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Research Paper

# Detailed estimation of generated woody biomass ash for use as fertilizer material

Minori Ike [a], Hiroyuki Kawagoe [b], Kazuyuki Oshita [a], Masaki Takaoka [a,*]

[a] *Department of Environmental Engineering, Graduate School of Engineering, Kyoto University, C1-3, Kyotodaigaku Katsura, Nishikyo-ku, Kyoto 615-8540 Japan*
[b] *CN-research, 1-17, Takasago-cho, Gifu 500-8407 Japan*

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ABSTRACT

The physical and chemical characteristics of woody biomass ash (WBA) are highly dependent on the ash type, fuel, and furnace type. WBA recycling requires knowledge of its amount and characteristics. In this study, the amount of WBA recoverable as fertilizer in Japan was estimated considering the ash type, furnace type, and fuel type, using data obtained in a questionnaire-based survey of 105 of the 220 biomass power plants in Japan. The results showed that the amount of ash was > 1.5 times larger than that calculated according to fuel type. The discharged ash contained moisture, sand, and impurities. The slopes of the estimation model of the actual versus calculated amount were larger for gasification power generation, followed by stoker furnaces and fluidized bed furnaces. The bottom ash ratio in WBA from all furnace types was 0.37. With an estimated biomass combustion by the 220 biomass power plants in Japan of $3.4 \times 10^7$ t in 2026, the amount of generated ash would be 6.9–12 $\times 10^5$ t. Bottom ash accounted for 2.7–4.7 $\times 10^5$ t, with circulated fluidized bed furnace-derived ash comprising > 60 % of the total. The estimated annual amount of ash suitable for fertilizer use was 6.2–11 $\times 10^5$ t. The K content of WBA in 2026 was estimated to be 1.8 times larger than that in annually imported fertilizer. This K resource should be fully exploited and the efficient use of K extraction residue should be pursued to achieve an effective circular economy.

## 1. Introduction

With the demand for climate change mitigation measures, the importance of biomass power generation is gaining increasing attention. In Japan, the Feed-in Tariff (FIT) system, introduced in 2011, has led to a rapid increase in the consumption of wood and palm kernel shells (PKS) as solid biomass fuels. Power generation through the direct combustion of biomass discharges ash that requires proper use or disposal. The landfilling of large amounts of woody biomass ash (WBA) leads to a depletion of available sites, and disposal costs are a burden to businesses. According to the model constructed by Hope et al. (2017), the median disposal cost per ton of ash in Canada is CA$77 (US$54) if the power plant owns an existing landfill site and CA$108 (US$76) if the ash is landfilled in a municipal landfill. According to a survey of 16 biomass power generation facilities in Japan, the average ash treatment cost per ton of ash is 20,000 JPY (US$130). In some power plants, the costs account for 18 % of the construction and operation cost of power generation (Mori no energy Kenkyusho, 2017).

However, WBA is also a resource that can be recycled into construction materials (Rahman et al., 2020), adsorption materials (Pengthamkeerati et al., 2008), and geopolymers (Silvestro et al., 2023). $K_2O$ accounts for up to ~ 32 % (Vassilev et al., 2017), suggesting the use of WBA as a fertilizer material in agriculture. Fertilizer use of WBA allows recycling of nutrient elements contained in wood to soil. Recirculation of WBA in soils leads to the return of valuable nutrients to ecosystems and counteracts soil acidification (Vassilev et al., 2013). Table S1 lists studies on the agricultural use of WBA (Albuquerque et al., 2021; Asquer et al., 2019; Cruz et al., 2017; Eberhardt and Pan, 2013; Kilpimaa et al., 2013; Maeda, 2018; Rey-Salgueiro et al., 2016; Tajima et al., 2020; Vakalis et al., 2017; Lucchini et al., 2014; Obernberger and Supancic, 2009). For utilization as K fertilizer material, WBA need to be enriched in K, and contain little heavy metals. For example, Japanese official standards for by-product fertilizer (MAFF Japan, 2024) regulates their materials to contain Ti, Cr, Ni, As, Cd, Hg, and Pb of less than 0.04, 0.1, 0.01, 0.004, 0.00015, 0.0001, and 0.006 times K content. Additionally K content should be higher than 1.0 %.

Determining the amount of generated WBA is essential to assessing its potential as recoverable resource for K fertilizer production in a

* Corresponding author.
*E-mail address:* takaoka.masaki.4w@kyoto-u.ac.jp (M. Takaoka).

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country like Japan. The ash content of woody biomass fuel varies depending on the type of fuel (Ike et al., 2021a), with the amount of WBA produced by power plants ranging widely, from 0.5 % to 12 % of the initial fuel (Mori no energy Kenkyusho, 2017). Orihashi et al. (2024) estimated an amount of WBA generated in Hokkaido region of $3.28 \times 10^4$ t, based on a questionnaire survey. Feuerborn estimated that $1.05 \times 10^6$ t of WBA was produced in Germany in 2016, with waste wood ash accounting for $6.5 \times 10^5$ t (IEA Bioenergy, 2018); this study identified wood type, the amount of bark, leaves, and cuttings, and the combustion technology as important determinants of the generated ash amount. Štirmer et al. (2018) estimated that 20,890 t of WBA was generated in Croatia in 2018, assuming a rate of fuel use of 5 t/h and the amount of generated ash was 3.1 % of the fuel amount, based on a survey of power plants in operation. Meanwhile, Dufossé et al. (2022) estimated that 2,800–8,900 t-dry WBA was generated in Brittany, France, in 2017, with bottom ash (BA) accounting for 80 %; however, they did not specifically identify the furnace type at each facility, instead assuming that all biomass power plants in the region employed stoker furnaces. The results of a questionnaire survey in Japan indicated that the actual amount of ash generated depended not only on the fuel type but also on the type of combustion furnace (Ike et al., 2021b). The amount of WBA generated in Japan during fiscal year 2023 was estimated to be $8.9 \times 10^5$ t, with more than half derived from circulating fluidized bed boilers (CFBs) (Ike et al., 2021b). However, this estimate did not distinguish between ash type, i.e., BA versus fly ash (FA), although it is an essential factor influencing ash properties. Additionally, data were obtained from only 30 questionnaire respondents. Detailed estimates that consider ash type and furnace type are therefore still needed. For use as ash must have as potash fertilizer, ash must have sufficient K content, and the toxic heavy metal contents must be low enough such that they do not adversely affect the environment.

