

# Recycling Technology of Bamboo Using Potassium Hydroxide

K. Nakaaze and T. Wajima

**Abstract**—The bamboo industry in Japan is declined, and disordered bamboo forests are increasing. Although maintenance of bamboo forest is needed, a large amount of bamboo wastes after logging is generated and left untreated. Therefore, new utilization of bamboo wastes after logging are desired. In this research, we aimed to develop a new recycling technology for bamboo using potassium hydroxide. By pyrolyzing bamboo using potassium hydroxide under an inert atmosphere, thermal decomposition of organic contents and alkali fusion of silica component inside the bamboo were carried out simultaneously to recover combustible gas, charcoal and silica component. The thermal decomposition behavior of bamboo, the properties of the obtained charcoal and extraction of silica in the presence of potassium hydroxide were investigated, and the optimum condition of bamboo recycling treatment was examined. As a result, it was found that when 1 g of bamboo was pyrolyzed at higher than 500 °C with 3 g of KOH, the almost silica was extracted, a large amount of fuel gas generated, and a carbonized material with specific surface area of about 1000 m<sup>2</sup>/g was obtained.

**Index Terms**—Bamboo, potassium hydroxide, alkali fusion, pyrolysis, silica.

## I. INTRODUCTION

The bamboo industry has declined due to the decrease in demand and an increase in the imported products. Approximately 350,000 ha is disordered in approximately 400,000 ha of the whole bamboo forest area in Japan. Bamboo growth is much faster than other trees, and it cause destruction of existing forests, induction of sediment collapse, damage of houses, etc. On the other hand, bamboo can be used as an effective natural resource by controlling the growth.

Bamboo is a Gramineae plant that absorbs a lot of silica (SiO<sub>2</sub>) from the ground when growing. When bamboo is used as a biomass fuel, cracking by silica causes the problems for furnaces, chimney and so on. Silica is widely used for many industries and is important resources for Japan. In previous studies, silica is extracted from rice husk ash using alkali fusion method [1]. In addition, it is possible to recover charcoal, fuel gases by pyrolysis of bamboo, and the addition of hydroxide promotes thermal decomposition of bamboo to produce the charcoal with high surface area and the high amount of gases [2].

In this research, we aimed to develop a new recycling technology for bamboo using potassium hydroxide (KOH).

Bamboo was heated in an inert atmosphere together with potassium hydroxide, and thermal decomposition treatment of bamboo body and alkali fusion treatment of silica component inside the bamboo was carried out simultaneously to recover combustible gas, charcoal and silica component. The thermal decomposition behavior of bamboo, the properties of the carbonized residue and the extraction of silica in the presence of potassium hydroxide was investigated, and the optimum condition of bamboo recycling treatment was examined.

## II. EXPERIMENT

Bamboo powder, which was collected from Chiba prefecture, Japan, was pulverized to powder with diameter of less than 3 mm and air-dried to be used in this study. Table I shows the bamboo powder composition. The moisture content was measured using a moisture meter. In addition, the bamboo powder was burned at 700 °C in the air atmosphere, and the residual amount was defined as the ash content. Fixed carbon and Volatile matter amount were entrusted to Center for Analytical Instrumentation of Chiba University for measurement. The silica content in the bamboo sample was measured as described in the previous paper [2].

TABLE I: COMPOSITION OF THE BAMBOO POWDER

Moisture	Ash	Fixed carbon and Volatile matter			Si
		C	H	N	
11 %	2 %	44.9 %	5.4 %	0.2 %	2 mg/g

Experimental procedure for pyrolysis with KOH was shown in Fig. 1. Bamboo powder (1 g) was placed in a cylindrical stainless (SUS316) reactor together with KOH (1 - 3 g) and heated to 300 - 600 °C in an electric tube furnace under a nitrogen atmosphere for 0 - 2 h.

During heating, nitrogen gas was kept flowing at a flow rate of 50 mL/min. After heating, the reactor was cooled to room temperature while flowing nitrogen at the same flow rate, then nitrogen gas flow stopped, distilled water was added into the reactor, stirred with magnetic stirrer and filtered to recover an insoluble solid and a solution with soluble components in water. The concentration of silicon in the filtrate was measured with an atomic absorption spectrophotometer (PerkinElmer, AAnalyst 200), and the extracted amount of silica component was calculated. In addition, the gas generated during thermal decomposition was collected in a gas pack, and the amount of generated gas was measured using gas chromatograph (GC-8A,

Manuscript received September 4, 2019; revised December 7, 2019.

