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Production of High-Porosity Biochar from Rice Husk by the Microwave Pyrolysis Process

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Abstract: This study focused on the highly efficient pyrolysis of rice husk (RH) for producing high-porosity biochar at above 450 °C under various microwave output powers (300–1000 W) and residence times (5–15 min). The findings showed that the maximal calorific value (i.e., 19.89 MJ/kg) can be obtained at the mildest microwave conditions of 300 W when holding for 5 min, giving a moderate enhancement factor (117.4%, or the ratio of 19.89 MJ/kg to 16.94 MJ/kg). However, the physical properties (i.e., surface area, pore volume, and pore size distribution) of the RH-based biochar products significantly increased as the microwave output power increased from 300 to 1000 W, but they declined at longer residence times of 5 min to 15 min when applying a microwave output power of 1000 W. In this work, it was concluded that the optimal microwave pyrolysis conditions for producing high-porosity biochar should be operated at 1000 W, holding for 5 min. The maximal pore properties (i.e., BET surface area of 172.04 m²/g and total pore volume of 0.1229 cm³/g) can be achieved in the resulting biochar products with both the microporous and the mesoporous features. On the other hand, the chemical characteristics of the RH-based biochar products were analyzed by using Fourier-transform infrared spectroscopy (FTIR) and energy-dispersive X-ray spectroscopy (EDS), displaying some functional complexes containing carbon–oxygen (C–O), carbon–hydrogen (C–H), and silicon–oxygen (Si–O) bonds on the surface of the RH-based biochar.



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Keywords: rice husk; microwave pyrolysis; biochar; texture characteristics; calorific value; surface complex

1. Introduction

As a cereal grain, rice may be the most widely consumed staple food in Asia and Africa, providing human nutrition and calorific intake by its richness in starch (one of the carbohydrates) and other components such as protein and fiber. However, rice husk, the most significant by-product, will be generated when rough rice (or paddy rice) is husked in a milling plant. In general, each kg of milled white rice results in approximately 0.28 kg of rice husk as a by-product during milling [1]. This hard biomass material is mainly composed of silica and lignocelluloses to protect the rice seed during the growing season [2–4]. Due to its rich contents of lignocellulosic constituents (about 80 wt%, dry basis), the rice husk is mostly used as a biomass fuel for energy production by combustion [5–8] and gasification [9–12]. In Taiwan, the energy utilization of rice husk has indicated an increasing trend [13]. In 2022, about 123 thousand metric tons was reused as an auxiliary fuel, as compared to about 78 thousand metric tons used in 2018. To increase the energy density and combustion performance, rice husk briquettes and/or pellets can be produced using densification [14,15]. It should be noted that we still cannot change the heating values of these biomass fuel products (or their calorific values). In this regard, carbonized rice

husk has been extensively studied under a limited supply of oxygen (O_2) and at moderate pyrolysis temperatures to enhance its calorific value, carbon content, and pore properties in recent years [16–23]. The biochar produced from rice husk can be used as soil amendment, liquid-phase adsorbent, or as a precursor for activated carbon [24–27].

Concerning the novel production of biochar from agricultural biomass or organic waste, the microwave-assisted pyrolysis (MAP) process has been widely adopted and reviewed in recent years [28–33]. As compared to the conventional pyrolysis process (i.e., heat flow from the outside to the inside due to the power from electricity or fuel combustion), MAP can reduce the energy consumption because the heat is generated inside of the biomass feedstock by molecular vibration from microwave stimulation, thus causing rapid heating within the material and high energy efficiency [34,35]. It was concluded that the microwave system shows a rapid, targeted, and energy-efficient heating process compared to the conventional electrical oven and combustion furnace processes. However, only a few studies have been reported that used MAP for producing biochar from rice husk alone [22,36–38]. Sahoo and Remya investigated the effect of heating time and microwave power on biochar yield from rice husk [22], resulting in a high-quality biochar with a significant increase in calorific value (Max. 25.46 MJ/kg) and specific surface area (Max. 190 m^2/g), which could be used as a potential source of energy, nutrient captive media, and soil amendment. Zhang et al. studied the yields and properties of the products obtained from microwave pyrolysis (set at 700 W and held for 20 min, reaching the pyrolysis temperature of about 550 $^{\circ}C$) of rice husk samples after undergoing different pretreatment processes (including water washing, torrefaction, and a combination of the two) [36], showing that the resulting biochar products had a high surface area (S_{BET} 157.81–267.84 m^2/g), which could be potentially used as soil amendments. Shukla et al. produced rice husk biochar at the operating conditions of a microwave power of 900 W, a holding time of 15 min, and a pyrolysis temperature of about 600 $^{\circ}C$, which was further used as an adsorbent for the removal of nutrients (nitrate and phosphate) from the aqueous solution, due to its high BET surface area of 190 m^2/g [37]. Halim et al. prepared rice husk biochar at 500 and 800 $^{\circ}C$ with a microwave power of 1000 W applied for approximately 9 and 15 min (i.e., heating rate of about 55 $^{\circ}C/min$), concluding that the resulting biochar products had high calorific values (i.e., 19.42 and 19.71 MJ/kg, with an increase rate of about 23.5%) [38]. Obviously, the resulting rice husk biochar from the microwave pyrolysis can be used as bio-coal fuel, or soil amendments, due to its high porosity and/or calorific value.

