

## Article

# Value-Added Performance and Thermal Decomposition Characteristics of Dumped Food Waste Compost by Pyrolysis

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**Abstract:** Food waste compost has a high Na content, which interferes with plant growth when used as a soil enhancer and therefore makes it difficult to use. And, compared to the amount of compost produced every day, the amount of consumption required in farms is smaller, and the rest is buried underground, which releases greenhouse gases and pollutes underground water. This research compared and analyzed thermal degradation behavior, calorific value, and gas spectrometry during the pyrolysis between food waste compost and sawdust to suggest producing food waste compost biochar by pyrolysis as a new alternative solution to utilize the massive amount of food waste compost. Biochar from pyrolysis of food waste compost had a high carbon content of 51% at 300 °C, and the carbon content decreased as the pyrolysis temperature increased. According to the thermogravimetric analysis (TGA) and derivative thermo-gravimetric (DTG) analysis results, compost showed the largest weight reduction from 240 °C to 365 °C. The weight reduction temperature ranges for compost and sawdust were quite similar. This occurred because food waste of the compost was degraded, but sawdust of compost remained nearly during the composting process. A gas chromatography and mass spectrometry (GC-MS) analysis found that the gases were fragments of fatty acids, protein, and hemi-cellulose. These results could also have been caused by degradation of microorganisms involved in the composting process, sawdust, and small fragments of food waste. In the calorific value of biochar, the highest value (24.33 kJ/g) was obtained 300 °C. At a low pyrolysis temperature, carbon fixation occurred easily since the food waste in compost was degraded by microorganism, and the volatilization of sawdust, which plays an important role in determining the calorific value, was also small. That is why the highest calorific value was shown at 300 °C, not 400 °C or 500 °C. Hence, it seems that food waste compost can be used as a promising alternative fuel at a low pyrolysis temperature, as other lignocellulosic refuse-derived fuels (RDF).

**Keywords:** food waste compost; sawdust; pyrolysis; biochar; thermogravimetric analysis (TGA); calorific value

## 1. Introduction

Even though food waste, which has a high content of organic matter, contains much potential energy, it is not used frequently. It takes compost produced from the composting process, which is mainly applied for food waste treatment and recycling, a lot of time to fully mature, and it is difficult to produce compost with consistent quality. In addition, when the compost has high Na content, it interferes with plant growth, which makes it difficult to use [1,2]. The salt content in food waste in Korea is high because of its unique food culture, and it is difficult to use food waste as compost [3]. As of 2015, 33.9% of the

13,546.9 tons/day of the food waste generated in Korea is treated via composting, and only 6.49% is recycled for farms [4]. This amount accounts for just 2.1% of the total food waste, and it shows that the recycling rate is very low. Furthermore, compared to the amount of compost produced every day, the amount of consumption required in farms is smaller, and the rest is not consumed and has to be used as landfill, which releases greenhouse gases, pollutes underground water [5], and causes other environmental problems. Accordingly, a new solution is needed to utilize the excess food waste compost that is not used for its original production purposes and requires treatment.

Pyrolysis is a process that breakdown of large complex molecules into several smaller molecules [6]. Gases, such as carbon dioxide and carbon monoxide, liquids such as bio-oil, or solid chars such as charcoal are generated during this process [6]. Pyrolysis reduces the large volume of biomass which is difficult to recycle and converts it into the material which has an economic value, such as bio-oil and biochar [7]. In fact, many studies have been conducted on the recycling of organic waste using pyrolysis. Iman and Capareda [8] analyzed the characteristics of synthetic gases and biochar produced by pyrolysis on dry grass, at temperatures ranging from 400 °C to 600 °C and demonstrated that biofuel can be produced through pyrolysis. Jahiru reviewed the previous studies that used pyrolysis and produced biofuels, but most were limited to botanical waste such as rice, straw, nut shells, and sugarcane [9].

There have also been studies that used compost as biomass. Agustin [10] performed a study using the gases generated from the composting process, including a study on compost degradation to produce hydrogen gases, but it did not utilize the compost itself. Ghorbel et al. [5] performed pyrolysis on farm breeding compost and cardboard, compared them, and revealed that the value of compost as a biofuel was not good enough, as cardboard had a much higher calorific value than compost. Ryu et al. [11] performed a study that combined mushroom compost with coal tailings and recycled it as a pellet-type fuel, but compost was only used to play a supporting role for coal tailings. In addition, the main source of compost used in these studies was vegetable waste, and no study performed pyrolysis of food waste compost to produce solid fuels. This is because there was a lack of awareness about the necessity of re-treating the waste that had been previously treated, or they were not convinced of the possibility of converting it into valuable matter. A new study is required to explore the scope of fuels other than those researched previously.

Lee et al. [12] researched the possibility of turning food waste containing grain, vegetables, or meat into a fuel. Pyrolysis at temperatures ranging from 200 °C to 400 °C produced a product with calorific value ranging from 23.7 to 29.7 kJ/g, whose energy content did not lag behind Ghorbel [5] calorific value from cardboard pyrolysis of 22.8 to 26.8 kJ/g, Phan et al. [13] calorific value from waste wood char pyrolysis of 27.1 to 31.4 kJ/g, and Ryu et al. [14] calorific value from pine wood pyrolysis of 31.7 to 32.5 kJ/g. In other words, it is possible to recycle food waste compost into a solid fuel, unlike compost containing vegetable matter only.

Hence, after performing pyrolysis of food waste compost, this study aims to compare and analyze the calorific values and thermal degradation of biochar produced at pyrolysis temperatures in the range 300–500 °C. Gas chromatography and mass spectrometry (GC-MS) of gases generated from food waste and sawdust contained in compost will also be used to examine the value of biochar as an energy-storing fuel.

