Effect of Hydrotalcite Addition on Gasification during the Pyrolysis of Food Waste

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Manuscript received October 20, 2023; revised November 15, 2023; accepted March 3, 2024; published June 27, 2024

Abstract-Approximately 1.3 billion tons of food waste, or one-third of the food produced globally, is generated annually, which is enough to feed 2 billion people. Food waste is generated throughout the supply chain, during the procurement of raw materials for products, manufacturing, sales, and consumption. Furthermore, food waste is one of the most significant environmental problems. Although reductions in carbon dioxide emissions are being made around the world and are attributed to the use of fossil fuels, food waste involves the loss of various resources that are necessary elements in the production process and the release of greenhouse gases that contribute to climate change. In this study, synthetic hydrotalcite (Mg₁. xAlx(OH)2(CO3)x/2·mH2O) was added to simulated food waste (cooked rice), and its effect on the production of combustible gases (CH4, C2H4, C2H6, C3H6, and C3H8) during pyrolysis at 500 °C was examined. Changing the concentration of synthetic hydrotalcite affected the yield of combustible gases.

Keywords—food waste, pyrolysis, hydrotalcite, flammable gas, alkali catalyst, carbon dioxide, food problem

I. INTRODUCTION

Food loss constitutes a significant loss of resources invested in food production, transportation, and storage. Additional negative externalities of food production include ecotoxicity from pesticides, eutrophication, soil erosion, loss of organic matter, and loss of biodiversity [1]. Between 20% and 30% of a natural product's environmental impact is due to food consumption. Thus, food loss has a significant impact on the environment [2]. The 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) was held in Paris, France in November 2015, where multiple governments agreed to work toward limiting global temperature rise to less than 2 °C, including 196 countries and regions worldwide, all making Greenhouse Gas (GHG) reduction commitments for the first time. The Japanese government has set a goal of reducing GHGs by 26% by 2030, compared with 2013 levels. However, fossil fuels continue to dominate the global energy supply chain [3], accounting for over 80% of energy consumption [4]. In addition, the combustion of fossil fuels emits large amounts of GHGs and is a major cause of global warming [5]. Moreover, approximately 1.3 billion tons of food waste, or one-third of the food produced globally, is generated annually, which is equivalent to the diet of 2 billion people [6]. Food waste is generated throughout the supply chain, including the procurement of raw materials for products, manufacturing, sales, and consumption [7], for significant environmental problems accounting worldwide [8]. Considering the depletion of fossil fuels and the excessive carbon emissions, the use of renewable energy sources, such as biomass, is being promoted [9, 10].

Landfilling, incineration, composting, and methane fermentation are the most commonly used methods for disposing of food waste [11]. Landfilling and incineration have caused environmental problems such as greenhouse gas emissions and leachate [12].

Food waste involves the loss of valuable resources and the release of GHGs that contribute to climate change [13]. Additionally, it is expensive to process food waste, and approximately a quarter of the water used in the raw material production stage is wasted [14].

According to the Food and Agriculture Organization of the United Nations, food waste accounts for approximately 8% of global anthropogenic GHG emissions and approximately 38% of energy consumption in the food supply chain [15]. Furthermore, food waste accounts for 30%–40% of municipal solid waste [16] and contains mainly carbohydrates, proteins, and fats [17]. Thus, mitigating and using food waste are considered sustainable and environmentally friendly ways to add value to the supply chain. Until the Great East Japan Earthquake in 2011, Japan's power source mix was 31.1% nuclear, 63.1% thermal, 5.1% hydro, and 0.5% renewable energy. Before the earthquake, there were 54 nuclear power plants, but after the earthquake, numerous nuclear power plants were shut down, and the operating rate of thermal power plants, which generate electricity using fossil fuels, increased to compensate for the loss in nuclear power plants. One promising alternative to fossil fuels is biofuels made from biomass [18], including agricultural, municipal, and commercial wastes [19]. In this study, unavoidable food waste is considered to be an underutilized resource, and we enhanced the conversion of food waste into useful gases by employing an additive, specifically a synthetic hydrotalcite, during pyrolysis.

II. LITERATURE REVIEW

Previously, we reported that gasification can be maximized during the pyrolysis of natural organic materials by adding theolite, a type of molecular sieve [20]. Zeolite-based catalysts are considered environmentally friendly and have been used as molecular sieves under atmospheric pressure for dehydration and oil calcination [21–23]. Zeolite-catalyzed pyrolysis is also advantageous because it requires much lower costs than high-pressure hydrogenation [24].