In previous studies [39,40], the torrefied products from rice husk and its pretreatment by soda leaching (0.25 M NaOH) were produced at 240–360 $^{\circ}C$ with holding times of 0–90 min by the conventional method (electricity-resistance heating) in order to enhance its fuel properties. Torrefaction operated at the proper conditions would be optimal to produce torrefied products with significantly higher calorific values of 19.71 MJ/kg (raw rice husk without pretreatment) and 28.97 MJ/kg (rice husk with NaOH pretreatment), as compared to that of rice husk (i.e., 13.96 MJ/kg). In this work, the production of biochar products from rice husk was performed in a modified microwave oven as a function of output power (300–1000 W) for a holding time of 0–20 min. The calorific values and the textural and chemical characteristics of the resulting biochar products were analyzed by using adiabatic calorimetry, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and Fourier-transform infrared spectroscopy (FTIR). These analytical results were further discussed and correlated with the microwave pyrolysis conditions.

2. Materials and Methods

2.1. Materials

In this study, the starting biomass material (i.e., rice husk) for producing biochar products was collected from a local rice-milling factory, which is located in Puzi Township (Chiayi County, Taiwan). Prior to the determinations of the thermochemical properties and the microwave pyrolysis experiments, the feedstock was dried at about 100 $^{\circ}C$ for 24 h in

an air-circulation oven to obtain a stable weight within 0.5% of water loss. Thereafter, the sample was stored in a desiccator or air-circulation oven for subsequent use.

2.2. Thermochemical Properties of RH

Based on the test methods of the American Society for Testing and Materials (ASTM), a proximate analysis (i.e., moisture content, ash content, volatile matter content, and fixed carbon content) of the as-received rice husk was performed in triplicate. The fixed carbon (FC) content was calculated by the difference. According to a previous study [41], the primary inorganic elements in the RH ash were silicon (Si) and potassium (K), accounting for 4.987 wt% and 0.582 wt%, respectively. Its calorific value was measured by using an adiabatic calorimeter (CALORIMETER ASSY 6200; Parr Instrument Co., Moline, IL, USA). There were three replicates for the determination of the calorific value, where about 0.3 g of the dried sample was used for each analysis. On the other hand, a thermogravimetric analyzer (TGA) instrument (TGA-51; Shimadzu Co., Tokyo, Japan), under a nitrogen (N_2) flow rate ($50\text{ cm}^3/\text{min}$), was used to examine the thermal decomposition behavior of the dried rice husk in a temperature range of 25 to $1000\text{ }^\circ\text{C}$ under four heating rates of 5, 10, 15, and $20\text{ }^\circ\text{C}/\text{min}$. When observing the microscopic structures on the surface of the rice husk and resulting biochar products by scanning electron microscopy (SEM), their elemental compositions were also characterized by energy-dispersive X-ray spectroscopy (EDS).

2.3. Microwave Pyrolysis Experiments

Using rice husk as a starting material, the resulting biochar products (noted as BC-RH) were obtained by using a modified microwave oven (Mei Lin Energy Technology Co., Ltd., Kaohsiung, Taiwan), which can be operated at an oscillation frequency of 2450 MHz and an electric power consumption of 1350 W (Figure 1). The oven was equipped with a K-type thermocouple for monitoring the temperature profile of the quartz tube (length of 30 cm by inner diameter of 2 cm), which served as a pyrolysis reactor, where about 5.0 g of dried rice husk was placed for each microwave pyrolysis experiment. Prior to the microwave pyrolysis process, the nitrogen (N_2) flow (about $500\text{ cm}^3/\text{min}$) was purged for 5 min to ensure oxygen-free environment. Subsequently, the pyrolysis experiments were performed with a series of sets by the combination of the microwave output power (300–1000 W) and holding time (5–15 min). After the completion of microwave pyrolysis for each experiment, the resulting biochar was collected and weighted for calculating its mass yield compared to the initial loading weight (i.e., ca. 5 g). To code the resulting biochar products easily, they were indicated by the notation of the BC-RH power time. As an example, the biochar product BC-RH-800W-20M referred to the RH-based biochar product that was pyrolyzed by applying 800 W and holding for 20 min in the microwave system.