The authors are with the Department of Urban Environment Systems, Graduate School of Engineering, Chiba University, Japan (e-mail: nakaaze.kouji@chiba-u.jp, wajima@tu.chiba-u.jp).

SHIMAZU). The solid residue was dried, and the weight of the residue was measured. The surface shape of the residue was observed with a scanning electron microscope (SEM) (JEOL, JSM-6510A) and specific surface areas of the residue were measured by a BET specific surface area measuring equipment (MacrosorbModel-12, manufactured by MOUNTECH).

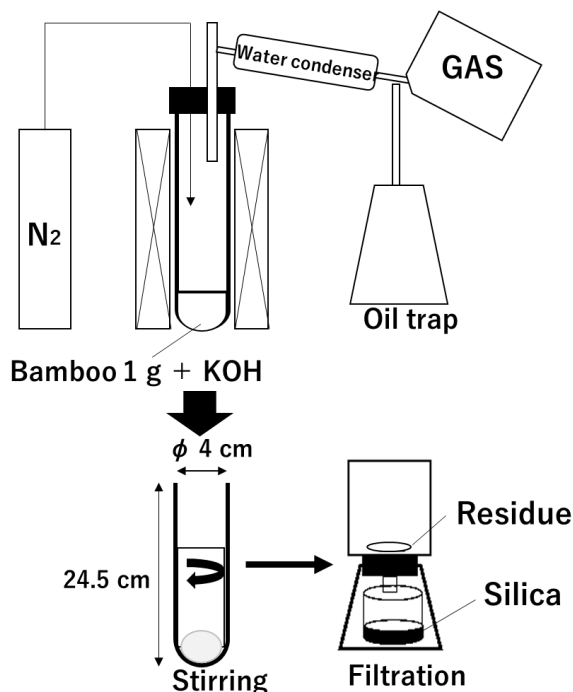


Fig. 1. Schematic diagram of an experiment and the reactor dimensions.

### III. RESULTS AND DISCUSSION

Residual weights under each condition are shown in Fig. 2. The heating time is 1 h. As the temperature rises, the residual weight decreases (Fig. 1). When the thermal decomposition temperature is 300 °C, the residual weight is 0.15 g, and the residual weight decreases to 0.05 g with increasing heating temperature to 600 °C. At 500 °C, when potassium hydroxide addition is 1 g, the residual weight is 0.12 g, and the residual weight decreases slightly to 0.07 g with increasing potassium hydroxide addition (3 g). This suggests that an increase in the thermal decomposition temperature and amount of hydroxide addition promotes thermal decomposition of bamboo to reduce the weight of the residues.

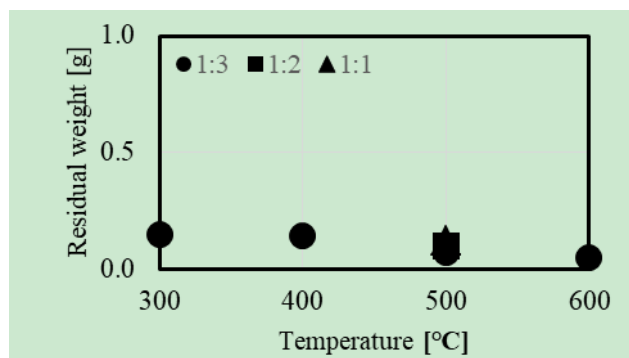


Fig. 2. Residual weights after pyrolysis.

Fig. 3 shows the specific surface area of the residue obtained under each condition. The heating time is 1 h. The

specific surface areas of the residue increase with increasing temperature and potassium hydroxide addition, and the residue with about 850 m<sup>2</sup>/g of specific surface area can be obtained when potassium hydroxide addition was 3 g at 500 °C and 600 °C.

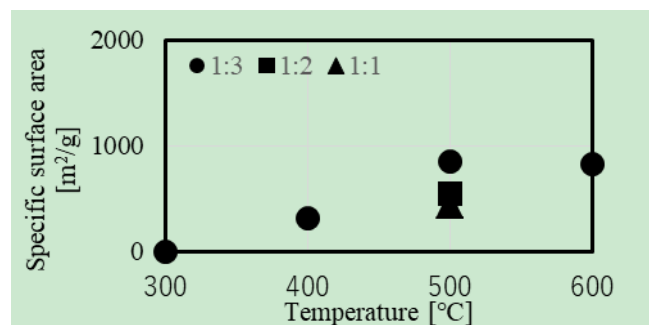


Fig. 3. Specific surface area of the residue after pyrolysis.