Biomass resources are generally composed of 20%–40% hemicellulose, 40%–60% cellulose, and 10%–25% lignin [25]. Lignin is reported to gradually degrade over a wide temperature range of 280 to 600 °C, whereas hemicellulose and cellulose degrade relatively quickly at

lower temperatures of 200 to 350 °C [26]. The literature on pyrolysis and chemical recycling is extensive [27-29]. In the pyrolysis of rice husks, we reported that the addition of synthetic molecular sieves, а zeolite, enhances gasification [30]. We also reported that the addition of hydrotalcite promotes the pyrolysis of forest residue and increases the yield of oil [31]. Heating organic matter in the absence of oxygen transforms it into char, gas, and liquid compounds, and the products and yield depend on the temperature and heating rate. Higher temperatures generally decrease the yield of liquid compounds and increase gas production, whereas lower temperatures decrease gas yields [32]. The goal of biomass gasification is to maximize gaseous products. In this study, synthetic hydrotalcite is added to simulated food waste and pyrolyzed to maximize gaseous products. Hydrotalcite is classified as a layered double hydroxide composed of metal complex hydroxides. Specifically, the host layers contain divalent Mg2+ and trivalent Al³⁺, and the interlayers contain anion species (Figs. 1 and 2).



Fig. 1. Schematic diagram of magnesium hydroxide.



Fig. 2. Schematic diagram of hydrotalcite.

The hydrotalcite used in this study has the same basic structure as magnesium hydroxide, $Mg(OH)_2$, but readily reacts with acids and performs ion exchange at a pH of 3.5 to 5. In addition, this hydrotalcite is mainly used as a heat stabilizer in Polyvinyl Chloride (PVC) films for agricultural insulation, as an acid acceptor in rubbers and plastics, and as a raw material for gastrointestinal drugs in pharmaceutical applications.

Hydrotalcite has gained significant attention in recent years as a catalyst, gas removal material, and ion exchanger, and by controlling the molar ratio of Mg^{2+} and Al^{3+} of hydrotalcite, it can be used as an efficient catalyst [33].

In this study, we used synthetic hydrotalcite as an additive in the pyrolysis of simulated food waste and determined its effect on the production of flammable gas.

III. MATERIALS AND METHODS

Herein, cooked rice was used as a simulated food waste. Synthetic hydrotalcite (KW-500) was obtained from STEOLAS Holdings Inc., Ltd. The composition of the hydrotalcite is shown in Table 1.

| Table 1. Composition of hydrotalcite (wt.%) | | | | | |
|---|--------------------------------|-------|--|--|--|
| Substance | Al ₂ O ₃ | MgO | | | |
| KW-500 | 40.31% | 37.9% | | | |

A predetermined amount of KW-500 was added to 20 g of simulated food waste to form a mixed sample. For comparison, predetermined amounts of sodium hydroxide (NaOH, Wako Co., Ltd.) and sea sand (methanol-washed product, 425 to 850 μ m, Wako Co., Ltd.) were added separately to 20 g of simulated food waste. The experimental conditions are shown in Table. 2.

| Condition | Sample | Additive | |
|-----------|------------------------|----------|--|
| Ι | Cooked rice | — | |
| II | Cooked rice + KW-500 | 8:1 | |
| III | Cooked rice + KW-500 | 4:1 | |
| IV | Cooked rice + KW-500 | 2:1 | |
| V | Cooked rice + NaOH | 2:1 | |
| VI | Cooked rice + sea sand | 2:1 | |

Fig. 3 shows the experimental equipment used in this study. The mixed sample was placed in a metal reactor, and to remove oxygen from the reactor, nitrogen gas was injected at a flow rate of 50 mL/min for 60 minutes.

After nitrogen substitution, the nitrogen flow was stopped, and a thermal decomposition experiment was conducted. The decomposition temperature of the sample portion of the metal reactor was measured using a thermocouple, and the temperature was raised to 500 °C at a rate of 5 °C/min.

After reaching 500 °C, the sample was allowed to cool naturally. The non-condensable gas generated during thermal decomposition was collected in a gas pack through the bubbling of an alkaline aqueous solution (0.1 mol/L, NaOH) and analyzed qualitatively and quantitatively.

In addition, to investigate changes in the KW-500 structure due to heat, the sample used in Condition IV was analyzed by X-Ray structure Diffraction (XRD).



Fig. 3. Experimental apparatus.

The generated gas was analyzed qualitatively and quantitatively using a gas chromatograph (GC-2014FID, SHIMADZU). After diluting the bubbling alkaline aqueous solution (0.1 mol/L, NaOH) 50 times, a qualitative analysis of the halogens was performed using an ion chromatography analyzer (SHIMADZU, IC-20).