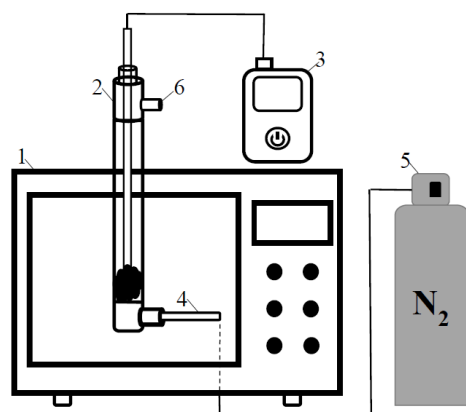


Figure 1. Schematic diagram of the microwave pyrolysis system. The system's components are denoted as numbers in parentheses, which are the microwave oven (1), quartz tube reactor (2), temperature monitor with K-type thermocouple (3), nitrogen gas inlet tube (4), nitrogen (N_2) gas cylinder (5), and the outlet (to hood) (6).

2.4. Determinations of Calorific Values and Textural Characteristics of RH-Based Biochar Products

As mentioned in Section 2.2, the calorific values of the RH-based biochar products were determined with a bomb calorimeter. In order to characterize the textural characteristics of the resulting biochar, the accelerated surface area and porosimetry system (ASAP 2020; Micromeritics Co., Norcross, GA, USA) were used to determine the pore properties (i.e., surface area pore volume and pore size distribution), which were based on the nitrogen adsorption–desorption isotherms at 77 K (i.e., $-196\text{ }^{\circ}\text{C}$). Prior to this property analysis, the biochar samples (about 0.25 g, dried at $100\text{ }^{\circ}\text{C}$) were degassed using a vacuum setpoint ($\leq 10\text{ }\mu\text{mHg}$ or 1.33 Pa) at $200\text{ }^{\circ}\text{C}$ for about 10 h. The data on the specific surface area were based on the Brunauer–Emmett–Teller (BET) model [42,43], using a relative pressure (P/P_0) range of 0.05 to 0.30. The total pore volume was given by the ratio of the volume of liquid adsorbate (N_2) at saturation (usually at a relative pressure of 0.995) per gram to the liquid nitrogen density at 77 K (i.e., 0.8064 g/cm^3). The micropore surface area and micropore volume were calculated using the t -method, which is based on the Harkins and Jura equation [43]. Concerning the dual (slit-cylinder) pore size distribution, the Barrett–Joyner–Halenda (BJH) equation (i.e., a modified Kelvin equation) was adopted to calculate the mesopore (pore width in a range between 2 nm and 50 nm) size distribution of the resulting biochar by using its isotherm data in the desorption branch [43]. Furthermore, the Horvath–Kawazoe (HK) method was used to determine the micropore size distribution (pore width or diameter of less than 2 nm) under the relative pressure range of 0 to 0.00115, which was assumed to be the slit-pore geometry [43].

The microscopic structure and elemental compositions on the surface of the resulting biochar were analyzed with a scanning electron microscope (S-3000N; Hitachi Co., Chiyoda, Tokyo) and an energy-dispersive X-ray spectroscopy (7021-H; HORIBA Co., Kyoto, Japan), applying a 15 kV acceleration potential. Prior to the SEM–EDS analysis, the dried samples (including the feedstock rice husk and biochar products) were ground into powders, which were deposited with a gold (Au) film using an ion sputter (E1010; Hitachi Co) to provide the conductive samples. The analysis of the functional groups on the surface of the potassium bromide (KBr)-containing samples (made into discs with a diameter of 1.2 cm) was conducted by using an FTIR instrument (FT/IR-4600; JASCO Co., Easton, MD, USA), where the reflectance spectra were recorded by using a range of $4000\text{ to }400\text{ cm}^{-1}$ with a scanning resolution of 4 cm^{-1} .

3. Results and Discussion

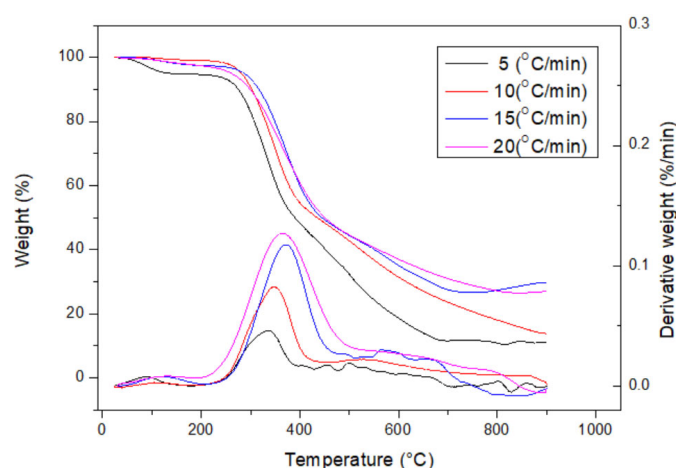
3.1. Thermochemical Characteristics of RH