Fig. 4 shows SEM photographs of the residue after pyrolysis with KOH at 500 °C. The heating time is 1 h. The structure of tubular tissue, which is originated from raw bamboo, is observed in the residue without KOH at 500 °C (Fig. 4 (a)), while the structure of residue with KOH addition at 500 °C is different. With increasing KOH addition, the tubular structure is disappeared, flat surface with pore is observed in the residue with 1 g of KOH (Fig. 4(b)), and rough surface with pore is observed in the residue with 2 g and 3 g of KOH (Fig. 4 (c), (d)) to cause high specific surface area.

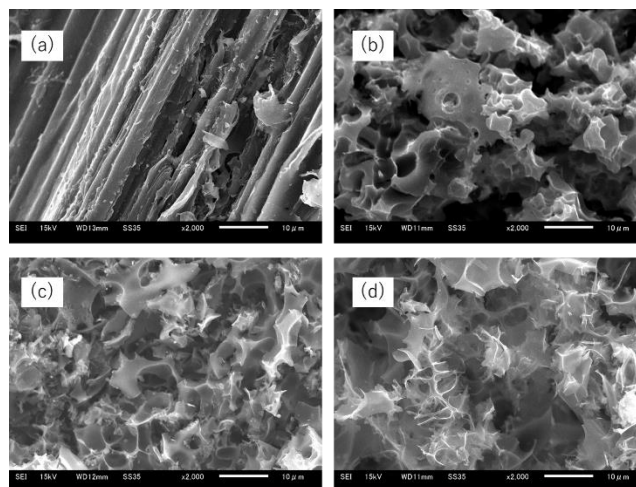


Fig. 4 SEM photographs of the residue after pyrolysis at 500 °C, (a) without KOH, (b) with 1 g of KOH addition, (c) with 2 g of KOH addition, (b) with 3 g of KOH addition.

The extracted amount of silicon under each condition are shown in Fig. 5. The heating time is 1 h. The silicon extraction amount is 0.6 to 1.8 mg/g, which is almost same as the silicon content of bamboo (1.1 mg/g) [3]. This suggests that regardless of the thermal decomposition temperature, almost silica content in bamboo can be extracted by pyrolysis with KOH.

Generated gas amounts under each condition are shown in Fig. 6. The heating time is 1 h. As the temperature rises and the amount of hydroxide addition increases, the amount of generated gas increased. When potassium hydroxide addition is 3 g, the gas amount is about 1.0 L at 500 °C and 600 °C. These results indicate that hydroxide can promote the

gasification of bamboo and the promotion is more effective at higher temperature of 500 °C.

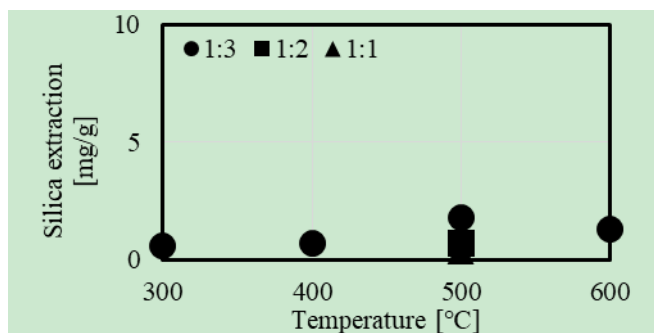


Fig. 5. Extracted amount of silicon under each condition.

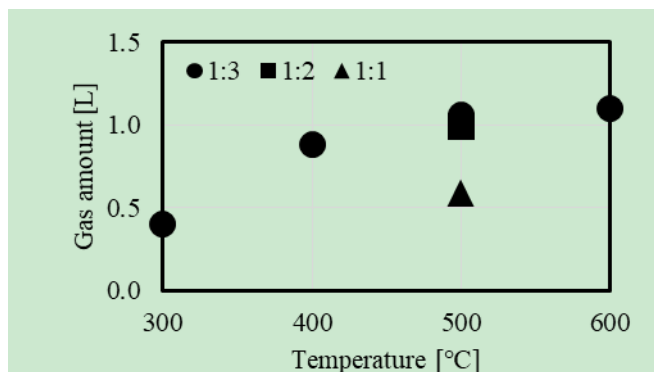


Fig. 6. Gas amounts generated during the pyrolysis.

