types of pellets used in this study. According to the European standard specification for fuel pellets, the ash content of pellets should be less than 3 wt%. Results showed that, except for HRP1, all the mixed pellets (HRP2, HRP3, HWP1, HWP2, HWP3, HWP4, and PRP1) had low ash content. These pellets successfully met the European standard specification. On the contrary, pellets solely made with one raw material (except the Sakhalin fir residue) such as URP, HRP, HWP, and PRP showed very high ash content and failed to meet the European standard. Liu et al. reported that the combustion process and the mineral constituents of the source fuel influence the ash content in the fuel pellet [38]. In case of USP and mixed fuel pellets, source fuel was entirely or mostly untreated Sakhalin fir residue and they had very low ash contents, while source fuels of URP, HRP, HWP, and PPR showed high ash content in proximate analysis. As such, the hypothesis was validated.

Table 5. Physicochemical characteristics, gross calorific value, and energetic biomass utilization efficiency (BUE_E) of different fuel pellets.

Pellets	Proximate Analysis (wt%)				Ultimate Analysis (wt%)						GCV (MJ/kg)	BUE_E (in%)
	MC	VM	FC	AC	C	H	N	O	Cl	S		
URP	13.70	64.58	5.15	16.3	43.80	4.61	0.82	50.13	0.02	0.04	13.40	99.11
HRP	6.10	74.26	6.67	12.9	44.91	5.24	0.14	48.94	0.01	0.04	18.50	99.30
HRP1	8.75	79.88	7.42	3.90	46.60	6.00	0.26	46.36	0.02	0.03	19.95	98.79
HRP2	9.18	80.82	7.54	2.40	46.90	6.12	0.28	45.92	0.02	0.03	20.25	99.01
HRP3	9.41	81.31	7.61	1.62	47.05	6.20	0.30	45.70	0.02	0.03	20.40	99.07
HWP	2.90	87.25	5.23	4.60	56.77	7.07	0.64	35.09	0.40	0.01	28.30	99.47
HWP1	8.65	82.99	7.30	1.02	48.90	6.43	0.37	43.62	0.09	0.03	21.90	99.12
HWP2	8.96	82.76	7.42	0.82	48.45	6.40	0.35	44.07	0.07	0.03	21.55	99.08
HWP3	9.70	82.21	7.68	0.36	47.45	6.30	0.31	45.17	0.03	0.03	20.75	99.12
HWP4	9.75	82.11	7.74	0.35	47.60	6.35	0.30	44.07	0.02	0.03	20.60	98.58
PRP	4.30	80.50	9.40	5.30	76.30	11.5	0.26	11.47	0.33	0.02	22.70	99.34
PRP1	9.54	82.07	7.80	0.54	48.68	6.55	0.30	43.70	0.03	0.03	20.70	98.96
USP	9.80	82.15	7.72	0.30	47.40	6.30	0.31	45.32	0.02	0.03	20.60	98.94
A. Coal	5.20	40.30	27.90	26.00	81.10	5.10	2.10	10.90	ND	0.80	32.84	-
I. Coal	9.60	43.70	42.40	4.30	67.80	4.70	0.92	21.50	ND	0.25	25.83	-
R. Coal	3.40	39.00	42.70	14.90	68.00	4.00	0.87	11.60	ND	0.35	27.80	-

3.2.5. Gross Calorific Value

For distinguishing the combustibility of a substance, calorific value is considered to be the most crucial parameter. The gross calorific values (GCV) obtained from the experiment are shown in Table 5. Except for URP, all other pellets showed high calorific value and fulfilled the European standard specification (≥16 MJ/kg). In particular, hydrothermally treated pellets and mixed pellets showed very high calorific value. According to Chen et al., the material composition of pellets profoundly affects its calorific value [49]. In this case, the above result was obtained because of the molecule breakdown and moisture removal by the dehydration process during hydrothermal treatment.