Table 1 lists the proximate analysis and calorific values of the as-received feedstock RH, which were determined in triplicate. As indicated in the review reports [2–4], this biomass featured a high ash content of 13.93 wt%, thus resulting in a lower calorific value (16.94 MJ/kg , dry basis), as compared to those of the woody biomass. Therefore, ash melting (or slagging) may cause severe problems in biomass-derived fuel combustion systems [41,44–46], especially for rice residues and their resulting biochar products. Figure 2 shows the thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) curves of the feedstock RH, which were obtained at four heating rates (i.e., 5, 10, 15, and $20\text{ }^{\circ}\text{C/min}$) under the nitrogen (N_2) flow (i.e., $50\text{ cm}^3/\text{min}$). In the initial stage, the slight weight loss started at about $100\text{ }^{\circ}\text{C}$, which should be indicative of the thermal desorption of the moisture adsorbed/attached to the samples. Obviously, these curves similarly revealed the significant thermal decomposition behaviors in the pyrolysis temperature range of $250\text{--}450\text{ }^{\circ}\text{C}$. This was caused by the near-devolatilization of the lignocellulosic components (i.e., hemicellulose, cellulose, and lignin) at above $450\text{ }^{\circ}\text{C}$; however, the weight loss occurred at higher temperatures. In the microwave pyrolysis system (Figure 1), the process temperature profile was monitored to show the temperature above $450\text{ }^{\circ}\text{C}$. In this regard, the resulting biochar products from the microwave pyrolysis experiments should be fully carbonized and charred in this work.

Table 1. Proximate analysis and calorific value of rice husk (RH).

Property	Value
Proximate analysis ^{a,b}	
Moisture (wt%)	7.14 ± 0.78
Ash (wt%)	13.93 ± 0.09
Volatile matter (wt%)	70.60 ± 1.51
Fixed carbon ^c (wt%)	8.34
Calorific value (MJ/kg) ^{a,d}	16.94 ± 0.21

^a Mean ± standard deviation for three determinations; ^b the values were determined by an as-received sample; ^c by difference; and ^d the values were determined by a dry sample.

**Figure 2.** Thermogravimetric analysis/derivative thermogravimetry (TGA/DTG) curves of dried RH samples at the heating rates of 5, 10, 15, and 20 °C/min.

3.2. Mass Yield and Calorific Value of RH-Based Biochar Products

In this work, there were several microwave pyrolysis experiments as a function of the output power (i.e., 300–1000 W) and residence time (i.e., 5–15 min). Obviously, the mass yields indicated a declining trend, due to more serious pyrolysis reactions occurring at larger output powers when holding for 5 to 10 min. Taking an example at a residence time of 5 min, the mass yields were 36.62% (300 W), 32.08% (440 W), 27.46% (800 W), and 25.60% (1000 W). The maximal variations of the mass yields of the RH-based biochar products seemed to occur in the range of 300 W to 440 W at a short holding time (5 min). As compared to a previous study [39], the time scale for the microwave pyrolysis of RH was significantly lower than that of conventional conductive heating, thus ensuring a high heat transfer rate. In addition, the calorific values of the RH-based biochar products showed a slight variation in correlating with the process parameters of the microwave pyrolysis. It was found that the maximal calorific value (i.e., 19.89 MJ/kg) was produced under the mildest microwave conditions of 300 W with a holding time of 5 min in the present study, having a slight increase by 17.4% in comparison with 16.94 MJ/kg (seen in Table 1). This result was due to the enhancement of the carbon content and the reduction in the oxygen content in the RH-based biochar product produced from the microwave pyrolysis system, which will be further verified by the elemental compositions in the EDS analysis (seen in Section 3.4).