Vassilev et al. (2013) determined that the inorganic content of fuel wood and woody biomass contained the elements Ca (31 %) > Si (10 %) > K (8.9 %) > Mg (6.7 %) > Al (2.7 %) > Fe (2.4 %) > Na (2.1 %) > P (1.5 %) > S (1.1 %); these values were averages and the actual elemental contents varied widely, by more than one order of magnitude. The variable elemental composition of WBA reflects several factors, including the fuel wood, furnace type, and ash type. Sigvardsen et al. (2019) analyzed WBA from 11 sorces in a multivariate analysis and concluded that the ash type (BA or FA), furnace type (CFB or grate), and biofuel had the largest influences on the physicochemical characteristics of WBA. Pei et al. (2024) showed a significantly higher heavy metal (Cr, Ni, Cu, As, and Pb) content in FA from facilities using waste wood as fuel. Maeda (2018) also reported higher contents of heavy metals (Cr, Zn, As, Pb, Cd and Hg) in ash from facilities that used waste wood as fuel than in those that did not. Cruz et al (2019) reviewed physicochemical characteristics of 77 samples of ash derived from boilers using woody biomass, agricultural biomass, and other forms of biomass as fuel. They found higher amounts of Ca, S, K, Cl, and toxic heavy metals (As, Cd, Pb, and Zn) and lower amounts of Si in FA than in BA; additionally, significantly higher concentrations of Ca, K, Mg, and heavy metals (Cd, Co, Cr, Cu, and Ni), and a significantly lower Si concentration, were found in BA derived from grate furnaces than that from fluidized bed boilers.

The lack of information on the furnace, ash, and fuel types, as well as the amount of WBA generated, hinders estimations of the amount of resources available as fertilizer material, given that these factors strongly influence the characteristics and recycling potential of WBA as well as the amount the ratio of BA and FA (CEDEN, 2019).

Thus in this study, a questionnaire survey was conducted with the objective of obtaining an accurate estimate of the amount of WBA available in Japan as a recoverable resource in agriculture, and specifically as fertilizer material. The trends in the fuels burned in Japan and the furnace types used to burn those fuels were investigated, from which the amount of WBA expected to be produced by power plants in Japan in 2026 was estimated. The novel method used to calculate the amount of ash took into account of fuel type, ash type, and furnace type and can be adopted to changing trends in fuel type and furnace type. Although PKS is technically an agricultural residue, included in the subject of this study's estimation. PKS is used as a fuel like wood and is often co-fired with wood in many power plants.

## 2. Materials and Methods

### 2.1. Woody biomass power plants

The biomass power plants selected for assessment in this study were picked up from the FIT-certified power plants list in Japan (as of March 2022) (METI Japan, 2022a). Each power plants were determined if mainly (more than a half) combust woody biomass fuel, either wood or PKS, checking the websites. PKS is a solid biomass fuel, and its import from Indonesia and Malaysia to Japan has rapidly increased in recent years (Sasatani, 2020). Coal and biomass co-combustion plants mainly (more than a half) fueled by coal were excluded from the study. Finally 220 power plants that were mainly fueled by wood or PKS were selected and they had a total power generation of 5096 MW. The 220 targeted power plants included some currently planned to start operation in 2026;144 were currently operating, and the operation of 76 was planned for in 2022.

### 2.2. Questionnaire survey

A questionnaire survey targeting the 220 biomass power plants was conducted between 2020 and 2022; responses were obtained from 105 of the plants. Contact was made with the power plants using the phone number or postal address listed on the FIT list (METI Japan, 2022a). Some of the power plants belong to Japan Woody Bioenergy Association (JWBA) or Biomass Power Association (BPA), and contacts were made in cooperation with these associations. The questionnaire were designed based on the survey of biomass fuel demand and supply by JWBA (2024). The questions addressed fuel consumption, fuel properties (moisture content, ash content, and calorific value), the mixing ratios of different fuels, furnace type, the amount of ash generated, and the time at which operation began. Table S2 summarizes the information of 220 target plants. The questionnaire sheet is attached in the supplemental.