## 2. Materials and Methods

### 2.1. Materials

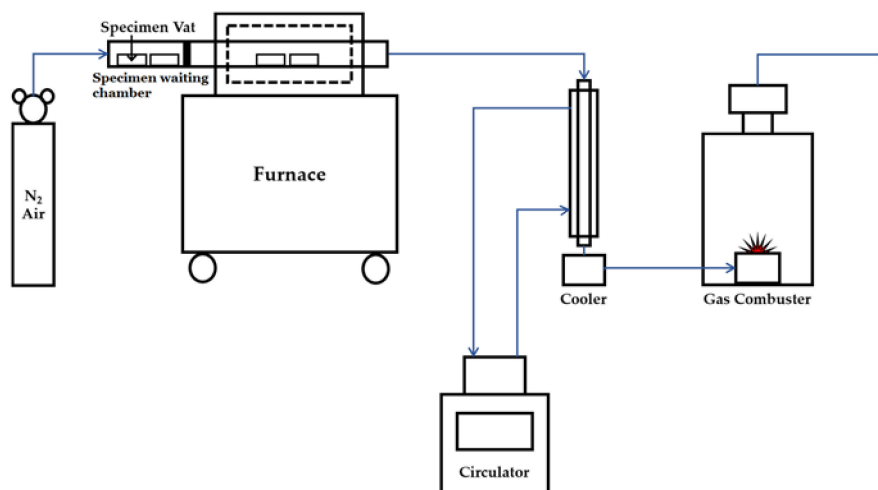
Food waste compost was collected from the Un-Jeong Environment Management Center, Paju-si, Gyeonggi-do, Korea. To remove large foreign matter, this study used food waste compost sieved through a 1.18 mm sieve.

The Un-Jeong Environment Management Center receives 20 tons of food waste from the region each day and washes it with water to remove salt. 10 tons of solid matter is obtained from the dehydrating process and is converted into compost in an aerobic composting tank. 1.1 tons of sawdust is added each day as a bulking agent. The aerobic composting tank goes through two stages. The 1st stage involves 14 days

of accelerated degradation, and the 2nd stage involves 20 days of maturation. The process produces 3 tons of compost every day.

## 2.2. Experimental Method

The experiment was carried out in four steps, including sample homogenization, pyrolysis, washing, and dehydration. Food waste compost was placed in a pyrolysis furnace at 300 °C, 400 °C, and 500 °C for 2 h. Nitrogen gas was added at 5 L/min to prevent oxidation. The 200 g of food waste compost sample was put in an open container with a width, length, and height of 5 cm, 20 cm, and 4.5 cm, and was then placed into the pyrolysis furnace. Figure 1 shows the reactor design.



**Figure 1.** The pyrolysis reactor design diagram.

After the sample completed pyrolysis, it was cooled down to room temperature. Some portion of the sample was washed in distilled water at a 1:10 ratio for 30 min to remove any remaining salt, which is characteristic of Korean food waste. Biochar in the washed sample was separated using a 47 mm glass microfiber filters (Whatman, Maidstone, UK), and was dried again at 100 °C. Samples from each pyrolysis temperature were analyzed for chemical composition, thermal degradation behavior, calorific value, and gases released during pyrolysis. Whole experiment proceeded three times, and analysis results represent average values. This process allowed the food waste compost pyrolysis characteristics to be examined as a potential solid fuel. Sawdust was added to the food waste composting process as a bulking agent. Sawdust is not degraded well by microorganisms and is likely to remain in the compost. This study also compared sawdust with a compost samples when analyzing the characteristics of compost and pyrolysis biochar.

## 2.3. Analysis Method

To obtain the elemental composition of food waste compost and biochar after pyrolysis, this study used the CHNS analyser (2400 Series II CHNS, Perkin Elmer, Boston, MA, USA). The raw compost and sawdust were analyzed only once as it is considered homogeneous as it was made using a specimen in the form of fully blended and sieved powder. All the biochar samples obtained from the three times of experiments were analyzed, and average values are stated. This study measured the Cl content using the combustion ion chromatography (AQF-2100H, Mitsubishi Chemical Analytech, Chigasaki, Japan) to determine the salt content in food waste compost, as well as the amount of salt removed from the biochar. An atomic absorption photometer (AAnalyst400, PerkinElmer, Boston, MA, USA) was used to measure the Na content.

To measure the energy amount of the biochar, this study measured the calorific value using a calorimeter (6400Automatic Isoperibol Calorimeter, Parr, Moline, IL, USA). The thermal degradation behavior was

investigated with a thermogravimetric analyser (TGA), and the heating rate was set at 10 °C/min and 20 °C/min in different experiments. The balance purge and sample purge was nitrogen gas 40 mL/min, 20 mL/min each. GC injection temperature is 320 °C, and 520 °C. Gases generated during pyrolysis were analyzed using thermogravimetric analysis (TGA)—gas chromatography (GC)—mass spectrometry (MS), and based on TGA results, this study analyzed released gases during the highest weight loss period.

### 3. Results and Discussion

#### 3.1. Characterization of Raw Material and Biochar

The chemical composition of the sawdust, food waste compost, and food waste is shown in Table 1. This study referenced other papers for data on food waste. Jo et al. [15] used mixed food produced according to the average composition of Korean food waste. Similar to this study, Zhang, Ruihong, et al. [16] were provided with food waste from a waste management company in Northern California. Kwon and Lee et al. [17] were provided with food waste from a university cafeteria in Seoul.