3.3. Pore Properties of RH-Based Biochar Products

Table 2 summarizes the data of the main pore properties (i.e., BET surface area, total pore volume, micropore surface area, and micropore volume) of the RH-based biochar products produced by the microwave pyrolysis process. Figure 3 shows their N₂ adsorption-desorption isotherms (i.e., −196 °C). Figures 4 and 5 show their pore size distributions based on the Barrett–Joyner–Halenda (BJH) method and the Horvath–Kawazoe (HK)

method, respectively. Using the results in Table 1 and Figures 3–5, the main findings were addressed as follows:

1. The pore properties of the RH-based biochar products significantly increased as the microwave output power increased from 300 to 1000 W, with a holding time of 5 min, giving more pore formation and the increments of the surface area and pore volume. The maximal pore properties (i.e., BET surface area of 172.04 m²/g and total pore volume of 0.1229 cm³/g) were obtained at a microwave output power of 1000 W at a holding time of 5 min. Obviously, the pore formation was more developed as the pyrolysis reaction increased at a higher microwave output power, leading to larger pore properties;
2. As shown in Table 1, the residence time also played a determining role in the pore properties of the RH-based biochar products in the microwave pyrolysis process. For example, the values of the BET surface area decreased with an extending residence time from 5 min to 15 min at a microwave output power of 1000 W, showing a BET surface area of 172.04 m²/g (BC-RH-1000W-5M) to 154.04 m²/g (BC-RH-1000W-10M) and 63.43 m²/g (BC-RH-1000W-15M). This result may be attributable to the collapse or destruction of the formed pores by severe microwave pyrolysis at longer reaction times. Therefore, the optimal microwave pyrolysis conditions for producing high porosity should be performed at a microwave power of 1000 W and a holding time of 5 min. The maximal BET surface area (i.e., 172.04 m²/g) and total pore volume (i.e., 0.1229 cm³/g) listed in Table 1 were slightly lower than those shown in similar studies [22,36,37];
3. As shown in Figure 3, the resulting biochar products are characteristic of microporous and mesoporous features, thus displaying Type I and Type VI isotherms [42,43]. It can be seen that the slight hysteresis loops (Type VI isotherms) start from approximately 0.15 of relative pressure in the N₂ desorption isotherms. According to the classification by the International Union of Pure and Applied Chemistry (IUPAC) [43], the hysteresis loops should be associated with Type H4 loops, indicating narrow slit pores. In this work, the mesopore size distributions obtained by the BJH method using the N₂ desorption isotherm data are depicted in Figure 4. It shows the peak at about 3.8 nm, displaying the mesopores (pore width in the range between 2 nm and 50 nm) in the resulting biochar products;
4. Figure 5 further depicts the micropore size distribution of the optimal biochar product (i.e., BC-RH-1000W-5M), using the HK equation for a more accurate description of its micropores [43]. Obviously, the resulting biochar is a microporous material, which showed significant micropores at about 0.6 nm.

Table 2. Pore properties of RH-based biochar products.

Biochar Product ^a	S _{BET} ^b (m ² /g)	S _{micro} ^c (m ² /g)	V _t ^d (cm ³ /g)	V _{micro} ^c (cm ³ /g)
BC-RH-300W-5M ^d	1.36	0.92	0.0030	0.000
BC-RH-440W-5M	8.64	6.67	0.0141	0.003
BC-RH-600W-10M	63.97	51.87	0.0476	0.027
BC-RH-800W-5M	75.34	49.47	0.0594	0.025
BC-RH-800W-10M	58.65	35.77	0.018	0.000
BC-RH-1000W-5M	172.04	120.48	0.1229	0.063
BC-RH-1000W-10M	154.04	116.36	0.1138	0.059
BC-RH-1000W-15M	63.43	47.87	0.0523	0.025

^a Sample notation indicates the resulting RH-based produced by applying a microwave power of 300 W, holding for 5 min, using 5 g RH. ^b BET surface area (S_{BET}) based on a relative pressure range of 0.05–0.30 (15 points).

^c Micropore surface area (S_{micro}) and micropore volume (V_{micro}) were obtained by using the *t*-plot method. ^d Total pore volume (V_t) was obtained at a relative pressure of about 0.995.

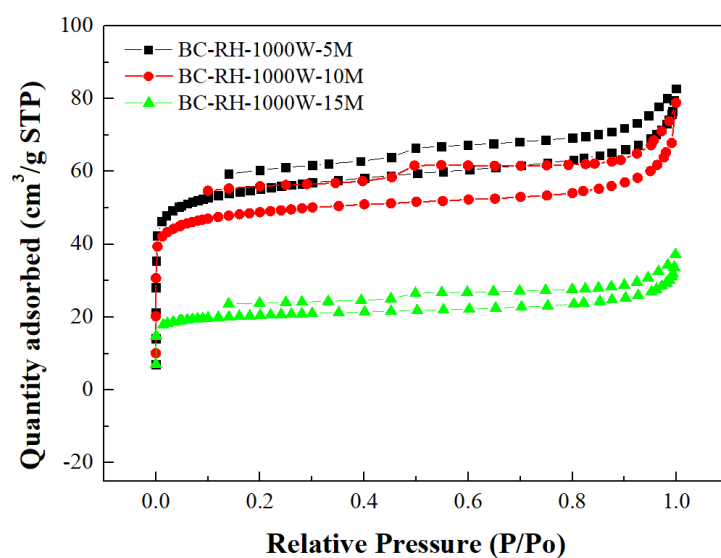


Figure 3. N₂ adsorption–desorption isotherms of some RH-based biochar products.