### 2.3. Estimation

Of the 105 plants that responded, 74 plants provided information on the amount of generated ash, $A_G$ (t). For 31 plants that did not provide $A_G$ and 115 plants that did not respond to the questionnaire, this value was calculated from the fuel and furnace types, such that WBA amounts were estimated for all 220 plants. The combusted fuel and furnace type of the plants that did not answer the question or respond to the questionnaire were found on the website to the extent possible. The formula used in the calculation of ash was created from the results of the questionnaire survey. Among the 70 respondents to $A_G$, 47plants also provided their fuel consumption and ash content of fuel, and the ash amount in the fuel, $A_C$ (t-dry) were calculated for them. Based on the data of 47 plants, linear functions for determining $A_G$, with $A_C$ as a variable, were obtained (Eq. 1):

$$A_G = (p_{bfb\_1}, p_{cfb\_1}, p_{g\_1}, p_{ss\_1}, p_{ts\_1}, p_{unknown\_1}) \cdot \textit{(Furnace type)} \cdot A_C. + (p_{bfb\_2}, p_{cfb\_2}, p_{g\_2}, p_{ss\_2}, p_{ts\_2}, p_{unknown\_2}) \cdot \textit{(Furnace type)} \quad \text{Eq.1.}$$

where $A_G$ is the generated amount of ash, $A_C$ is the calculated amount of ash contained in fuel, $p_{bfb\_1}$, $p_{cfb\_1}$, $p_{g\_1}$, $p_{ss\_1}$, $p_{ts\_1}$, $p_{unknown\_1}$, $p_{bfb\_2}$, $p_{cfb\_2}$, $p_{g\_2}$, $p_{ss\_2}$, $p_{ts\_2}$, and $p_{unknown\_2}$ are constants, and $(Furnacetype) = \begin{pmatrix} BFB \\ CFB \\ G \\ SS \\ TS \\ unknown \end{pmatrix}$

Equation 1 was applied for all 47 plants and for the five furnace types in this group: bubbling fluidized bed (BFB), CFB, stepped stoker furnace (SS), traveling stoker furnace (TS), and gasification power generation (G).

Fig. 1 shows the estimation procedure for the amount of ash generated by 146 plants that did not provide data on $A_G$. In those cases, $A_G$ was calculated using Eq.1 according to the furnace type of each plant. The constants for Eq.1 ($p_{bfb\_1}$, $p_{cfb\_1}$, $p_{g\_1}$, $p_{ss\_1}$, $p_{ts\_1}$, $p_{bfb\_2}$, $p_{cfb\_2}$, $p_{g\_2}$, $p_{ss\_2}$, and $p_{ts\_2}$) were determined by the least-squares method for each furnace type. The ratio of BA to $A_G$ ($b_{bfb}$, $b_{cfb}$, $b_g$, $b_{ss}$, and $b_{ts}$) was similarly assessed according to furnace type, using the average value for each (excluding outliers). $A_C$ was calculated by multiplying of the fuel consumption F (t), moisture content (%) and ash content (% of dry mass) of the fuel used in each plant. Despite the questionnaire and the additional research on website, furnace type of 29 plants were still unknown. For these 29 power plants, $A_G$ was calculated using Eq.1 with constants ($p_{unknown\_1}$ and $p_{unknown\_2}$) based on the data from the 47 plants that provided information, and BA ash ratio was set to the average value of all of the plants ($b_{unknown}$). Among the 146 plants whose $A_G$ were unknown, 68 plants also did not provide information about $F$. For them, $F$ was calculated based on the output scale $S$ (MW), the annual operating days $D$ (d), and the net calorific value of the fuel, using the formula shown in Fig. 1. The power generation efficiency $E$ (–) was calculated using the equation of Aruga et al. (2006), with S as a variable. $S$ values were obtained from the list of FIT-certified plants (METI Japan, 2022a). For plants with no information about $D$, the average value (330 d) from the 100 plants for which $D$ was obtained, either from the questionnaire or published online, was used. For plants with no information about the moisture content, ash content, or net calorific value of the fuel, the average values from the questionnaire survey for each fuel type were used. Since the ash content (% of dry mass) follows a log-normal distribution (Ike et al., 2021a), it was determined using the average of the logarithmic values. Average of the natural logarithm of ash content was calculated, and exponential of it was used for ash estimation. Fuels for woody biomass were classified into six types: wood chips (WC), wood pellets (WP), branches and leaves (BR), bark (B), waste wood (WW), and PKS. For the 41 plants that burned multiple fuel types but did not report the mixing ratio, the fuels were assumed to be mixed in equal amounts. Later, the mixing ratio of PKS was re-assumed based on its imported amount. PKS is an imported agricultural residue, the annual amount of consumed PKS was set not to exceed the annual imported amount. At a few facilities, coal was partly co-fired with woody biomass as a supplemental fuel. The ash content and calorific value of coal was assumed to be 11 % of dry mass and 29 MJ/kg, respectively (CRIEPI, 2002). If the fuel type was unclear, WC was assumed to be used in those plants, based on previous research (Ike et al., 2021a).

In the estimation process, each plant was assumed to use the same type and amount of fuel and to produce the same amount of ash each year. For the 57 facilities with no information about the business start year, operation was assumed to have started 2 years and 8 months after the date of FIT certification, which was the average lag time of the remaining 163 facilities.

