Research Article

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Three combined pretreatments for reactive gasification feedstock from wet coffee grounds waste

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Abstract: In this study, a new pretreatment for using wet food biomass waste as a high calorific and reactive feedstock for gasification is presented. The method involves the addition of calcium hydroxide, hot water treatment, and dewatering in vegetable oil. Hot water treatment at 230°C reduced the oxygen/carbon atomic ratio of coffee grounds waste to improve the calorific value, but this treatment also formed an inactive cross-linked structure caused by dehydration reactions. By mixing the coffee grounds waste with calcium hydroxide powder before the hot water treatment, cross-linking was suppressed and the gasification rate of the char significantly increased because of the catalytic effect. With or without hot water treatment, the time required to complete gasification for the chars of the grounds mixed with calcium hydroxide was reduced to about one-third of that for the char of the untreated grounds. After heating in vegetable oil at 150°C, moisture was completely removed from the coffee grounds and they became impregnated with a large amount of the oil. As dewatering in oil did not affect the gasification rate of the chars, a combination of these three treatments was found to efficiently convert wet food biomass waste into a gasification feedstock.

Keywords: wet biomass waste, gasification, calcium hydroxide, hydrothermal treatment, dewatering in oil

1 Introduction

Excess wet biomass, especially food waste, is a serious environmental problem all over the world. Food waste contains carbohydrates, protein, fat, and fiber and is generally used as a fertilizer or feed for domestic animals. However, there are alternative supplies of fertilizer and feed, which are inexpensive and easier to handle. Although food waste is continuously discharged from food processing plants and the foodservice industry, it is difficult to preserve because of the high water and protein content. In addition, food waste is expensive and energy-intensive to gather or transport. Therefore, drying food waste is an attractive method to reduce the weight and avoid decay, but the conventional methods are less than ideal. Air-drying food waste can generate an unpleasant smell and can cause spontaneous ignition because of the heat produced by oxidation or fermentation. Superheated steam drying results in less oxidation of the food waste [1,2] but requires an enormous amount of energy to generate the steam. In this study, we present an oil dewatering method where the moisture is replaced by oil. A dewatering method for Australian brown coal using solvents was reported by Miura et al. [3]. While Miura's method was carried out under high pressure, the dewatering presented in this study was carried out at atmospheric pressure. The vegetable oil absorbed by the food waste can be used directly as a high-calorie gasification feedstock. As heat is transferred between the food and the oil in a slurry, the energy efficiency of the oil dewatering method is high.

Conventional thermochemical conversion processes, including combustion, gasification, and flash pyrolysis, are unsuitable for wet biomass because of the heat of evaporation of moisture. To overcome this problem, gasification in supercritical water has been proposed and actively investigated [4–8]. However, supercritical water treatment under severe conditions requires a high capital cost and leads to difficult operability. Furthermore, if

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complete gasification under the supercritical conditions is not achieved with the addition of supplemental water, the ammonia and nitrogen-containing organic effluent from the food waste is also discharged [9,10]. Therefore, the two objectives of this study were to perform the hot water treatment and oil dewatering under more moderate conditions and to carry out the conventional gasification at the lowest possible temperature. If wet biomass is converted into a high calorific and reactive feedstock that exhibits a catalytic effect during gasification, it can be used as an energy resource or raw material for syngas. From this viewpoint, the wet biomass was treated without supplemental water by adding a calcium compound as a catalyst precursor and the hot water treatment used the moisture, which the food waste had retained. Calcium compounds are known to act as a gasification catalyst [11], and Leppalahti *et al.* [12] reported that limestone reduces hydrogen cyanide in the gasification gas. Calcium oxide can assist in capturing CO₂ during chemical looping gasification [13]. In chemical looping gasification, solid or liquid metal oxides [14] are used as oxygen carriers. As the hot water treatment promotes the dehydration reaction of the hydroxyl groups in cellulose [15], the oxygen/carbon atomic ratio of biomass would be reduced through this treatment, resulting in an improvement of the calorific value. Furthermore, it has been reported that a hydrothermal or oil treatment can lead to the suppression of self-ignition for coal [16,17]. In this article, the validity of these three methods was examined (Ca-loading, hot water treatment, and oil dewatering) as pretreatments for gasification feedstock.