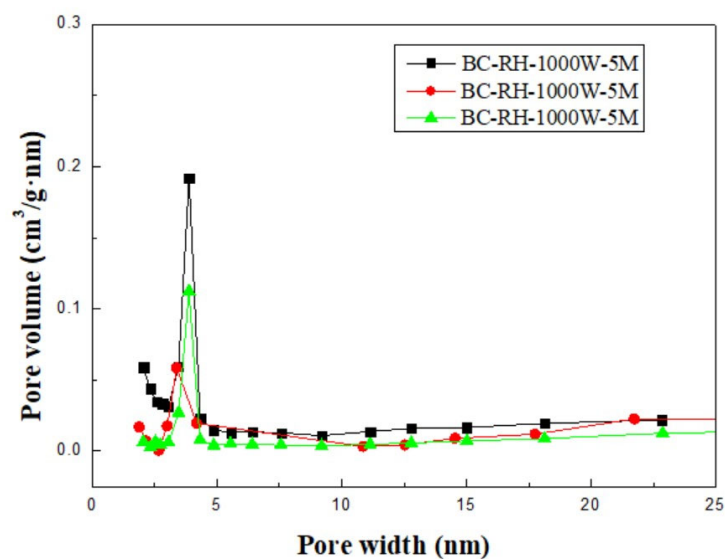


Figure 4. Mesopore size distributions of some RH-based biochar products.

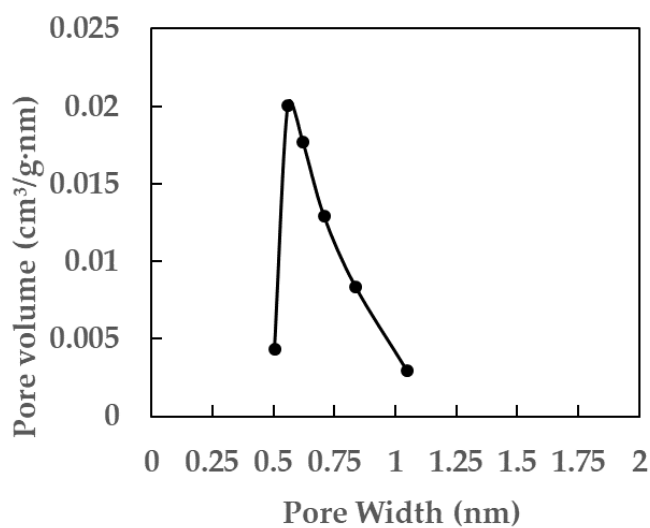
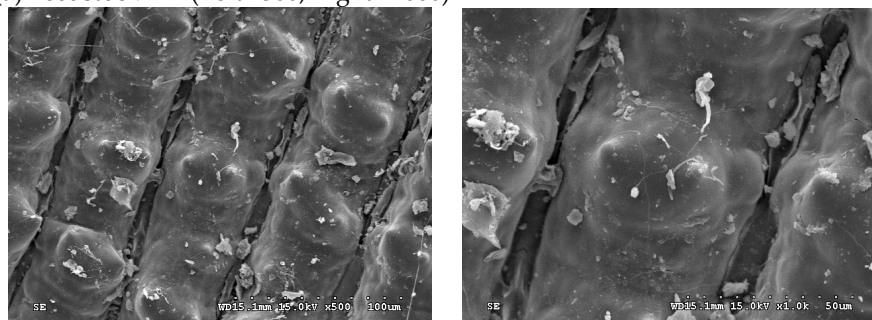


Figure 5. Micropore size distribution of the optimal biochar product (i.e., BC-RH-1000W-5M).

3.4. Textural and Chemical Characteristics of RH-Based Biochar Products

In order to provide the microstructural and chemical characteristics of the RH-based biochar products, their textural changes were observed by using a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscope (EDS). Figure 6 reveals the SEM images of the RH and BC-RH-1000W-5M at different magnifications ($\times 500$ and $\times 1000$), showing similarly shaped surfaces [41]. However, the surface of the RH-based biochar has become more corrugated after the microwave pyrolysis, which can be seen in Figure 6b. As a consequence, the resulting biochar had higher pore properties. This could be attributed to the thermal deformation and structural decomposition of the outer layer, composed of lignocellulosic components and minerals (e.g., silica), under microwave pyrolysis.