**Table 1.** Physical-chemical characterization of food waste compost and sawdust.

Sample	C	H	N	Moisture	Dry Basis			Reference
					Ash	Volatile	Fixed Carbon	
Food waste compost	29.7	4.3	2.9	21.6 ± 4.4	9.8	78.3	11.9	This study
Sawdust	24.4	2.9	-	28.6 ± 3.1	0.6	83.3	16.14	
Mixed food	47.5	12.2	2.9	85.7 ± 2.9	3.8 ± 0.1	79.0 ± 2.7	17.25	Jo et al. [15]
Food waste	46.8	-	3.2	-	-	85.3 ± 0.7	4.54	Zhang, Ruihong, et al. [16]
Cafeteria food waste	-	-	-	80.0 ± 2.3	1.3 ± 0.3	93.6 ± 1.9	-	Kwon and Lee et al. [17]

Carbon and volatile content in food waste compost were found to be lower than that of food waste in other studies because organic matter contained in food waste was degraded and volatilized by microorganisms through the composting process [18]. While the carbon content in food waste was greatly decreased, its nitrogen content did not change very much because nitrogen is a nutrient necessary for the growth of microorganisms and is absorbed into microorganisms to form their cells, while some nitrogen is degraded and volatilized into ammonia.

The carbon content in food waste compost decreased by about 40% compared with food waste down to 29.7%, which is twice as high as the 14.8% content in farm breeding compost from Ghorbel study [5]. Unlike Ghorbel's finding that farm breeding compost has little value as a fuel, food waste compost is more promising as a source of energy.

Food waste compost showed higher carbon and ash content than sawdust, but a lower moisture content. Notably, the amount of ash produced from sawdust was small, whereas, the ash content in food waste compost was more than 50 times higher. It was also higher than the content of food waste. The high ash content in food waste compost is due to the composting process, where the remaining inorganic matter that was not degraded after the organic matter is degraded and volatilized are concentrated. Table 2 shows the C, H, N, and S content in biochar produced after pyrolysis of food waste compost and the salt content analysis results:

**Table 2.** Element and salt content analysis of biochar at various pyrolysis temperatures.

(wt %)	C	H	N	S	Cl	Na
Compost	29.73	4.27	2.90	-	0.66	0.77
300 <sup>1</sup>	51.04 ± 0.11	5.53 ± 0.09	4.55 ± 0.09	-	0.18 ± 0.03	0.64 ± 0.02
300 <sup>2</sup>	51.83 ± 0.16	5.39 ± 0.10	4.68 ± 0.22	-	1.13 ± 0.14	1.57 ± 0.12
400 <sup>1</sup>	48.67 ± 0.46	4.28 ± 0.09	3.74 ± 0.05	-	0.30 ± 0.03	1.11 ± 0.08
400 <sup>2</sup>	47.58 ± 0.45	3.75 ± 0.74	3.25 ± 0.88	-	1.73 ± 0.03	1.91 ± 0.05
500 <sup>1</sup>	51.72 ± 1.31	2.24 ± 0.21	3.39 ± 0.31	-	1.03 ± 0.24	1.52 ± 0.01
500 <sup>2</sup>	48.42 ± 0.55	1.94 ± 0.07	3.61 ± 0.39	-	2.52 ± 0.02	2.64 ± 0.00

<sup>1</sup> Washed biochar. <sup>2</sup> Unwashed biochar.

According to the salt content of compost before pyrolysis, around 1.4% of the salt content remained, despite the fact it was washed to remove salt from the food waste before the composting process. It shows that washing raw food waste cannot completely remove salt content, even though some salt on the surface can be washed away, and additional treatment is required. In addition, salt remaining after washing is one of the primary factors that decreases its value as compost.

The Cl and Na content of biochar after pyrolysis of food waste compost increased as the pyrolysis temperature increased, which demonstrated that salt was not volatilized but concentrated during pyrolysis, while the organic matter was reduced in weight and volatile substances were released as gases. Na and Cl did not exist independently. Instead, they existed as solid NaCl. Therefore, salt was not volatilized during pyrolysis [19]. After washing, the Cl and Na content decreased rapidly, demonstrating that they were removed through washing after carbonization. The Na content after washing was relatively higher than the Cl content because some Na ions from washing water were absorbed due to biochar's cation exchange capacity (CEC) [17]. When the Cl content is high in combustion fuel, it can cause corrosion and boiler slagging, and it is regulated as it can produce hazardous substances such as hydrochloric acid (HCl) and polychlorinated dibenzodioxins (PCDD). The British-adopted European Standard (BS EN 15359: 2011) [20] for solid recovery fuel defines Grade 1 fuel as having a Cl content less than 0.2%, Grade 2 as less than 0.6%, and Grade 3 as less than 0.8%. The Cl content in biochar washed after pyrolysis at 300 °C to 400 °C was 0.18% and 0.3%, which put them into Grade 1 and Grade 2, respectively.

Another characteristic found in the table is the carbon content in biochar more than doubled compared to raw food waste compost. That content level is similar to or higher than that of food waste, which means that its possibility as a fuel is further increased. Its carbon, nitrogen, and hydrogen content all tended to decrease as the pyrolysis temperature increased because volatile substances were released as gases, and degradation and weight reduction occurred during pyrolysis.

Differences were also observed before and after washing. There were few differences at 300 °C, and differences increased as pyrolysis temperature increased. It seems that each element content per unit weight increased relatively as concentrated NaCl was removed during washing.

### 3.2. Thermogravimetric Analysis

To examine the thermal degradation behavior of food waste compost, sawdust and compost were analyzed with a TGA.