2 Materials and methods

2.1 Materials

Wet coffee grounds were used as raw materials. The coffee grounds contained 63.4 wt% of water when received from a beverage company in Japan. This inherent water retained by the coffee grounds was used for the hot water treatment and for combining with calcium hydroxide to ensure that Ca-loading was evenly dispersed. The coffee grounds were ground into particles less than 500 µm before use. A commercial microcrystalline cellulose (Nakalai Tesque Inc.), organosolv-lignin (Sigma-Aldrich Co.), and xylan (Sigma-Aldrich Co.) were used to study the individual components of biomass. For the oil used in dewatering, any oil that is immiscible with water can be used. In this work,

rapeseed oil (Nakalai Tesque Inc.) was used. The analyses of these samples are listed in Table 1.

2.2 Addition of calcium compounds

A saturated aqueous solution of calcium hydroxide (Wako Pure Chemical Industries, Ltd.) or calcium acetate (Wako Pure Chemical Industries, Ltd.) was used as the catalyst precursor. The coffee grounds were soaked in the Ca solution using the impregnation method. These Ca-impregnated coffee grounds were used to compare their gasification rates. A mixture of 2.73 g of wet coffee grounds directly added to 0.28 g of calcium hydroxide powder was also prepared.

2.3 Hot water treatment and dewatering in oil

The hot water treatment of the coffee grounds was performed in a small stainless steel reactor (10 mL in volume) that was filled with 4 g of the wet grounds and either an extra 4 mL of distilled water or no extra water. No extra water was added in the hot water treatment to the wet coffee grounds mixed with calcium hydroxide powder. After purging with nitrogen gas, the reactor was immersed in a sand bath and heated to a temperature between 25°C and 230°C, where the reaction pressure rapidly increased up to the saturated vapor pressure. After 30 min, the reactor was dipped into a sufficient amount of water to immediately cool the vessel and terminate the reaction. The water-soluble products were recovered as filtrates and analyzed using a total organic carbon (TOC) analyzer and a liquid chromatograph (LC). The calcium-loaded coffee grounds were not filtered after the hot water treatment to avoid leaching of calcium. The

Table 1: Ultimate analyses and ash contents of samples used

Sample	Ultimate analyses (wt%, d.a.f.)				
	C	H	O + S (diff.)	N	Ash (wt%, d.b.)
Cellulose	44.4	6.2	49.4	N.D.	0.0
Lignin	62.2	5.7	32.1	N.D.	3.4
Xylan	42.7	5.8	51.5	N.D.	3.9
Coffee grounds	55.1	7.2	35.4	2.3	2.6
Rapeseed oil	79.9	11.7	8.4	N.D.	0.0

gaseous products were collected using a gasbag and analyzed with a gas chromatograph.

The dewatering in oil was conducted on the wet coffee grounds as follows. The biomass sample was mixed with rapeseed oil in the ratio of 1 to 10 by weight in a hard glass tube reactor. It was then heated to a temperature between 25°C and 230°C at atmospheric pressure by immersing the reactor in a temperature-regulated oil bath. Through this treatment, the coffee grounds became swollen with some oil and the moisture was removed from the samples to a certain degree. Separation of the grounds from the oil adhered to its exterior was conducted by filtration. As combined pretreatments, the dewatering at 150°C was also performed on the coffee grounds mixed with $\text{Ca}(\text{OH})_2$ followed by the hot water treatment at 230°C.

2.4 Gasification

The reactivities of the as-received and the treated coffee grounds were isothermally measured using a thermogravimetric analyzer (Shimadzu Co., TGA-50). Approximately 2 mg of the coffee grounds was mounted on a platinum cell and heated at a rate of 20 K min^{-1} up to 900°C under a flow of pure nitrogen gas and maintained at 900°C for 30 min. Then, the nitrogen gas was replaced by CO_2 gas at a constant temperature (600–900°C) to gasify the char with CO_2 . The char conversion is expressed as a weight percent on a dry, ash-free basis.