## 3. Results and Discussion

### 3.1. Fuel properties

The fuel properties of the six types of woody biomass fuel used in the

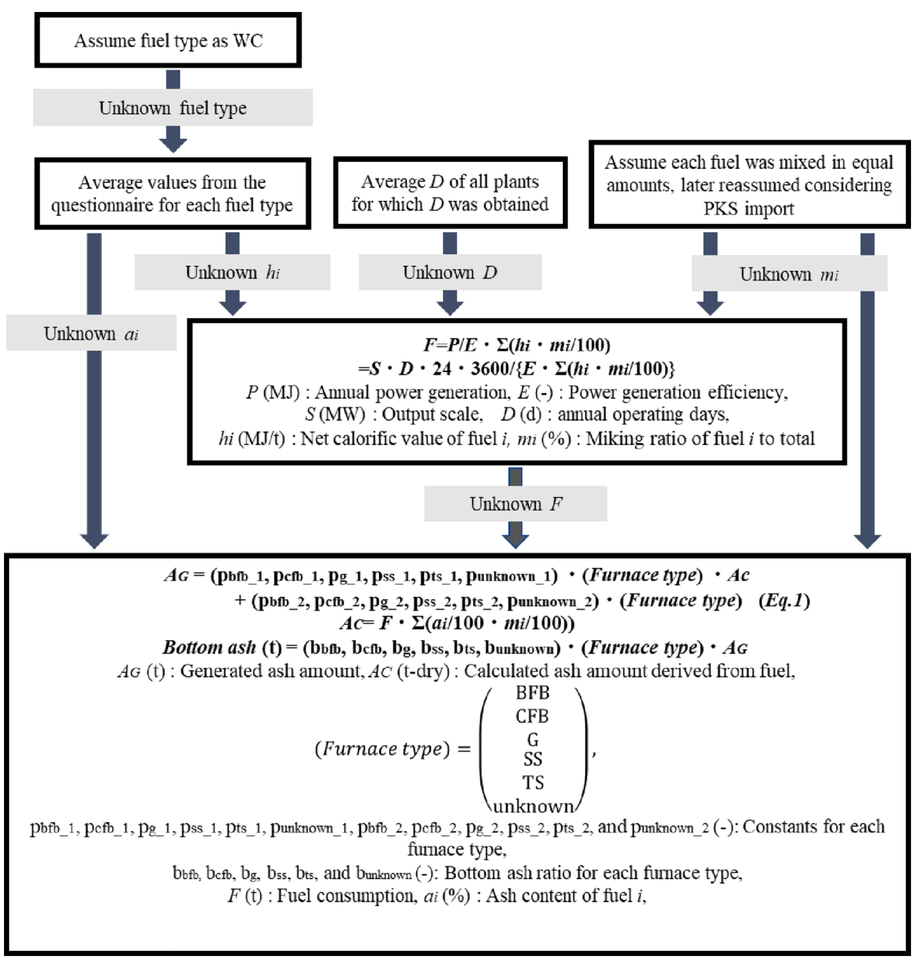


**Fig. 1.** Ash estimation procedure for plants lacking ash quantity data.

105 respondent plants were determined from the questionnaire survey data. Some plants reported using more than one fuel type. Table 1 shows the average values of the fuel properties and the number of data items (N) collected for each fuel type; for the ash content, the averages of the logarithmic values and the standard deviations (SD) are listed. The ash content distributions of the five types of fuel, excluding BR and WP with a smaller number of data, were closer to a log-normal than normal distribution, consistent with our previous literature review (Table 1) (Ike et al., 2021a), which was based on a database of biomass feedstock, Phyllis 2 (ECN and TNO, 2020), and 29 additional studies.

The moisture content of the questionnaire data exceeded the values from the literature (Table 1). Data included in our previous literature survey were obtained from worldwide sources. Considering the gap, the woody biomass fuels used in Japan appear to contain more moisture than fuels used in other countries (Table 1). Power plants preferably use fuels with lower moisture contents, but they often have to accept low-grade fuel because of the continuously rising price of woody biomass fuel and supply limitations, such that some power plants cannot purchase the planned amount and type of fuel (JWBA, 2024). Additionally, the properties recorded in the literature may have been obtained from samples provided for research that are not representative of the fuel used in actual power plants. The net calorific value for all fuel types in this study was 1–3 MJ/kg below the average value found in literature. A higher moisture content leads to a lower net calorific value due to the increased latent heat of vaporization. The difference in ash in this study compared with our previous literature review was smaller than the difference in moisture content and net calorific value.

WC is mainly derived from tree trunks, but it may also contain BR. The ash content of WC with B and BR is affected by the high ash contents of B and BR (literature values in Table 1). According to the cumulative distribution of the ash content of WC, along with information on its BR content (Fig. S1), WC containing BR had a greater ash content than WC that did not, with logarithmic averages of 2.4 % of dry mass and 0.83 % of dry mass, respectively. Previous research also showed that leaves contain more ash than sapwood and heartwood (Islam et al., 2019; Nakagawa and Matsumura, 2004).

**Table 1**
Fuel properties of woody biomass fuel used in Japan.

| Fuel type | | Moisture (%) | LHV(MJ/kg) | Ash content (% of dry mass) | |
|---|---|---|---|---|---|
| | | Average [N] | Average [N] | Logarithmic average [N] | SD |
| WC | Questionnaire | 40 [202] | 12 [182] | 1.0 [127] | $e^{1.2} = 3.3$ |
| | Literature review | 25 [70] | 14 [50] | 0.94 [70] | $e^{0.79} = 2.2$ |
| WP | Questionnaire | 11 [16] | 15 [16] | 0.86 [10] | $e^{0.41} = 1.5$ |
| | Literature review | 7.5 [90] | 17 [84] | 0.45 [88] | $e^{0.69} = 2.0$ |
| PKS | Questionnaire | 22 [42] | 15 [38] | 2.8 [26] | $e^{0.26} = 1.3$ |
| | Literature review | 13 [14] | 16 [11] | 3.2 [13] | $e^{0.64} = 1.9$ |
| BR | Questionnaire | 46 [6] | 12 [5] | 1.0 [2] | $e^{0.98} = 2.7$ |
| | Literature review | 28 [28] | 14 [19] | 3.3 [37] | $e^{0.69} = 2$ |
| B | Questionnaire | 48 [15] | 13 [14] | 3.0 [12] | $e^{0.80} = 2.2$ |
| | Literature review | 26 [35] | 14 [24] | 4.2 [43] | $e^{0.92} = 2.5$ |
| WW | Questionnaire | 30 [24] | 12 [26] | 3.4 [17] | $e^{0.72} = 2.1$ |
| | Literature review | 18 [42] | 15 [38] | 2.0 [42] | $e^{0.47} = 1.6$ |