Figure 2a,b show TGA and DTG results for sawdust. The weight is reduced as moisture is evaporated at temperatures below 100 °C. If this range is excluded, there are two decomposition ranges: one from 275 °C to 360 °C, and another from 500 °C to 550 °C. Weight reduction in the range of 275 °C to 360 °C seems to be the result of hemi-cellulose decomposition [5,21] and lignin decomposition, which takes place gradually over temperatures ranging from 160 °C to 900 °C [22]. According to the thermal degradation behavior of pine sawdust in Ningbo Gao [23], hemi-cellulose decomposition took place at temperatures ranging from 225 °C to 375 °C, similar to the results found in this study. In the range of 500 °C to 550 °C, like the findings of Ulloa et al. [24], TGA-DTG results from coal and in radiated pine sawdust blend, weight reduction could be explained by the transition into aliphatic or aromatic compounds due to char decomposition and lignin volatilization.

According to the food waste kinetic study by Jo et al. [15], the key differential thermogravimetric (DTG) peaks in food waste were reached from 325 °C (10 °C/min) to 366 °C (20 °C/min) due to carbohydrate decomposition, and from 336 °C to 376 °C and from 399 °C to 446 °C due to protein and fat decomposition, and from 330 °C to 360 °C and from 200 °C to 500 °C due to cellulose and lignin decomposition. According to the DTG peaks in Figure 3 for food waste compost, there were two decomposition ranges of 250 °C to 370 °C and 500 °C to 560 °C, which were different from the results presented by Jo et al. The 250 °C to 370 °C temperature range was similar to the hemi-cellulose decomposition range (240 °C to 365 °C) described by Vamvukaa [21] and Ghorbel [5], whereas the 500 °C to 560 °C range was similar to the saturated fatty acid degradation range (480 °C to 550 °C) stated by Souza et al. [25] and the polypeptide decomposition range (500 °C or higher) described by Bihari-Varga et al. [26].

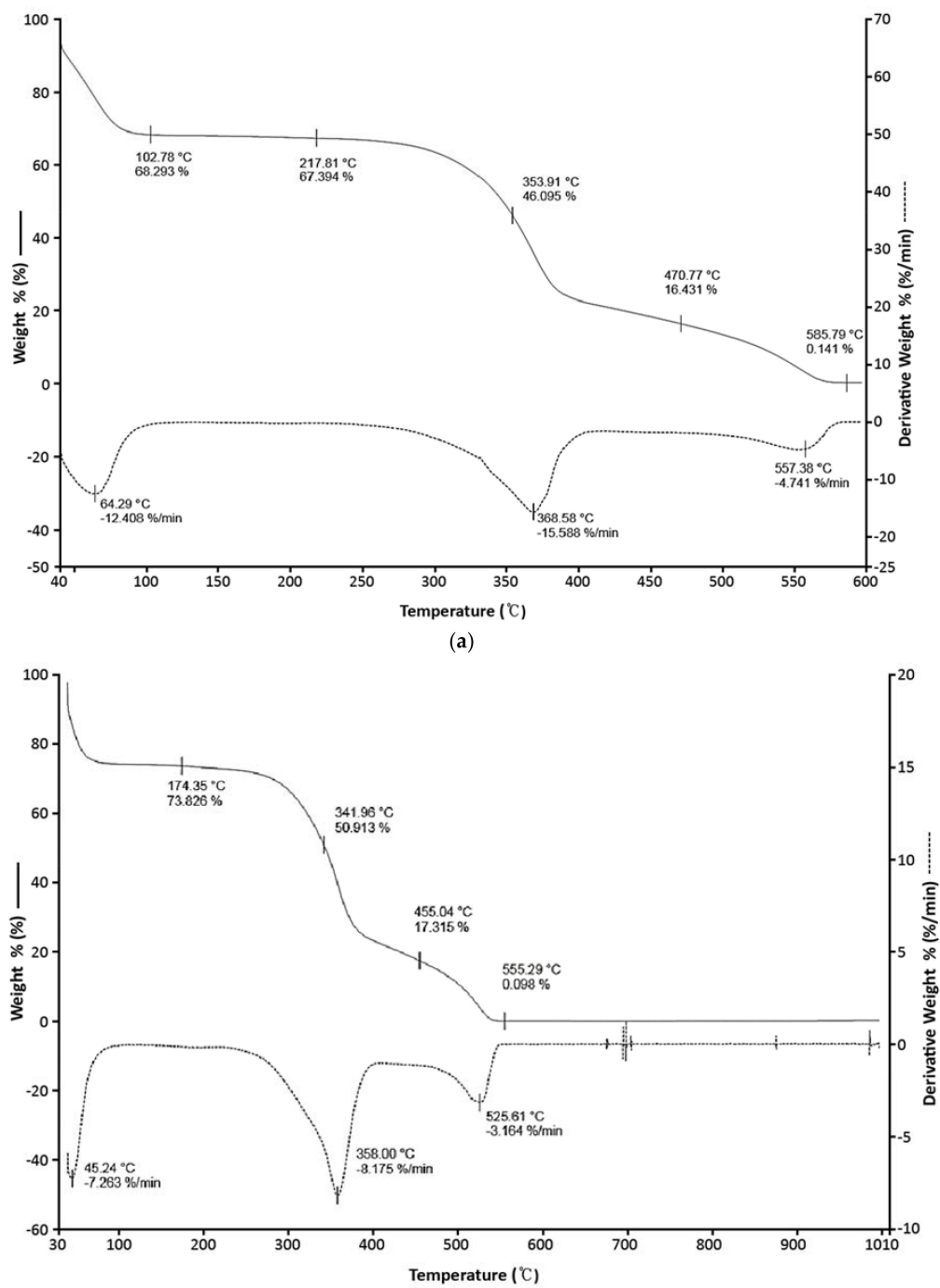


Figure 2. (a) Sawdust at 600 °C, 20 °C/min; (b) Sawdust 1000 °C, 10 °C/min.