(a) Feedstock RH (Left $\times 500$; Right $\times 1000$)



(b) BC-RH-1000W-5M (Left $\times 500$; Right $\times 1000$)

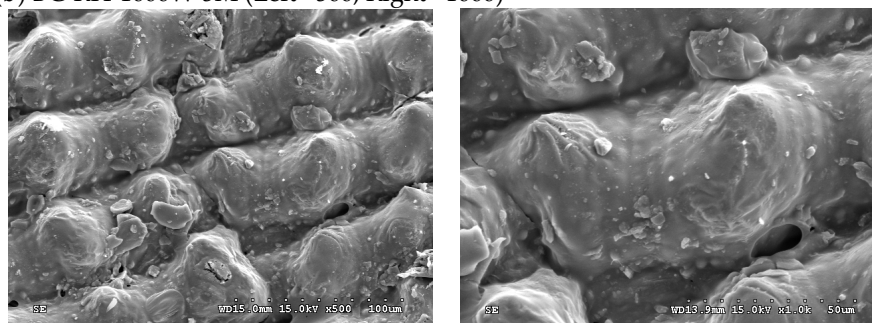


Figure 6. SEM/EDS analyses of (a) feedstock RH and (b) the optimal biochar product (i.e., BC-RH-1000W-5M).

On the other hand, energy-dispersive X-ray spectroscopy (EDS) was adopted to preliminarily determine the elemental compositions of the resulting biochar products. As indicated in Figure 7, the EDS spectrum of the optimal biochar BC-RH-1000W-5M contained significant amounts of carbon (C, 41.16 wt%), oxygen (O, 29.56 wt%), silicon (Si, 27.99 wt%), and potassium (K, 0.85 wt%) on the outer surface. As compared to the EDS spectrum of the feedstock RH (seen in Figure 6a), these observations were attributed to the devolatilization of the lignocellulosic constituents by releases of oxygen-containing gases (e.g., H_2O , CO, and CO_2) during the microwave pyrolysis process, thus causing the carbon content to increase and the oxygen content to reduce. Furthermore, Figure 8 displays the FTIR spectra of the feedstock RH and some of the biochar products (BC-RH-1000W-5M and BC-RH-1000W-10M). Based on the functional groups of the carbon materials [47–50], the peak at around 3500 cm^{-1} corresponds to the hydroxyl (O–H) functional group of the water molecule (H_2O) by stretching vibration, suggesting that there are more hydrophilic features in the feedstock RH. Comparing the other FTIR peaks of the feedstock RH with those of the RH-based biochar products, it can also be observed that the peaks of the latter were slightly dissipated, as elucidated above. The peaks at about 2960 and 2360 cm^{-1} could be due to the C–H and C–C bonds from the aromatic/aliphatic structures. The peak at 1385 cm^{-1} may be attributed to the oxygen-containing functional groups like the phenolic

C–O bond or the C–C stretching vibrations in the aromatic ring. The peak at 1107 cm^{-1} could correspond to the C–O groups in the polysaccharides or the Si–O bonds associated with silica in the RH-based biochar (also seen in Figure 7).

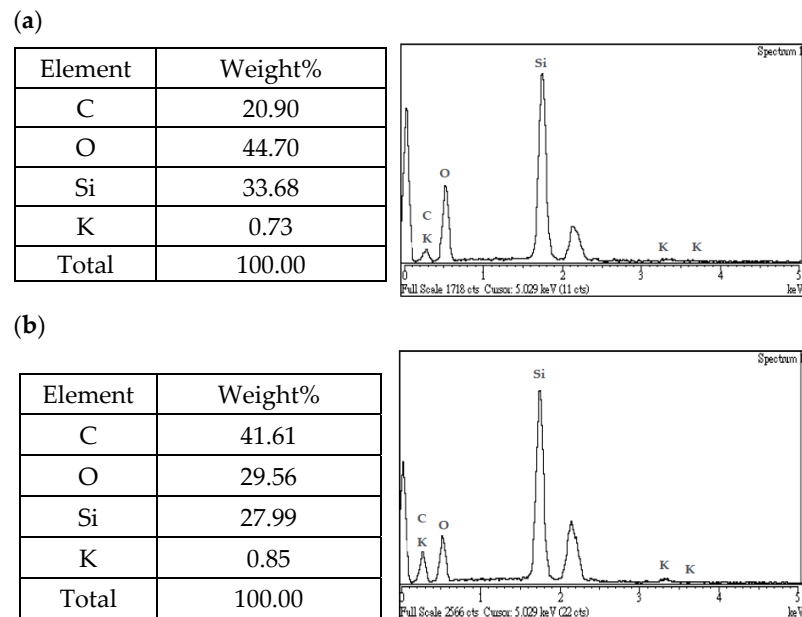


Figure 7. Elemental compositions of feedstock RH and the optimal biochar product (i.e., BC-RH-1000W-5M) by EDS analysis. (a) Feedstock RH and (b) BC-RH-1000W-5M.