3.2.6. Physicochemical Characteristics

Table 5 illustrates the results of the proximate analysis of various types of pellets used in this study. As the pellets were manufactured at a high temperature (180 °C) and pressure (200 MPa), around 10 wt% moisture loss was observed in the pellets compared to their initial feedstock. Results of the proximate analysis depict that all the fuel pellets had highly volatile contents. In particular, HWP and USP and mixed pellets (HRP2, HRP3, HWP1, HWP2, HWP3, HWP4, and PRP1) showed more highly volatile contents (more than 80 wt%) compared to different types of fuel pellets (sewage sludge, fir, rice straw) found in the literature [50]. Except for URP, all other pellets showed a moisture content lower than 10%, which satisfied the European standard specification. URP and USP had a high moisture content as these pellets were made of untreated feedstocks. In the case of fixed carbon, it ranged between 5 and 10 wt%. URP showed the lowest fixed carbon content because it was made of untreated rice straw, which contains a high amount of moisture. On the contrary, PRP showed the highest fixed carbon content, as it was made of pyrolytic plastic waste residue. Usually, after pyrolysis processing, a portion of carbon is converted into fixed carbon, and such results were obtained in this study. Jian et al. have done extensive work on the thermogravimetric characteristics of co-pelletized fuel pellets made of sewage sludge and biomass (Chinese fir, rice straw) [50]. As we have also used fir and rice straw for making mixed fuel pellets, their work helped us to draw a few conclusions. According to their study, high biomass content in a mixed fuel pellet will increase the mean activation energy and reactivity. In our study, all mixed pellets had at least 71.40 wt% biomass content, indicating that we could expect high reactivity and activation energy during the combustion of these pellets. Jian et al. concluded that fir pellets display low slagging propensity. As all of our mixed fuel pellets contained high amounts of Sakhalin fir residue (at least 71.40 wt%), we could expect that our pellets would show a low slagging tendency as well.

Table 5 shows the results of the ultimate analysis. The percentage of carbon, hydrogen, and oxygen were nearly the same in all the pellets, except for HWP and PRP. In the case of nitrogen and sulfur, their compositions varied among the pellets. However, all the pellets satisfied the European standard specification for nitrogen and sulfur contents. Higher chlorine content was found in HWP and PRP pellets. This is because hydrothermally treated hospital solid waste contains a high percentage of PVC, and PRP is made from the residue obtained from the pyrolysis of plastics. In addition to these pellets, HWP1 and HWP2 pellets also failed to meet the criteria of European standard specifications, as these pellets contain a higher amount of hydrothermally treated hospital solid waste.

3.2.7. Energetic Biomass Utilization Efficiency

A new yet simple methodology called energetic biomass utilization efficiency (BUE_E) was used to evaluate and compare the energy content of input feedstock and end products. The BUE_E value is the ratio of the HHV value of the product over the HHV value of the feedstock, and is calculated by comparing the actual higher heating values of the feedstock needed to produce 1 g of product divided by the HHV of 1 g of feedstock, and reported as input % [51]. Table 5 depicts that the BUE_E value of different fuel pellets ranging between 98.58 and 99.47 in%, which indicates that material loss took place during the pelletization process, although this amount of loss is not significant. The highest amount of material loss (1.42 in%) was found in the HWP4 pellet, and the lowest amount of material loss (0.53 in%) was found in the HWP pellet. From the above BUE_E results, it can be concluded that pelletization of URS, HRS, HHW, PPR, and USR feedstocks into fuel pellets is an energy-efficient process as the efficiency of energetic biomass utilization is high in this process.

3.3. *Comparison of Fuel Pellet Quality with Coal*

Figure 4 shows a comparison of elemental ratios between fuel pellets and coal. To measure fuel pellet quality, we compared the elemental ratios and physicochemical characteristics of fuel pellets with Australian coal (A. Coal) [52], Indonesian coal (I. Coal) [53], and Russian coal (R. Coal) [54]. Figure 4 depicts that pellets made of hydrothermally treated hospital solid waste, hydrothermally treated rice straw, and pyrolytic plastic waste residue had higher O/C ratios and H/C ratios compared to coal. For coal, the O/C ratio ranged between 0.15–0.35, and the H/C ratio ranged between 0.055–0.070, whereas for fuel pellets it ranged between 0.80–1.20 and 0.10–0.14, respectively. The pellets made of hydrothermally treated hospital solid waste and hydrothermally treated rice straw (or a mixture of the two) showed very high H/C ratios, illustrating that hydrothermal treatment improved their H/C ratios. When comparing the GCV value of fuel pellets with coal (shown in Table 5), it was found that pellets made from hydrothermally treated hospital waste, pyrolytic plastic residue, and mixed pellets from feedstock had a GCV that was as good as coal. Moreover, these pellets showed less ash content and sulfur content compared with coal. Thus, we can say that the addition of hydrothermally treated wastes and pyrolytic waste residue valorized the biomass fuel pellet.