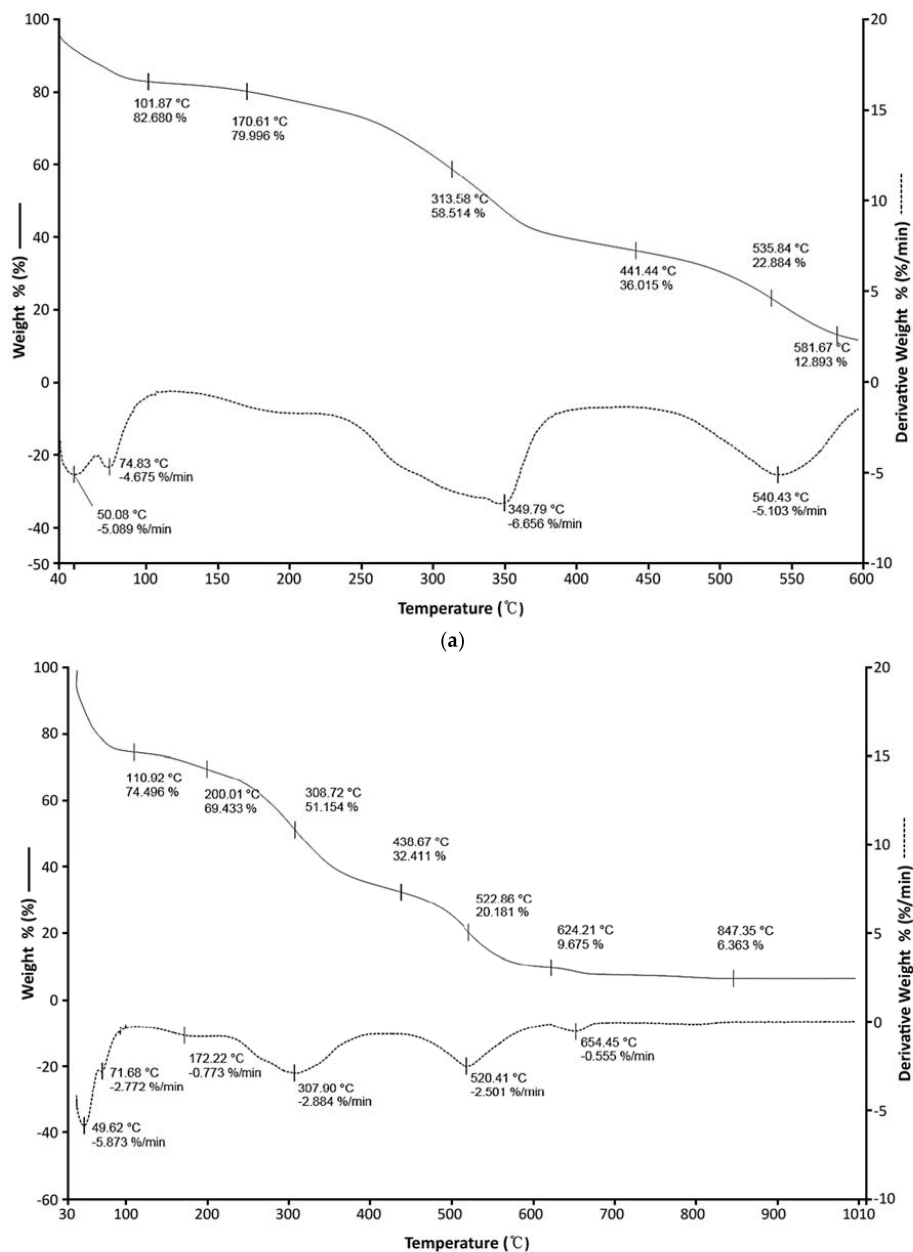


Figure 3. (a) Compost at 600 °C, 20 °C/min; (b) Compost at 1000 °C, 10 °C/min.

As mentioned earlier, these differences could be interpreted as a phenomenon that occurred as compost was degraded by microorganisms beforehand, even though the raw material properties were similar. Carbohydrates, proteins, and fat in food waste are digested by microorganisms during the composting process and are degraded into glucose, polypeptide, and fatty acids, or most of them convert into carbon dioxide or ammonia. In the end, small fractions of food waste remain in the final compost [18].

When the thermal degradation tendencies of sawdust and compost were compared, their decomposition took place in nearly the same temperature ranges. This happens when most of the food in food waste compost is degraded, and sawdust, which is not degraded, accounts for most of the compost. Their hemi-cellulose decomposition ranges of 275 °C to 360 °C and 250 °C and 370 °C were nearly identical. When their second decomposition ranges were compared, it was found that compost tended to be degraded more than sawdust. According to James [18], fat in food waste composting was degraded more slowly than protein or carbohydrate, and after 412 h

of composting, protein fractions were very low while fat fractions remained high. Hence, one can see that decomposition in compost is greater than sawdust because the decomposition of fatty acids, a byproduct of fat decomposition, and the decomposition of char, which also occurred in sawdust, took place simultaneously in the second decomposition range in food waste compost.