2.5 Analyses

Ultimate analyses of the samples were performed using an elemental analyzer (BEL Japan, Inc., ECS4010). Any solid chemical structures, such as functional groups, were analyzed using an FTIR spectrometer (JEOL. Ltd., JIR-SPX60). The TOC and the concentration of saccharides in the aqueous solution were estimated using a TOC analyzer (Shimadzu Co., TOC-VCHS) and an LC (Shimadzu Co.), respectively. For the LC analysis, an aqueous mixture containing 70% acetonitrile was used as the mobile phase and was fed at 1 mL min^{-1} to the LC equipped with a column (TOSOH Co., TSKgel Amide-80) and a refractive index detector. The crystallinity of the cellulose and the form of the calcium compounds were determined using X-ray diffractometry (Shimadzu Co., XD-610, $\text{Cu-K}\alpha$, $\lambda = 1.54 \text{ \AA}$) at 30 kV and 30 mA. The water

content was measured with a Karl–Fisher moisture titrator (Kyoto Electronics Manufacturing Co., Ltd., MKS-510N). The analytical results, except for thermogravimetric analysis and X-ray diffraction, for the obtained samples are expressed as the average of the three times.

3 Results and discussion

3.1 Changes in the coffee grounds' properties through hot water treatment

Carbonization is one method to convert low-grade biomass into a calorific solid fuel, but the yield of char is usually very low. Therefore, the effects of the hot water treatment on the elemental composition of the coffee grounds were examined to improve their calorific value. Figure 1 shows the changes in the oxygen/carbon (O/C) atomic ratio of the coffee grounds after the hot water treatment without extra water. The O/C atomic ratio decreased with an increase in the temperature of the hot water treatment. The O/C ratio reached the minimum value of 0.26 at 230°C. Considering that the coffee grounds were not carbonized to a significant extent under a nitrogen atmosphere at 230°C, the water retained by the coffee grounds must have played a role in the decomposition of the functional groups containing oxygen. Given that the higher heating value of the grounds treated at 230°C corresponds to 29.1 MJ/dry-kg, calculated using the Dulong's formula, the hot water treatment is effective at raising the calorific value of low-grade food waste (22.6 MJ/dry-kg) using hygroscopic moisture. Therefore,

Figure 1: Changes in the O/C atomic ratio of the coffee grounds after the hot water treatment or dewatering.

the treated coffee grounds could be successfully used in combustion if they were sufficiently dewatered. In addition, the gasification of biomass is a promising method to produce syngas because of its high reactivity at low temperatures. From this viewpoint, the effects of the hot water treatment on the gasification reactivity of the coffee grounds' char were examined. Figure 2 shows the CO₂ gasification profiles at 900°C for the untreated and treated coffee grounds' chars. The gasification reactivity dramatically decreased with an increase in the temperature of the hot water treatment. It was also observed that the gasification reaction went to completion only after 8,800 s in the case of coffee grounds treated at 230°C, which was 20 times longer than for untreated coffee grounds. From this result, it was determined that the coffee grounds treated in hot water were unsuitable for gasification, likely because they were deactivated.

Next, the rationale for the deactivation of the coffee grounds through the hot water treatment was investigated. Feng *et al.* [18] reported that the activation energy was reduced in the gasification of sewage sludge char after a hydrothermal treatment. Figure 3 compares the carbon distributions of the various hot water treatment conditions with and without the addition of extra water. The gaseous products mainly consisted of CO₂ gas. With an increase in the hot water temperature, the yield of the treated solid residue decreased. In contrast, the yield of water-soluble organic compounds showed almost no change at temperatures above 180°C. This indicates that the coffee grounds contained a fixed quantity of a material that dissolves in hot water. At 230°C, a portion of these water-soluble compounds appear to have been decomposed into CO₂ gas. Hot water treatment at 230°C

Figure 2: CO₂ gasification profiles at 900°C for the untreated and treated coffee grounds' chars.

Figure 3: Carbon distributions under the several conditions of the hot water treatment with/without extra water addition.

resulted in a higher conversion to gas than that of woody biomass in our previous study [19]. This is thought to be because of the decomposition of water-soluble organic compounds containing functional groups produced by oxidation during the roasting of coffee beans. In our previous study, it was determined that the hemicellulose fraction in biomass could be recovered as saccharides through a hot water treatment. The coffee grounds contain hemicellulose, cellulose, lignin, proteins, and other extracts, such as caffeine. The yields of the saccharide, one of the water-soluble compounds, at each condition were found to be 2.9 kg/100 kg-dry coffee grounds at 230°C, 3.1 kg/100 kg at 230°C with extra water, 2.7 kg/100 kg at 180°C, 3.0 kg/100 kg at 180°C with extra water, and 0.07 kg/100 kg at 25°C with extra water. With the addition of extra water, the yields of the saccharide increased slightly. It is likely that the hydrolysis of hemicellulose was promoted in the presence of a large amount of water because of autohydrolysis by the organic acid products. Therefore, it may be possible to control the hydrolysis product distribution by regulating the amount of moisture or extra added water. From the perspectives of saving energy and reducing the wastewater discharged from the treatment, no extra water was added in the later hot water treatments. Given that Minowa *et al.* [20] reported that cellulose is also hydrolyzed at temperatures above 250°C, the hot water treatment at 230°C is a method to produce solid residue in good yields under mild conditions.