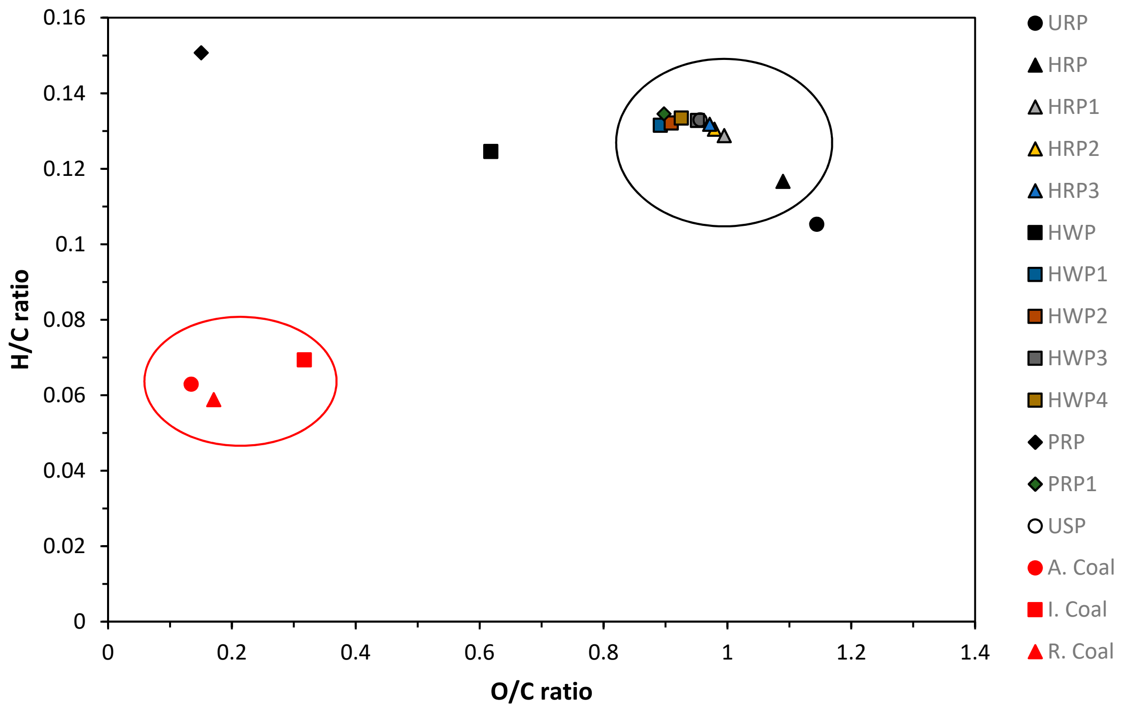

Figure 4. Comparison of elemental ratios between fuel pellets and coals.

4. Conclusions

Thirteen types of fuel pellets were made of hydrothermally treated clean hospital waste, hydrothermally treated rice straw, pyrolytic plastic waste residue, untreated rice straw, and Sakhalin fir residue. Pellets were made solely from these feedstocks, as well as by blending with Sakhalin fir residue. Fuel pellet quality was evaluated and compared according to the European standard specifications for residentially and commercially densified fuels. Results showed that, except for the USP pellet, all other pellets made with a single feedstock (URP, HRP, HWP, and PRP) failed to meet a few of the specifications of the European standard. On the contrary, most of the mixed fuel pellets (HRP2, HRP3, HWP3, HWP4, and PRP1) successfully satisfied the European standard specification. The exceptions were HWP1, HWP2, and HRP1, which failed to achieve the specification based on their chlorine (HWP1 and HWP2) and ash contents (HRP1). Due to the high chlorine content of HWP, a maximum of 1.5% could be utilized in a blend with USR in order to satisfy the criteria. When we compared the elemental ratios of fuel pellets with coals, we found that pellets made of hydrothermally treated hospital solid waste, hydrothermally treated rice straw, and pyrolytic plastic waste residue had a GCV as high as coal. Moreover, the addition of these feedstocks for the production of mixed fuel pellet valorized the fuel pellet quality. The main outcome of this study is the production of low chlorine clean biomass fuel pellets of high gross calorific values mixed with hydrothermally treated wastes and pyrolytic plastic waste residue. The results of this study open a new door for utilizing waste in a better way, especially hospital solid waste.