IV. RESULT AND DISCUSSION

A. Analysis of Generated Gas

Figs. 4–8 show the amounts of gas collected after pyrolysis, according to gas chromatography.









Fig. 6. Amount of C2H4/C2H6.



From Figs. 4 and 5, the amount of produced gas was maximized by employing NaOH as an alkaline catalyst. However, the combustible gas CH_4 was maximized using KW-500. The ability to maximize all of the flammable gases, namely CH_4 , C_2H_6 , C_2H_4 , C_3H_8 , and C_3H_6 , in the simulated food waste is attributed to the large amount of interlayer water in KW-500. In addition to the decomposition reaction due to heat, a hydrolysis reaction occurs because of the alkaline hydrotalcite. As shown in Fig. 8, the amount of CO_2 emissions is maximized using KW-500, which is ascribed to the carbonic acid contained in the hydrotalcite. Additionally, NaOH was not detected after pyrolysis, and it may have changed to sodium carbonate without a metal reactor. The results suggested that an optimal additive composition is required to maximize gas production.

B. IC Analysis of Alkaline Aqueous Solution

Table 3 shows the analysis results of the diluted alkaline aqueous solution (0.1 mol/L, NaOH). No halogens were detected using an ion chromatography analyzer.

| Table 3. IC analysis results | | | | | | | | |
|------------------------------|----|----|-----|----|-----|--------------|--|--|
| | Ι | II | III | IV | V | VI | | |
| Cl | nd | nd | nd | nd | nd | nd | | |
| Br | nd | nd | nd | nd | nd | nd | | |
| | | | | | nd: | not detected | | |

C. Residue

Fig. 9 shows the X-ray structure diffraction pattern of the residue after thermal decomposition.



Fig. 9. XRD analysis of KW-500 before and after pyrolysis

The peak intensity decreases significantly after pyrolysis, and several new peaks appear. However, because the peak values are confirmed for four points, it can be inferred that the layered structure of hydrotalcite is not completely broken. Moreover, KW-500 functioned well despite the application of 500 $^{\circ}$ C and the loss of interlayer water.

V. CONCLUSION

In this study, rice was used as simulated food waste and pyrolyzed at 500 °C to examine the effect of using KW-500 as an additive. KW-500 was originally developed for industrial purposes as a heat stabilizer in PVC, as an acid acceptor in rubbers and plastics, and as an antacid in gastrointestinal drugs. Using KW-500 as a pyrolysis additive, the reaction can be performed at relatively low temperatures, and the production of flammable gas can be maximized. Furthermore, the yield of flammable gas was increased compared with samples using NaOH, which is a typical alkaline catalyst.

The addition of KW-500 increases the production of flammable gas because the synthetic hydrotalcite is a composite hydroxide of magnesium and aluminum, providing catalytic effects. The main components of food are cellulose, hemicellulose, and lignin, which are chemically and physically stable, but KW-500 is alkaline and undergoes thermal decomposition and synthesis reactions in the metal reactor. The decomposition was likely accelerated because of hydrolysis reactions induced by the alkalinity of hydrotalcite. Although NaOH is a strong base, KW-500 was found to be superior in terms of resolution.

Moreover, the amount of produced gas is affected by the additive concentration. Overall, the results suggested that the gas generated during the pyrolysis of food waste can be maximized by adding KW-500 at a mass ratio of approximately 0.5.

Finally, XRD revealed that the characteristic layered structure of hydrotalcite is retained even after thermal decomposition at 500 °C, suggesting that it does not lose its functionality below this temperature.

CONFLICT OF INTEREST

All authors declare that (i) no support, financial or otherwise, has been received from any organization that may have an interest in the submitted work, and (ii) there are no other relationships or activities that could appear to have influenced the submitted work.

AUTHOR CONTRIBUTIONS

Y. Katako, M. Arai, C. Inaba, and S. Momiyama performed the experimental work and data analysis. The wording of the final paper was agreed upon by all authors.

FUNDING

This work was supported by the Nakatani Foundation, Kobe, Japan.

ACKNOWLEDGMENT

Synthetic hydrotalcite was provided by SETOLAS Holdings, Inc. (Takamatsu, Kagawa, Japan) for research purposes. We thank Mr. Daisuke Kudo and Ms. Harumi Takabatake of SETOLAS Holdings, Inc. for their insight on the properties of the synthetic hydrotalcite. We thank Robert Ireland, PhD, from Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript.

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