Generated gas component under each condition are shown in Fig. 7. When potassium hydroxide addition was lower than 2 g, incombustible gas (CO and CO<sub>2</sub>) are detected (15 ~ 27 % in the generated gas). On the other hand, when potassium hydroxide addition is 3 g, these gases are lower than 4 % and combustible gas (H<sub>2</sub> and CH<sub>4</sub>) are over 96 %. This suggests that an increase in the addition of potassium hydroxide improves the purity of fuel gases.

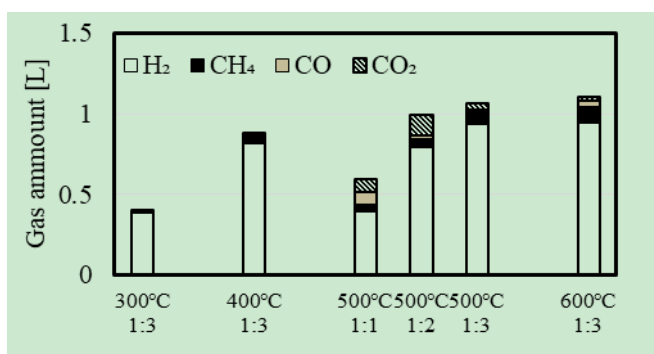


Fig. 7. Gas component generated during the pyrolysis.

From these results, it is suggested that the optimum condition of bamboo recycling treatment is more than 500 °C of heating temperature and 3 g of KOH addition.

The influence of the thermal decomposition time were investigated. Heating temperature and the potassium hydroxide addition was fixed at 500 °C and 3 g, respectively. Also, in order to investigate the effect of kind of hydroxide, the experiment using NaOH was compared with that using KOH under the same condition.

Residual weights during the pyrolysis are shown in Fig. 8.

Regardless of thermal decomposition time and kind of hydroxide, the weights are almost same (0.07 ~ 0.11 g). This

suggests that thermal decomposition of bamboo occurs rapidly regardless of kind of hydroxide under this experimental condition.

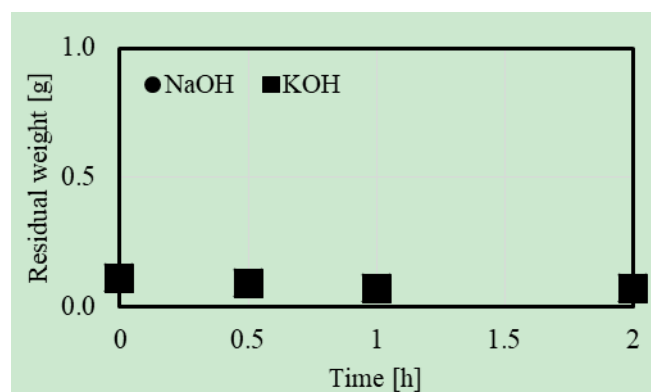


Fig. 8. Residual weights after pyrolysis with KOH and NaOH.

Fig. 9 shows the specific surface area of the residue during pyrolysis. When potassium hydroxide is added, the specific surface areas of the residue are about 1000 m<sup>2</sup>/g regardless of the thermal decomposition time. In the other hand, when sodium hydroxide is added, the specific surface areas are 1100 to 1500 m<sup>2</sup>/g.

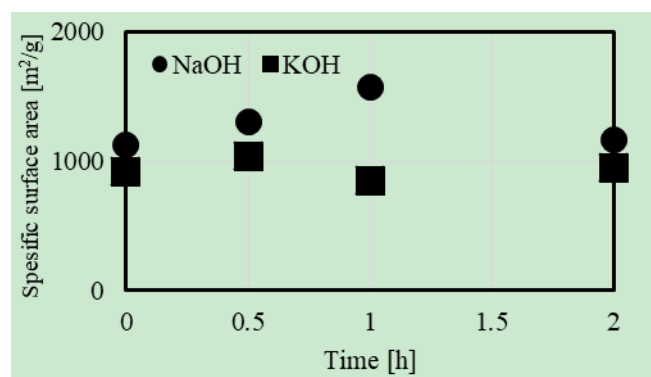


Fig. 9. Specific surface area of the residue after pyrolysis with KOH and NaOH.