### 3.3. Mass Spectrometry Analysis

To analyze the gases released during the pyrolysis of sawdust and compost, this study performed a TGA-GC-MS analysis within the largest decomposition temperature range. Figure 4 show GC-MS peak results for gases released from the TGA process of compost and sawdust, and each peak is described in Tables 3 and 4. Since Si-C compounds found in sawdust and compost TGA-GC-MS results around 12~36 (min) in Figure 4 are influenced by moisture which is one of the emitted gases ( $H_2O$ ,  $CH_4$ ,  $CO_2$ , etc.) during the decomposition process into several smaller molecules [27], it was excluded from the interpretation. The Si-C compounds are not produced by the degradation of food waste compost. But the detection was inevitable since it is a GC column substance measured by the moisture generated by the food waste compost's decomposition affects the GC column.

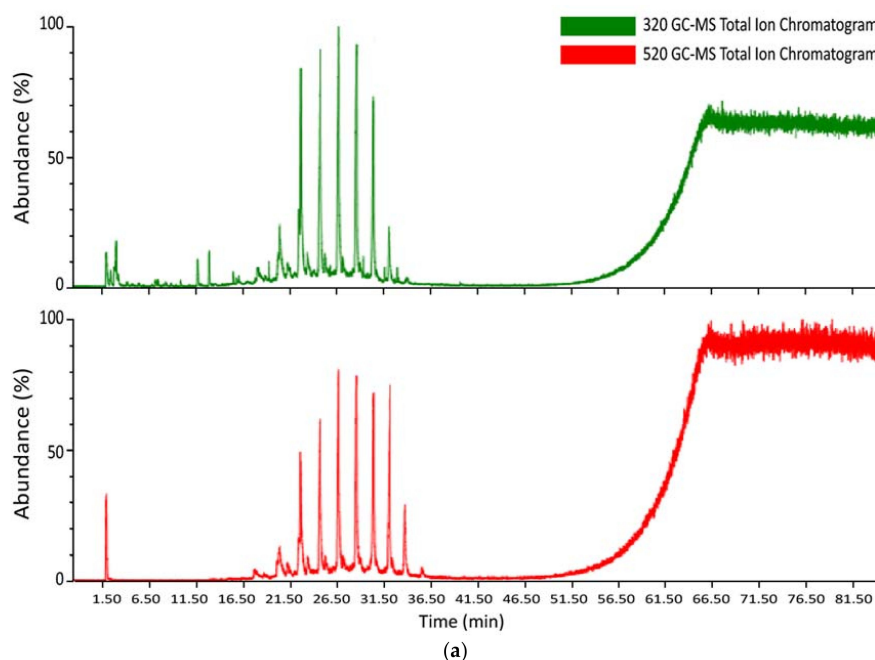


Figure 4. Cont.



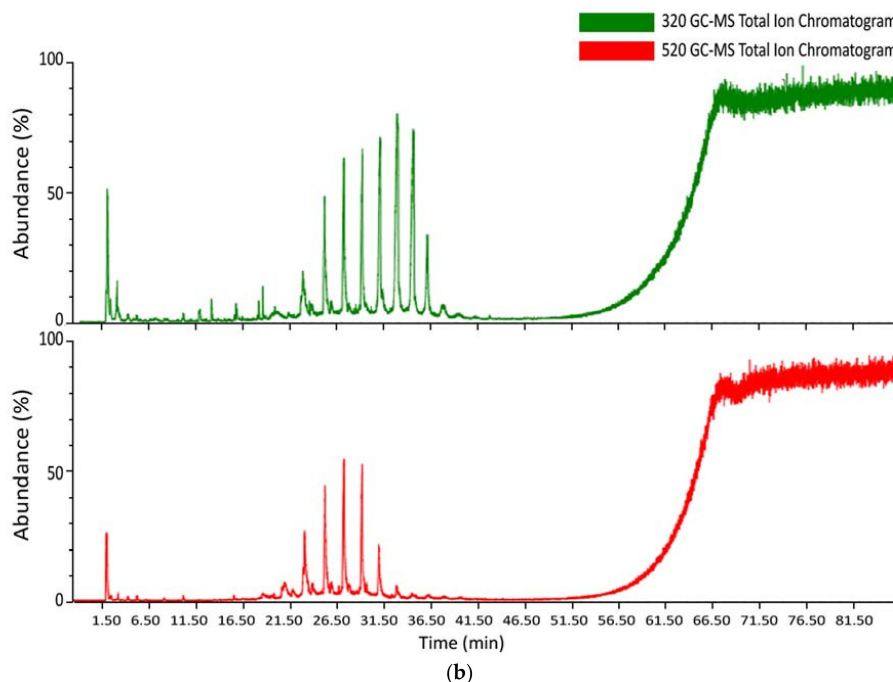


Figure 4. (a) Sawdust TGA-GC-MS results; (b) Compost TGA-GC-MS results.

Table 3. TGA-GC-MS analysis results for sawdust.

Temperature	Time (min)	MW	Compound Name	Formula
320 °C	1.973	130	thiocyanic acid, methylene ester	$C_3H_2N_2S_2$
	2.279	122	Butanoic acid, 4-chloro	$C_4H_7O_2Cl$
	6.617	96	furfural	$C_5H_4O_2$
	7.21	98	furanmethanol	$C_5H_6O_2$
	8.503	84	2(5H)-furanone	$C_4H_4O_2$

Table 4. TGA-GC-MS analysis results for compost.