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Nomenclature

ρ_b	Bulk density (kg/m^3)
ρ_u	Unit density (kg/m^3)
A_r	Aspect ratio
AC	Ash content
ASTM	American society for testing and materials
BUE_E	Energetic biomass utilization efficiency
EN	European standards
FC	Fixed carbon
GCV	Gross calorific value
HHW	Hydrothermally treated hospital solid waste
HRP	Pellet made of 100 wt% hydrothermally treated rice straw
HRP1	Pellet made of 28.60 wt% hydrothermally treated rice straw and 71.40 wt% untreated Sakhalin fir residue
HRP2	Pellet made of 16.70 wt% hydrothermally treated rice straw and 83.30 wt% untreated Sakhalin fir residue
HRP3	Pellet made of 10.50 wt% hydrothermally treated rice straw and 89.50 wt% untreated Sakhalin fir residue
HRS	Hydrothermally treated rice straw
HT	Hydrothermal treatment
HWP	Pellet made of 100 wt% hydrothermally treated hospital solid waste
HWP1	Pellet made of 16.70 wt% hydrothermally treated hospital solid waste and 83.30 wt% untreated Sakhalin fir residue
HWP2	Pellet made of 12.20 wt% hydrothermally treated hospital solid waste and 87.80 wt% untreated Sakhalin fir residue
HWP3	Pellet made of 1.50 wt% hydrothermally treated hospital solid waste and 98.50 wt% untreated Sakhalin fir residue
HWP4	Pellet made of 1.00 wt% hydrothermally treated hospital solid waste and 99.00 wt% untreated Sakhalin fir residue
MC	Moisture content
PPR	Pyrolytic plastic waste residue
PRP	Pellet made of 100 wt% pyrolytic plastic waste residue
PRP1	Pellet made of 4.76 wt% pyrolytic plastic waste residue and 95.24 wt% untreated Sakhalin fir residue
URS	Untreated rice straw
URP	Pellet made of 100 wt% untreated rice straw
USR	Untreated Sakhalin fir residue
USP	Pellet made of 100 wt% untreated Sakhalin fir residue
VM	Volatile matter

Appendix A

Table A1. Ultimate analysis of typical medical waste composition [55].

Sorts	Samples	Major Constituent	wt%						
			C	H	O*	N	S	Cl	Si
Plastic	Tube for transfusion	PVC	50.87	7.06	7.56	ND	0.46	34.05	–
	Sample collector for urine	PVC	42.81	5.95	3.12	ND	0.73	47.39	–
	One-off medical glove	LDPE	86.19	13.41	0.40	ND	ND	–	–
Rubber	Operating glove	Natural rubber	86.06	10.27	2.04	0.42	1.04	–	0.17
	Catheter	Natural rubber, $CaCO_3$	43.86	5.79	48.45	0.35	1.23	–	0.32
Cellulosic	Cotton swabs	Cellulose, hemicellulose, lignin	46.26	6.43	47.09	ND	0.22	–	–
	Toilet paper		41.63	5.71	52.35	ND	0.31	–	–
	Gauze		42.51	6.35	51.01	ND	0.13	–	–
	Absorbent cotton		42.90	6.69	50.19	ND	0.22	–	–
Protein	Absorbable catgut suture	Collagen	43.16	7.60	34.85	13.59	0.80	–	–
	Muscle of white rat	Actin, myosin	50.08	7.36	28.44	12.81	1.31	–	–
Synthetic fibre	Filling of dressing	PVA	54.50	5.18	40.16	ND	0.16	–	–

ND = Not detected; O*: obtained by mass balance, containing impurity content; PVC = polyvinyl chloride; LDPE = low-density polyethylene; PVA = polyvinyl alcohol.

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