Fig. 10 shows SEM photographs of the residue obtained using NaOH and KOH. Flat planes and several pores can be confirmed in the residue with NaOH addition (Fig. 10(a)), while these structures are not observed on the surface of the residue with KOH (Fig. 10 (b)). It is reported that the intercalation of alkali metal between the graphitic type layers is one of the steps in the chemical activation of carbon, and K can be inserted into highly crystalline materials such as graphite-like structures, while Na can only be inserted into poorly crystalline materials [4]-[6]. Furthermore, it is also reported that activated carbon is composed of three parts, such as graphite-like microcrystalline, single reticular-plane carbon and non-organized carbon [7]. Therefore, it is considered that Na react with only non-organized carbon and pores generated, and the other part of bamboo body remained as flat planes, while K react with all surface of bamboo and rough surface with pore is formed. The difference of the structure causes the difference of specific surface area.

The extracted amount of silica using KOH and NaOH are shown in Fig. 11. Regardless of kind of hydroxide and thermal decomposition time, silica extraction amounts are 1.0 to 1.8 g. This suggests that almost silica content in bamboo is

extracted rapidly regardless of kind of hydroxide.

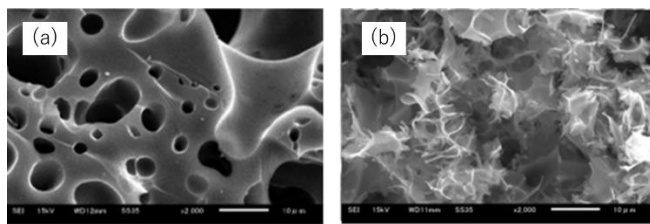


Fig. 10. SEM photographs of the residue after pyrolysis at 500 °C, (a) with 3 g of NaOH addition and (b) with 3 g of KOH addition.

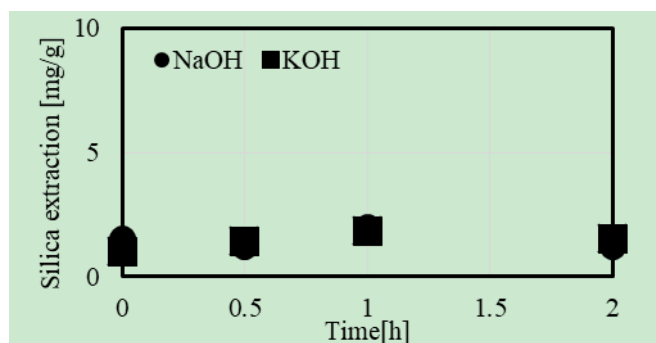


Fig. 11. Extracted amount of silicon under each condition with KOH and NaOH.

Generated gas amounts during pyrolysis are shown in Fig. 12. The amount of generated gas increases and becomes constant after 0.5 h pyrolysis regardless of the kind of hydroxide. These results indicate that the thermal decomposition occurs within 0.5 h.

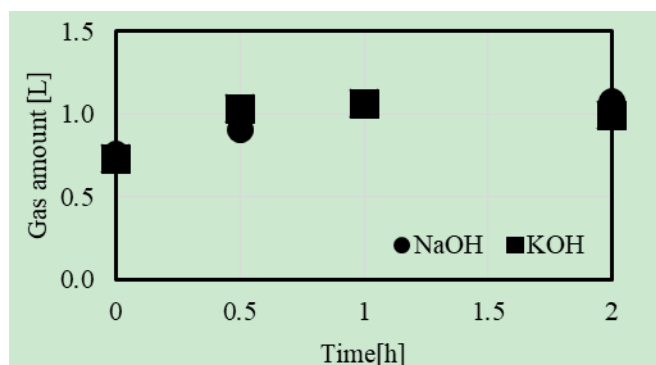


Fig. 12. Gas amounts generated during the pyrolysis with KOH and NaOH.

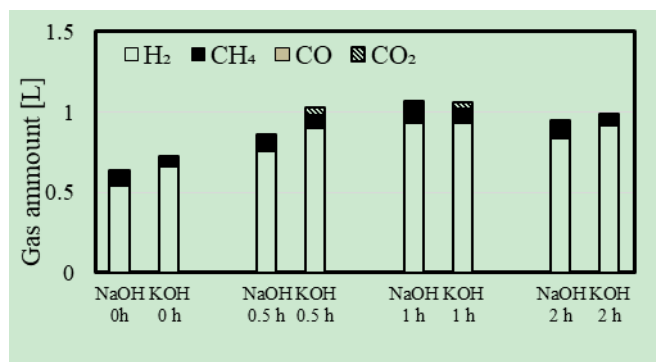


Fig. 13. Gas component generated during the pyrolysis with KOH and NaOH.