Temperature	Time (min)	MW	Compound Name	Formula
320 °C	1.962	285	fumaric Acid 2-dimethylaminoethyl-heptyl ester (N-contain)	$C_{15}H_{27}O_4N$
	2.296	88	Thiophene, Tetrahydro	$C_4H_8S$
	6.634	96	1H-pyrazole, 3,4-dimethyl(C)	$C_5H_8N_2$
	7.213	88	methylene cyclo propane carboxylic acid	$C_5H_6O_2$
	8.497	84	2(5H)-furanone(C,P)	$C_4H_4O_2$
	9.694	106	Benzaldehyde	$C_7H_6O$
	9.892	157	Glycine, N-Cyclopropylcarbonyl-methyl ester	$C_7H_{11}O_3N$
520 °C	2.356	202	1,3-propanediol, 2-methyl-dipropionate(Fatty acids, aliphatic compounds)	$C_{10}H_{18}O_4$
	2.866	78	Benzene	$C_6H_6$
	3.334	258	oxalic acid butyl 2-Ethylhexyl ester(Fatty acids, aliphatic compounds)	$C_{14}H_{26}O_4$
	5.764	214	pentanoic acid 2-Ethylhexyl ester	$C_{13}H_{26}O_2$
	8.384	214	propanoic acid, 2,2-Dimethyl-,2-Ethylhexyl ester	$C_{13}H_{26}O_2$

Based on the TGA results, the TGA-GC-MS analysis was conducted at the biggest weight reduction range around 320 °C and around 520 °C. Sawdust analysis result in Table 3 shows most of the substances are emitted is furan groups. Furans organics were produced by hemi-cellulose decomposition [23,27]. Compared with TGA-GC-MS analysis result and sawdust TGA result at a 320 °C, detecting of furan groups at 320 °C is reasonable because a large weight loss at 320 °C is caused by the decomposition of hemi-cellulose. On the other hand, sawdust GC-MS results at 520 °C show that only Si-C compounds are detected. As in the TGA results, most weight loss is done at around 320 °C, so the amount of emission gases at around 520 °C appears to be small. Si-C compounds detected in this section indicates that the substances slight decomposition occurs, and moisture from

the light gas ( $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ , etc.) produced during the decomposition process seems to have affected the GC-MS results.

Food waste compost analysis result at 320 °C shows that furan groups are detected as in sawdust. This indicates that the sawdust contained in the compost is broken down and discharged. Fatty acids, which are generated from thermo-chemolysis of fat during the composting process, are detected in the form of methyl esters in pyrolysis gases, and include propanoic acids and 2,2-dimethyl-2-ethylhexyl esters. In addition, C12–C19 polymeric carbon compounds are also found as products of fatty acid degradation [28]. In particular, while C12–C19 carbon compounds could have simply come from fat fractions in food waste, they also could have originated from degradation by microorganisms. As compost includes many microorganisms in the final product, both of those possibilities are considered.

Smidt, Ena, et al. [29] detected  $m/z$  202, 258 compounds as the decomposition products of fatty acids, or aliphatic compounds. Oxalic acid butyl 2-ethylhexyl esters, 1,3-propanediol, and 2-methyl-dipropanoate were detected in the TGA-GC-MS results. This confirmed that the second decomposition of food waste compost yielded fatty acids and aliphatic compounds, as mentioned in the TGA-DTG results. Nitrogen compounds, which are released by protein decomposition, were detected in the form of glycine and fumaric acid 2-dimethylaminoethyl-heptyl esters. Proteins in food waste, however, were not present with a high content in compost, and it seems that proteins were absorbed as elements essential for bacteria and microorganisms. In other words, they had been discharged by microorganism decomposition. In addition, low molecular weight compounds, such as benzene and benzaldehyde, are produced by microorganism pyrolysis [30], but they are also generated by lignin and hemi-cellulose decomposition. Therefore, it is difficult to track their exact origin.

### 3.4. Biochar Production

Table 5 shows biochar mass yield results. They were calculated by dividing the weight of the residue after pyrolysis by that of the input at each temperature.

**Table 5.** Food waste compost biochar yield.

Temperature (°C)	Before Pyrolysis (g)	After Pyrolysis (g)	Yield (%)
300	200.52 ± 0.38	88.52 ± 2.07	44.14 ± 0.95
400	200.32 ± 0.16	60.57 ± 0.04	30.24 ± 0.05
500	200.31 ± 0.12	45.09 ± 3.20	22.51 ± 1.61

As the pyrolysis temperature increased, the yield decreased by 14% from 300 °C to 400 °C, which was higher than the 8% decrease observed between 400 °C to 500 °C. The weight reduction was greatest from 300 °C to 400 °C as demonstrated in TGA results in Section 3.2.

Figure 5 compares the calorific values of food waste compost biochar, pre-pyrolysis raw material compost, and the food waste calorific values of Lee et al. [12] and Jo et al. [15]. Food waste compost showed 17.85 kJ/g, a lower calorific value than raw food waste 19.46 kJ/g, because the organic matter in food waste was degraded. As a result, the substances that increase the calorific value (e.g., carbon) was relatively lower. After pyrolysis, food waste compost has increased in the calorific value compared with raw food waste compost as the pyrolysis temperature changes from 300 °C to 500 °C. Considering a large amount of organic matter was degraded by microorganisms, the calorific value did not show a large decrease; sawdust played a supporting role. In fact, Chen and Leung [31] showed that sawdust had a calorific value of 18.064 kJ/g.