The hemicellulose in the coffee grounds was hydrolyzed into a certain amount of saccharide through the hot water treatment mentioned above. One reason that the treated coffee grounds were deactivated and unsuitable for gasification is that hemicellulose was released from

the biomass, leaving behind lignin or other humid compounds that are difficult to decompose. Other structural changes in the solid residue were also investigated. Figure 4 shows the FTIR spectra of the untreated coffee grounds and those treated with hot water. The spectrum of the coffee grounds treated at 230°C was strikingly different from the untreated coffee grounds. The hot water treatment at 230°C caused a decrease in the amount of hydroxyl groups (assigned at 2,400–3,700 cm^{-1}). While the hydroxyl groups decreased, the intensity of the peaks corresponding to carbonyl groups (assigned at 1,630–1,780 cm^{-1}) increased, indicating that the hot water treatment formed a cross-linked structure from the dehydration reaction of the functional groups. This cross-linked structure would lead to deactivation in the gasification reaction for the treated coffee grounds' char. Therefore, the utilization of hydrothermally treated coffee grounds as a feedstock for gasification requires a suppression of the formation of cross-links. A hot water treatment where the coffee grounds can be upgraded without deactivation is described in Section 3.3.

3.2 Dewatering in oil

In cases where a waste or virgin wet biomass feedstock is thermally processed for energy recovery, it may be necessary to partially dry or dewater the raw feed before the subsequent conversion. Solar drying in open air is a low-cost method for moisture reduction, but most food waste or biomass with high-water content will decompose or decay under these conditions. A spontaneous ignition is even possible because of the self-heating of oxidation.

Figure 4: FTIR spectra of the coffee grounds treated in hot water and of the untreated ones.

When wet biomass is dewatered in oil, the moisture is replaced with the oil. The success of this method relies on the affinity of the biomass for oil and water. Thus, in this section, the dewatering was performed using vegetable oil and any swelling of the biomass with oil was examined. If waste oil is used, the final biomass and oil mixture would be an excellent fuel for combustion because of its high-calorific value. First, to study each component of the biomass, including hemicellulose, cellulose, and lignin, they were impregnated with oil at room temperature and the oil uptake was measured. Figure 5 shows the amount of oil uptake for the single-component samples and for cellulose treated in hot water at 250°C. Lignin and the hydrothermally treated cellulose were swollen with a large amount of the oil, ca. 60 wt%. In contrast, the measured oil content of both xylan (representative of hemicellulose) and cellulose was smaller than 20 wt%. There are two possible explanations for these observations. The first is attributed to the surface properties of biomass. Biomass is classified as a hydrophilic material because it contains a large quantity of functional groups, such as hydroxyl groups. Looking at each component of biomass, polysaccharides, such as hemicellulose and cellulose, are richer in functional groups compared to lignin. As described in Section 3.1, when pure cellulose undergoes a hot water treatment, the O/C atomic ratio value drops from 0.8 to 0.4, where the latter value matches lignin's O/C ratio. In other words, the more hydrophobic surfaces the biomass contains, the more oil it can absorb. The second explanation for the high oil absorption by the hydrothermally treated cellulose is the collapse of the crystalline structure of cellulose through the hot water treatment. The crystallinity of the cellulose decreased with higher temperatures of the hot

Figure 5: Oil uptakes for the pure biomass components and the cellulose treated in hot water.

water treatment, as shown in Figure 6. By relaxing the firm crystalline structure, which previously prevented the oil from penetrating into the hydrogen bonding formed by the hydroxyl groups, the biomass can become highly swollen with oil. Therefore, a modification of the chemical or physical structure of the biomass feedstock was found to be an effective method to adjust the oil uptake.