### 3.2. Furnace type and combustion temperature

Ash generation depends on the fuel combustion temperature (Jenkins et al., 1996; Du et al., 2014), fuel type, and furnace type. Of the 105 power plants that responded to the questionnaire, 28, 41, 8, 9, and 17 power plants used BFB, CFB, G, SS, and TS furnace types, respectively. The other two plants did not respond their furnace types. The combustion temperatures were responded by 65 plants, and ranged from 680 °C to1250°C, with average of 842°C (SD: 89°C) (Fig. S2). The reported combustion temperature for fluidized bed and fixed bed furnaces is 850°C (Dahl et al., 2010; de la Grée et al., 2016). Meanwhile, Miles et al. (1996) measured flue gas exit temperatures of a BFB, three CFBs, and two stoker furnaces of 960°C, 882–900°C, 640–850°C, respectively. Fluidized bed boilers are generally operated at lower temperatures than fixed bed furnaces (Girón et al., 2013; Munawar et al., 2021), but this was not the case for the plants in our questionnaire survey. Nevertheless, the carbon amount is higher in ash of fixed bed and grate furnaces than in that of fluidized bed furnaces (de la Grée et al., 2016; Maeda, 2018), indicative of the higher combustion efficiency of the latter. The different amounts of ash provided by different furnace types is not due to the temperature but to differences in furnace structure.

### 3.3. Calculation of ash generation for furnace types

For the 74 power plants that provided information on the amount of generated ash, the total amount was 2.4 × $10^5$ t /year. To estimate the amount of WBA generated from power plants nationwide, the calculated fuel-derived ash amount, $A_C$ (t-dry), and the actual generated ash amount, $A_G$ (t), were compared.

The $A_C$ and $A_G$ values for 47 respondents are shown in Fig. 2. The linear approximation function (Eq. 1) was y = 1.8x + 250 for all 47 power plants (where y corresponds to $A_G$ and x to $A_C$). The covariance for the equation was 0.92. For all equations except that of G, the correlation between $A_G$ and $A_C$ was significant ($p < 0.05$); for G, the significance of the correlation could not be confirmed ($p = 0.18$) due to the small sample size (N = 3). The constants depending on furnace type were determined and shown in Table 2. For all furnace types, the slope of the approximation line was 1.5–2.8. $A_C$ was calculated as dry tons, but

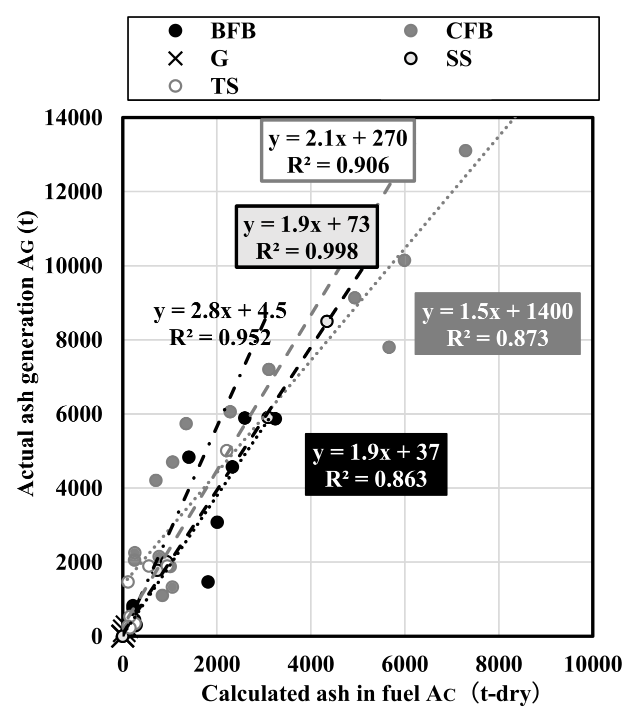


**Fig. 2.** Correlation between $A_C$ and $A_G$.

**Table 2**
Constants for estimations shown in Fig. 1.

| Constants | Values | Constants | Values | Constants | Values |
|---|---|---|---|---|---|
| $q_{bfb\_1}$ | 1.9 | $q_{bfb\_2}$ | 37 | $b_{bfb}$ | 0.21 |
| $q_{cfb\_1}$ | 1.5 | $q_{cfb\_2}$ | 1400 | $b_{cfb}$ | 0.42 |
| $q_{g\_1}$ | 2.8 | $q_{g\_2}$ | 4.5 | $b_{g}$ | – |
| $q_{ss\_1}$ | 1.9 | $q_{ss\_2}$ | 73 | $b_{ss}$ | 0.55 |
| $q_{ts\_1}$ | 2.1 | $q_{ts\_2}$ | 270 | $b_{ts}$ | 0.43 |
| $q_{unknown\_1}$ | 1.8 | $q_{unknown\_2}$ | 250 | $b_{unknown}$ | 0.37 |

because the actual amount of ash contains some water, $A_G$ is larger than $A_C$. According to a guide for wood power plants (Maugard, 2015), the amount of wood ash collected from the wet process is 1.4 times larger than that from the dry process. In addition, the impurities in fuel wood, such as sand, paint, and metal fittings in waste construction wood, are mixed into the fuel that enters the furnace. Their presence also causes $A_G$ to be larger than $A_C$, as the latter is derived from the original fuel. Orihashi et al. (2024) found that actual ash generation determined from a questionnaire survey was 1.5 times larger than the calculated estimate. Similarly, in the study of ash generation from municipal solid waste, its amount was 1.8–1.9 times larger than the calculated ash content (Takaoka and Ike, 2021).