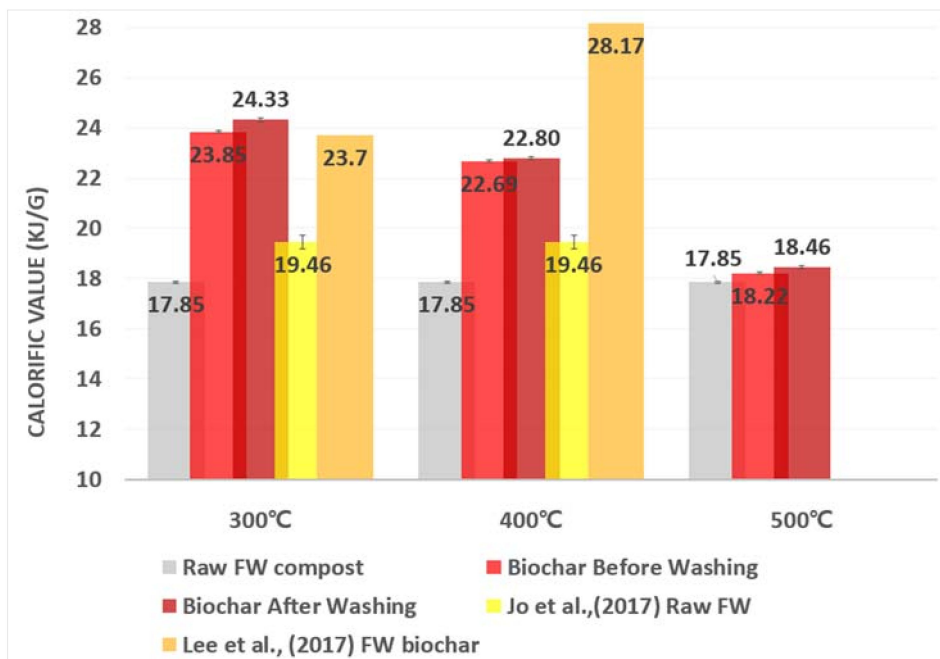
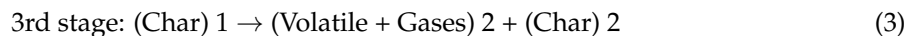
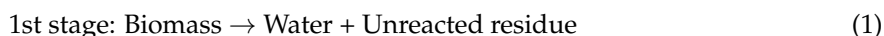


Figure 5. Calorific values of food waste compost biochar and raw material.

The calorific value of biochar, which was produced after pyrolysis of food waste compost, tended to decrease from 24.33 kJ/g to 18.46 kJ/g as the pyrolysis temperature increased. This tendency was also found in Ghorbel's study [5], in which the calorific value fell from 25.3 kJ/g to 22.8 kJ/g when the pyrolysis temperature increased from 250 °C to 350 °C and pyrolysis was performed for 2 h. By contrast, Lee et al. [12], who performed pyrolysis of food waste, found that the calorific value increased from 23.7 kJ/g to 28.17 kJ/g when the pyrolysis temperature rose from 200 °C to 400 °C. This occurs because Lee et al. [12] used food waste as a raw material, while this study used food waste compost. When raw food waste is used for pyrolysis, the carbon content increases as volatile substances and containing moistures are removed by supplied energy, and key components are carbonized [32]. Demirbas [33] interpreted the char generation process from biomass through pyrolysis with the following scheme:



In other words, while the raw food waste requires much energy for the 1st, 2nd, and 3rd stages, food waste compost has a lower moisture content and has already been degraded fracture by microorganisms. Therefore, the reaction at the 1st and 2nd stage can take place with lower energy. At 300 °C, Char 1 is produced and increases the calorific value. Since the compost has low volatile matter and water content, 300 °C is enough to conduct 1st and 2nd stage. But when the pyrolysis temperature increases, volatilization occurs in Char 1 and decreases the carbon content, the yield, and the calorific value.

In addition, in food waste compost, sawdust plays an important role in producing a calorific value. This is in contrast to raw food waste. As described in the TGA results, hemi-cellulose, a major component in sawdust, is degraded rapidly from 300 °C to 400 °C, and lignin and other components continue to be degraded at 400 °C or higher. Therefore, food waste compost shows a lower calorific value when the pyrolysis temperature increases from 300 °C to 500 °C.

Consequently, food waste compost already degraded by microorganisms has carbon fixation at a low pyrolysis temperature and produces a high calorific value. Sawdust, which plays an important role in producing the calorific value, shows little volatilization, and it shows a higher calorific value than food waste at 300 °C pyrolysis temperature.

#### 4. Conclusions

This study intended to examine the value of biochar produced from pyrolysis of food waste compost as an energy storing fuel. Food waste compost had a lower carbon and higher ash content than food waste because the organic matter was degraded. This decreased the carbon content during the composting process, while the ash content increased relatively. Biochar from pyrolysis of food waste compost had a high carbon content of 51% at 300 °C, and the carbon content decreased as the pyrolysis temperature increased. According to the TGA-DTG analysis results, compost showed the largest weight reduction from 240 °C to 365 °C. The weight reduction temperature ranges for compost and sawdust were quite similar. This occurred because organic matter in food waste was degraded, and sawdust, which showed relatively lower degradation, remained during the composting process. A GC-MS analysis on gases released in these ranges found that the gases were fragments of fatty acids, protein, carbohydrate, and hemi-cellulose. These results could also have been caused by degradation of microorganisms and sawdust involved in the composting process or small fragments of food waste. This study measured the calorific value of biochar and found that biochar showed the highest calorific value of 24.33 kJ/g at 300 °C in proportion to the carbon content. At a low pyrolysis temperature, carbon fixation occurred easily since the food waste in compost was degraded by microorganisms, and the volatilization of sawdust, which plays an important role in determining the calorific value, was also small. That is why it showed a higher calorific value than food waste at 300 °C. Hence, it seems that food waste compost can be used as a promising alternative fuel compared with other refuse-derived fuels (RDF) since food waste compost is able to convert into a fuel that shows similar calorific values to other fuels with a smaller energy supply.

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