Next, for the dewatering of wet biomass, the effect of the water content on the amount of oil uptake was examined. The change in the oil uptake of wet coffee grounds as a function of oil temperature during dewatering is shown in Figure 7. Figure 7 also shows the changes in the water content of the wet coffee grounds as a function of the oil temperature. With an increase in the oil temperature, the oil uptake for the coffee grounds increased and the water content decreased. In other words, for wet biomass, the oil was absorbed simultaneously with the rapid removal of water from the pores at temperatures greater than 100°C. This phenomenon is likely because of the suction pressure caused by the evaporation of moisture. By taking advantage of this effect, the wet biomass was almost completely dewatered at 150°C and was impregnated with the same weight of oil as coffee grounds. As shown in Figure 1, the O/C atomic ratio of the coffee grounds dewatered at 150°C was the same as untreated grounds. Unlike in the hot water treatment, the elemental composition of the coffee grounds did not change after oil dewatering. This is likely because the coffee beans were already parched at around 200°C and the coffee grounds did not chemically react in the oil.

To summarize the above discussion, the oil cannot penetrate into the hydrophilic pores of wet biomass at room temperature. If the structures of the functional

Figure 6: Changes in the crystallinity of cellulose through the hot water treatment.

Figure 7: Changes in the oil uptake and water content for wet coffee grounds with the oil temperature.

groups are altered from strong to weak hydrogen bonding, the oil can more easily penetrate into the pores. When heated to 100°C and above, the water adsorbed on the surface evaporates. In addition, the oil fills the gaps that were previously occupied by the evaporated water, replacing the water as the adsorbate. As the oil penetrates between the functional groups, an inhibition of spontaneous ignition and a water-repellent effect are predicted, in addition to an improvement in the calorific value.

3.3 Addition of catalyst precursor for gasification

Wet food biomass waste was treated with hot water to reduce the O/C atomic ratio and was dewatered in vegetable oil as mentioned above. Furthermore, the hydrothermally treated coffee grounds were significantly deactivated against gasification. In an attempt to make the coffee grounds more active for gasification, calcium compounds, which are a known gasification catalyst [21–23], were added to the coffee grounds. First, the type of calcium species for use as the catalyst was chosen. The coffee grounds were impregnated with a saturated aqueous solution of either $\text{Ca}(\text{OH})_2$ or $\text{Ca}(\text{CH}_3\text{COO})_2$. The solubility of $\text{Ca}(\text{CH}_3\text{COO})_2$ in water (34.7 g/100 g of water at 20°C) is much higher than that of $\text{Ca}(\text{OH})_2$ (0.16 g/100 g of water at 25°C). Consequently, this difference in solubility results in a disparity in the quantity of Ca loading in the coffee grounds. To avoid this problem, the wet coffee grounds were also directly mixed with $\text{Ca}(\text{OH})_2$ powder so that the amount of Ca-loading was the same as that prepared from the saturated $\text{Ca}(\text{CH}_3\text{COO})_2$ solution.

Figure 8: CO₂ gasification profiles at 900°C for some kinds of Ca-loaded grounds' chars.

Figure 8 shows the CO₂ gasification profiles at 900°C for the Ca-loaded coffee grounds' char. The coffee grounds soaked with the saturated Ca(OH)₂ solution showed almost the same reactivity as untreated coffee grounds. This result is likely because of the negligibly small amount of Ca loading. In contrast, the coffee grounds soaked with the saturated Ca(CH₃COO)₂ solution and the grounds directly mixed with Ca(OH)₂ powder demonstrated a significant catalytic effect. From these results, it was determined that the gasification reactivity of the coffee grounds depends strongly on the amount of Ca loading in the coffee grounds. It was reported that bituminous coal physically mixed with CaO did not show much catalytic effect in gasification [24]. The authors concluded that it was because of the lack of carboxyl groups. Ohtsuka and Asami [21] reported that Ca(OH)₂ at a loading of 5 wt% Ca promotes the steam gasification of

coals. In the present study, the coffee grounds directly mixed with Ca(OH)₂ powder demonstrated a high reactivity by the similar physical blending. This may be because the coffee grounds contain a large quantity of functional groups and water. The greatest catalytic effect of the coffee grounds soaked in saturated Ca(CH₃COO)₂ was determined to be because of the dispersion and the amount of catalyst. Figure 9 shows the X-ray diffraction patterns of the chars of the Ca-loaded coffee grounds made from soaking in a Ca(CH₃COO)₂ solution and from mixing with dry Ca(OH)₂ powder. The Ca-loaded chars, both from Ca(CH₃COO)₂ solution and from Ca(OH)₂ powder, gave the same XRD pattern as pure CaO. This result suggests that the precursors of the catalyst, Ca(CH₃COO)₂ and Ca(OH)₂, were decomposed into CaO during the pyrolysis of the coffee grounds, and therefore, it is CaO that resulted in catalysis of the char gasification. Based on this study, direct mixing with Ca(OH)₂ powder was chosen as an economical and simple method of adding a Ca precursor to coffee ground waste.