The slope of the approximation line for G was larger than the slopes of the other furnace types. The main component of ash generated in G is carbonized material. Carbon accounts for > 50 % of gasified ash (Modolo et al., 2013) and may reach 90 % (Eberhardt & Pan, 2013) of the total ash mass from G. Therefore, the ratio of $A_G$ to $A_C$ was larger for G than for the other furnace types. The intercept of the approximation line was the largest for CFB. In a CFB, sand must be added to the furnace as a circulation fluid; the generated ash therefore originates from the ash content of not only the fuel but also the sand. Because the amount of sand input is not proportional to $Ac$, the intercept of the approximation line may be large. The slopes were also higher for stoker furnaces than for fluidized bed boilers, which can be explained by the higher unburned carbon content in ash from grate combustion than from fluidized bed combustion (Girón et al., 2013). According to Maeda (2018), the total carbon concentration of WBA of stoker ash from stoker furnaces was 8.8, 9.3, 12.6, and 14.0 %, whereas that of fluidized bed boiler ash from fluidized bed boilers was 1.0 and 4.8 %.

The accuracy of the estimation method was examined. In Fig. 3, actual ash emissions are shown on the horizontal axis, based on the questionnaire responses; estimated ash generation calculated using the method of this study and the data from the 74 plants that reported the annual amount of generated ash are shown on the vertical axis. $A_C$ was known for 46 plants and calculated using the values in Table 1 for 28 plants. The error bars show the uncertainty, calculated from the SDs of the ash content. The solid and dashed lines represent y = x and the linear approximation equations, respectively. The values plotted close to the y = x line and were in good agreement with the estimated values. The slope of the estimation line was 0.92, indicative of only a slight possibility of a smaller estimated than actual amount of ash generation.

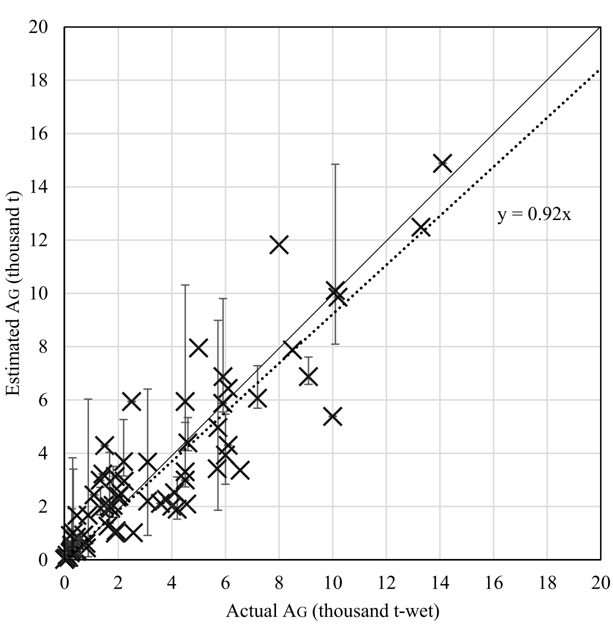


**Fig. 3.** Accuracy of ash estimation.

### 3.4. Bottom ash ratio

Fig. 4 shows the boxplot of BA ratio for the 48 power plants that provided data on the amounts of BA and FA. The BA ratio values for each furnace type used for estimation were shown in Table 2. Data from furnace type G were excluded because no information on the amount of BA and FA was available from the G plants. The outliers were presumed to be respondent errors. The interquartile range method identified two outliers, which were subsequently excluded. Besides the outliers, the values of BA ratio for BFB plants were small (0.07–0.28). Similarly, a Finnish BFB biomass power plant generated an amount of BA 0.17 times as large as that of all the generated ash (Dahl et al., 2010). “X” in Fig. 4 show the average value for each furnace type: the average values of BA ratio was 0.37 (SD: 0.21) for all 48 plants. A Japanese TS biomass plant described previously (Nagano, 2021) generated three times more BA than FA; a BA ratio > 0.7 was found only for the TS. For five stoker furnaces combusting municipal solid waste, Sakanakura (2021) calculated BA ratio of 0.69–0.93, with a higher FA ratio determined for fluidized bed boilers than for stoker furnaces. According to a French guideline (CEDEN, 2019), the BA ratios for furnace types follow the order grate furnace > spreader stoker > fluidized bed boiler, in agreement with the present results. In the fluidized bed boilers, the fluidized bed media in the furnace is agitated by the forced air, and the fuel is burned by floating combustion, resulting in a large amount of FA. Unburned materials are separated at the bottom of the furnace, but some of them are transferred to the fluidized bed media and returned to the furnace, resulting in less BA (TAKUMA Environmental Technology Research Group, 2017). Ohenoja et al. (2020) determined BA ratios for fluidized bed boilers of 20–25 %, consistent with the BFB value but smaller than the CFB value in this study.

### 3.5. Estimation of woody biomass combustion in Japan

The amount of ash generated at the 220 woody biomass power plants in Japan from 2013 to 2026 was estimated based on the fuel properties summarized in Section 3.1 and using Eq.1 (Section 3.4). In 2013, soon after the FIT system was initiated, estimated fuel consumption was 2 × $10^6$ t, which was estimated to reach 3.4 × $10^7$ t in 2026, with WC accounting for 37 % of total fuel consumption, WP for 34 %, and PKS for 21 %.