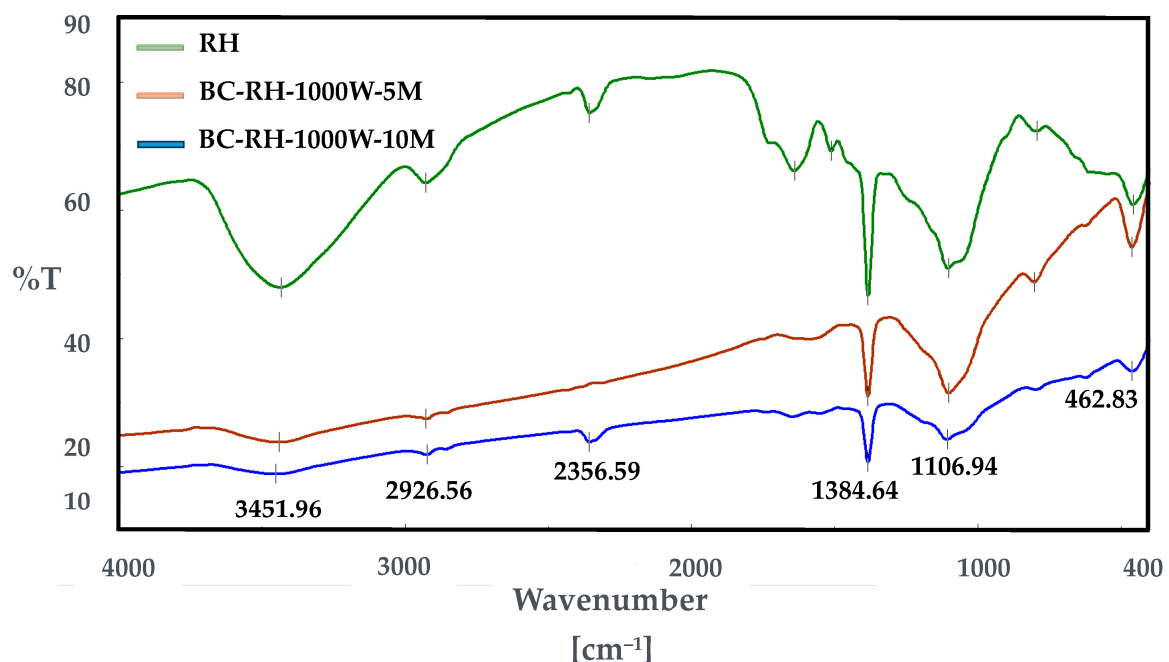


Figure 8. FTIR spectra of feedstock RH and some biochar products (i.e., BC-RH-1000W-5M and BC-RH-1000W-10M).

4. Conclusions

In this work, crop residue rice husk (RH) was used as a starting precursor for producing porous biochar via the microwave pyrolysis process. The results have indicated that the process parameters, including the microwave output power and the residence time, played determining roles in the calorific value and pore properties (i.e., the BET surface

area and the total pore volume) of the resulting RH-based biochar. When compared to the calorific value of the feedstock RH (i.e., 16.94 MJ/kg, dry basis), the findings showed that the maximal calorific value (i.e., 19.89 MJ/kg) can be obtained at the mildest microwave conditions of output power of 300 W and a holding time of 5 min. However, the high contents of silicon (Si) and the lower amounts of potassium (K) were still present, thus leading to a slight potential for slagging and fouling when using the RH-based biochar as an auxiliary fuel. In contrast, the pore properties of the RH-based biochar products significantly increased as the microwave output power increased from 300 to 1000 W, but they declined at longer residence times. In this work, it was concluded that the optimal microwave pyrolysis conditions used in the production of high-porosity RH-based biochar should be performed at a microwave output power of 1000 W and at a holding time of 5 min, where the maximal pore properties (i.e., a BET surface area of 172.04 m²/g and a total pore volume of 0.1229 cm³/g) can be achieved. Therefore, the resulting RH-based biochar products had the potential to be used as a soil amendment in agricultural applications or as a liquid-phase adsorbent in water purification and wastewater treatment.

Author Contributions: Conceptualization, W.-T.T. and R.-Y.Y.; methodology, L.-A.K.; formal analysis, L.-A.K.; data curation, L.-A.K.; writing—original draft preparation, W.-T.T.; writing—review and editing, W.-T.T.; visualization, L.-A.K. and W.-T.T.; supervision, R.-Y.Y. and J.-H.T. All authors have read and agreed to the published version of the manuscript.

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