Generated gas component using KOH and NaOH are shown in Fig. 13. Regardless of kind of hydroxide and thermal decomposition time, the percent of H<sub>2</sub> in the generated gas is about 85 to 90 %, CH<sub>4</sub> accounted for about 5 to 10 %, and the amounts of CO and CO<sub>2</sub> are minor (< 4 %),

which means that fuel gas can be recovered within 0.5 h by pyrolysis with hydroxide.

#### IV. CONCLUSION

We aimed to develop a new recycling technology for bamboo using potassium hydroxide. By pyrolyzing bamboo using potassium hydroxide under an inert atmosphere, thermal decomposition of organic contents and alkali fusion of silica component inside the bamboo were carried out simultaneously to recover combustible gas, charcoal and silica component.

As a result, it was found that when 1 g of bamboo was pyrolyzed at higher than 500 °C with 3 g of KOH, the almost silica was extracted, a large amount of gas generated, and a carbonized material with specific surface area of about 1000 m<sup>2</sup>/g was obtained. It is considered that thermal decomposition occurred completely within 0.5 hour under this condition. Comparing the results of KOH and NaOH, residual weights, gas amount and silica extraction amount were same results, while NaOH was superior to KOH for specific surface area of the obtained residue due to the different structure.

#### CONFLICT OF INTEREST

The authors declare no conflict of interest.

#### AUTHOR CONTRIBUTIONS

K. Nakaaze conducted the research, analyzed the data and wrote the paper, T.Wajima revised the manuscript, and all authors had approved the final version.

#### ACKNOWLEDGMENT

This work was supported by Takahashi Industrial and Economic Research Foundation.

#### REFERENCES

- [1] R. Yuvakkumar, V. Elango, V. Rajendran, and N. Kannan, "High-purity nano silica powder from rice husk using a simple chemical method," *Experimental Nanoscience*, vol. 9, pp. 272-281, 2014.
- [2] K. Nakaaze and T. Wajima, "A novel recycling technology of bamboo using NaOH," *Journal of Engineering and Science Research*, vol. 2, pp. 7-12, 2018.
- [3] Z. Yuan, Y. Wen, N. S. Kapu, R. Beatson, and D. M. Martinez, "A biorefinery scheme to fractionate bamboo into high-grade dissolving pulp and ethanol," *Biotechnology for Biofuels*, vol. 10, no. 38, 2017.
- [4] L. Muniandy, F. Adam, A. R. Mohamed, and E. P. Ng, "The synthesis and characterization of high purity mixed microporous/mesoporous activated carbon from rice husk using chemical activation with NaOH and KOH," *Microporous and Mesoporous Materials*, vol. 197, pp. 316-323, 2014.
- [5] M. A. Lillo-Rodenas, D. Cazorla-Amoros, and A. Linares-Solano, "Understanding chemical reactions between carbons and NaOH and KOH, An insight into the chemical activation mechanism," *CARBON*, vol. 41, pp. 267-275, 2003.
- [6] O. Boujibarab, F. Ghamouss, A. Ghosh, O. Achak, T. Chafik, "Activated carbon with exceptionally high surface area and tailored nanoporosity obtained from natural anthracite and its use in supercapacitors," *Journal of Power Sources*, vol. 436, no. 226882, 2019.
- [7] G. Selvaraju and N. A. B. Bakar, "Production of a new industrially viable green-activated carbon from Artocarpus integer fruit processing waste and evaluation of its chemical, morphological and adsorption

properties,” *Journal of Cleaner Production*, vol. 141, pp. 989-999, 2017.

Copyright © 2020 by the authors. This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited ([CC BY 4.0](#)).



**Kojiro Nakaaze** was born in August 1995 in Tokyo Prefecture. He attends in the master's course of the Department of Urban Environment Systems, Graduate School of Engineering, Chiba University, Japan.



**Takaaki Wajima** was born in February 1976 in Saga Prefecture. He has been an associate professor in the Department of Urban Environment Systems, Graduate School of Engineering, Chiba University, Japan, since 2013. He received his bachelor's degree and master's degree in resource engineering from Kyoto University, Japan, in 1998 and 2000, respectively, and his Ph.D in environmental mineralogy and technology from Kyoto University, Japan, in 2004. In 2004, he moved to the Institute of Ocean Energy at Saga University to work as a postdoctoral researcher, and 2007 to 2013 he was an Assistant professor at Akita University, Japan. His main research interests are waste recycling, resource recovery, and environmental purification.