For facilities with unknown fuel consumption, annual power generation was used in calculation. If the mixing ratio of fuel was unknown, the PKS ratio of each plant’s fuel consumption was assumed based on PKS imports in Japan. PKS is a crop residue that, in Japan, is entirely procured through import, the volume of which has been increasing rapidly over the last decade. In 2023, ~5.9 × $10^6$ t of PKS was imported (METI Japan, 2024). In this study, to ensure that annual PKS consumption at the 201 biomass power plants did not exceed the annual import, the unknown mixing ratio of PKS was set at 3 % for operations at the end of 2022. A life cycle assessment showed that in woody biomass power generation sector, the long-distance transport of fuel has the largest contribution to $CO_2$ emissions (Elisa et al., 2020). Thus, the dependence of Japan’s biomass energy on imported fuel raises questions about the carbon neutrality and sustainability. To address this issue, the Japanese government now requires FIT-certified power plants to

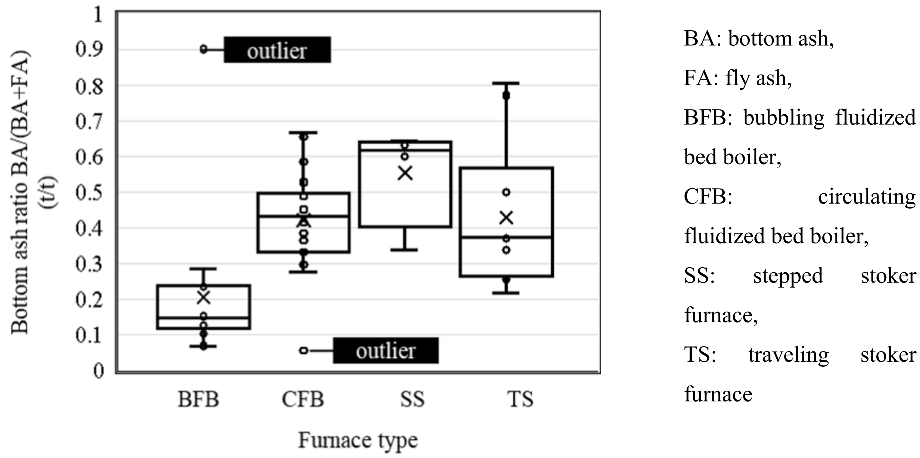


**Fig. 4.** Bottom ash ratio.

guarantee the sustainability of their PKS fuel through third-party certification (METI Japan, 2022b).

### 3.6. Estimation of WBA generation in Japan

The $A_C$ of the $3.4 \times 10^7$ t of fuel combusted in 2026 was estimated to be $4.3 \times 10^5$ (SD: 2.8–7.2 $\times 10^5$) t-dry on average. 37 % of total $A_C$ was derived from PKS, which has a relatively high ash content, while WC- and WP-derived $A_C$ accounted for 18 % and 20 %, respectively.

Of the 220 power plants included in the estimation, 36, 90, 24, 14, and 27 plants used BFB, CFB, G, SS, and TS furnaces, respectively. For the other 29 facilities, information on the furnace type was lacking. Almost a half of the plants used a CFB furnace, which aligned with the furnace types indicated by the questionnaire respondents. Applying the results obtained with Eq.1, the amount of ash generated in woody biomass power plants nationwide, changed according to the ash type (Fig. 5(a)). The error bars show the uncertainty, calculated from the SDs of the ash content. The average total amount of WBA generated in Japan in 2026 was predicted to be $8.6 \times 10^5$ (SD: 6.9–12 $\times 10^5$) t, of which BA and FA accounted for $3.4 \times 10^5$ and $5.2 \times 10^5$ t, respectively. In a