Finally, the above three treatments were combined. The coffee grounds mixed with Ca(OH)₂ followed by the hot water treatment were investigated. Figure 10 shows the O/C atomic ratio of the coffee grounds after the treatment combination. Table 2 shows the elemental compositions of those. The coffee grounds with Ca(OH)₂ added followed by the hot water treatment did not demonstrate a significant reduction in the O/C ratio in comparison to those treated using hot water only. This result suggests that Ca(OH)₂ acts as an inhibitor against the dehydration reaction between the functional groups. The resulting suppression of the cross-linked structure was also confirmed, as shown in Figure 4. With the addition of Ca(OH)₂, the hydroxyl groups that form the stronger hydrogen bonds (assigned at 2,600–3,300 cm⁻¹) did not

Figure 9: X-ray diffraction patterns for the chars of the Ca-loaded coffee grounds and CaO.

Figure 10: Changes in the O/C atomic ratio of the coffee grounds after the combined treatments.

Table 2: Ultimate analyses of the treated coffee grounds and their char yields at 900°C

Treatments	Ultimate analyses (wt%, d.a.f.)				
	C	H	O + S (diff.)	N	900°C char yield
Hot water at 230°C	67.0	7.4	23.2	2.4	0.28
Ca-loading and HW at 230°C	59.9	6.9	30.7	2.5	0.20
Ca-loading and HW at 230°C followed by dewatering at 150°C	58.4	6.8	32.3	2.5	0.15

significantly decrease through the hot water treatment. Figure 11 compares the gasification rates of the chars of the coffee grounds treated with the various methods. As compared with the untreated coffee grounds, the coffee grounds treated only with hot water at 230°C demonstrated a considerable decline in the gasification rate. In contrast, all coffee grounds samples mixed with $\text{Ca}(\text{OH})_2$ showed a drastic increase in the gasification rate. Dewatering in oil did not affect the gasification rate of the chars. These results confirm that $\text{Ca}(\text{OH})_2$ suppressed the cross-linking in the hot water treatment and acted as a catalyst for gasification. Finally, the catalytic effect was quantitatively analyzed using reaction kinetics. From the Arrhenius plots of the gasification rates at conversions of 0.5 for the coffee grounds with and without $\text{Ca}(\text{OH})_2$, the calculated apparent activation energies were as follows: 286 kJ mol^{-1} for the untreated coffee grounds and 239 kJ mol^{-1} for the Ca-catalyzed coffee grounds. Overall, the Ca-loaded coffee grounds were certainly reactive, and an increase in the gasification rate was demonstrated using catalyzed coffee grounds as a gasification feedstock.

4 Conclusions

A new pretreatment method for efficiently using wet biomass as a high calorific and reactive feedstock for gasification was presented. The method consists of three treatments: addition of $\text{Ca}(\text{OH})_2$, hot water treatment, and dewatering in oil. The impacts of the operating conditions of these treatments on the properties of the treated biomass were examined, and the following conclusions were obtained. Hot water treatment at 230°C reduced the O/C atomic ratio of the coffee grounds to 0.26 and

Figure 11: CO_2 gasification profiles at 900°C for the Ca-loaded coffee grounds' chars after the combined treatments.

produced an inactive cross-linked structure attributed to dehydration. During the dewatering process in vegetable oil at 150°C, water was completely removed from the coffee grounds and the grounds were impregnated with a large amount of oil. By physically mixing the coffee grounds with $\text{Ca}(\text{OH})_2$ powder in advance of the hot water treatment, cross-linking was suppressed and gasification rate increased significantly because of the catalytic effect of Ca. With or without hot water treatment, the time required to complete gasification at 900°C for the chars of the coffee grounds mixed with calcium hydroxide was reduced to about one-third of that for the char of the untreated coffee grounds. In summary, the combined method described herein is an effective approach to upgrade wet biomass into a valuable feedstock for conventional thermochemical conversion processes.

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