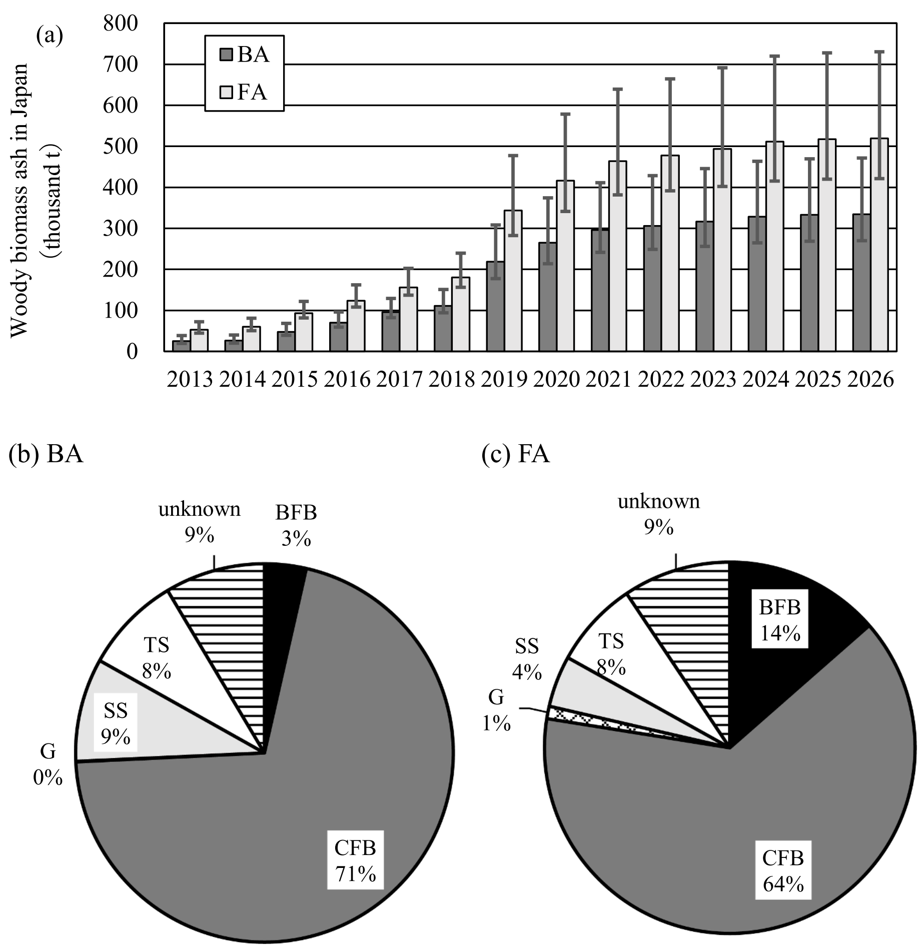


**Fig. 5.** Estimation of WBA generated in Japan.

previous study by Dufossé et al. (2022), the BA ratio was fixed at 0.8, much different from our result (0.4). thus, based on the questionnaire, more FA would be generated than assumes from the literature. According to Štirmer et al. (2018), the ash generation accounts for ~ 3.1 % of fuel consumption, which would imply $1.0 \times 10^6$ t ash generated in Japan in 2023; the results of this work are consistent with this estimate. Fig. 5(b) and (c) show the average amount of BA and FA derived from each furnace type. For both ash types, CFB-derived ash accounts for > 60 % of the total. These WBA were derived from FIT-certified power plants, but does not include ash generation from heat boilers. According to the national survey on woody biomass energy use in 2022 (MAFF Japan, 2023), annual WC consumption by power plants WC consumption by heat supply facilities (with combined heat and power plants) was $4.1 \times 10^6$ t-dry (equivalent to $6.8 \times 10^6$ t at 40 % moisture). Other woody biomass consumption by heat supply facilities was $1.4 \times 10^6$ t (MAFF Japan, 2023). The estimated fuel consumption in 2022 was 3.0 $\times 10^7$ t, and WBA generation by heat supply facilities is estimated to be 0.27 times WBA generation from power plants by simple calculation with fuel consumption.

The combustion of WW as fuel is not suitable for fertilizer use due to its high heavy metal content in FA (Maeda, 2018; Pei et al., 2024). Thus, excluding FA generated at power plants using WW as fuel, the average estimated amount ash available to be recycled as fertilizer was $7.6 \times 10^5$ (SD: 6.2–11 $\times 10^5$) t. Fig. 6 shows the distribution of this ash resource, expressed as the average values for 47 prefectures in Japan. Hokkaido prefecture, which has the largest land area and the largest number of power plants, had the largest potential resources for fertilizer, followed by Fukuoka and Aichi prefectures, which have large-scale power plants (> 50 MW) fueled by imported WP and PKS. Of the average $7.6 \times 10^5$ (6.2–11 $\times 10^5$) t, $3.4 \times 10^5$ (2.7–4.7 $\times 10^5$) t was BA and $4.2 \times 10^5$ (3.5–6.0 $\times 10^5$) t was FA. BA has lower heavy metal contents than FA (Obernberger & Supancic, 2009), but the K content is higher in FA (Cruz et al., 2019).

Of the average $A_C$ of $4.3 \times 10^5$ t-dry, wood-, PKS-, and coal-derived $A_C$ accounted for $2.1 \times 10^5$, $1.5 \times 10^5$, $5.8 \times 10^5$ t-dry, respectively. In previous studies, the average $K_2O$ content in PKS ash was 9.54 % (SD: 1.51–21.20 %) (Oladele and Okoro, 2016; Nnochiri et al., 2017; Ikubanni et al., 2020; Imoisili et al., 2020). Assuming a $K_2O$ content of 12.44 % for wood and woody biomass ash (Vassilev et al., 2017) and of 9.54 % for PKS ash, annual $K_2O$ generation by woody biomass power plants in Japan would be $4.0 \times 10^4$ t-dry on average, equivalent to $3.3 \times 10^4$ t-dry of K. Japan imported $6.38 \times 10^4$ t of KCl ores and $7.2 \times 10^3$ t $KNO_3$ ores in 2023 (METI Japan, 2024), equal to $1.9 \times 10^4$ t-dry of K considering a purity of 52 % and 45 %, respectively (JOGMEC, 2023). Therefore, the K potential in generated WBA is 1.8 times larger than that in imported fertilizer, indicating that Japan generates a sufficient or too much quantity of ash to meet the fertilizer demand. A portion of K in WBA is insoluble, such as that associated with silicon compounds, and not available for plants. The average ratio of extractable, bioavailable K to the total K concentration is 0.345 for WBA and 0.675 for K fertilizer (da Costa et al., 2020). The difference is due to the higher concentrations of K compounds bound to insoluble elements such as silicon in WBA. Even compared with bioavailable K equivalents, $4.7 \times 10^4$ t-dry of $K_2O$ is 0.92 times the K amount in imports, indicating that Japan generates a sufficient quantity of ash to meet the fertilizer demand. However, of the 154 plants using woody biomass for energy in the electricity, gas, heat, and water supply industries, only six also use the generated WBA for agricultural purposes and only 11 use it for other purposes (MAFF Japan, 2023). Among 75 respondents for the question about ash disposal of this study, 42 plants beneficially utilized WBA. 15 plants landfilled WBA, and 43 plants outsourced the disposal of WBA (multiple responses allowed). Therefore the power plants that dispose WBA as waste were still the majority. The full use of ash, utilization as K fertilizer, and in other applications of K-extracted residual ash, will contribute to the achievement of a circular economy in Japan. Maeda (2018) tested neutralized K-enriched portion of WBA if it is suitable as a fertilizer material, and the pot test on spinach showed fertilizer efficacy comparable to that of KCl. It is not necessary to monitor only the content of K, but also the its soluble content, the heavy metal content satisfying official standards (MAFF Japan, 2024), and suitable pH of neutralizer. Also, clarification of the relationship of such properties and ash, fuel and furnace types would highly contribute to more efficient us of WBA for fertilizer.

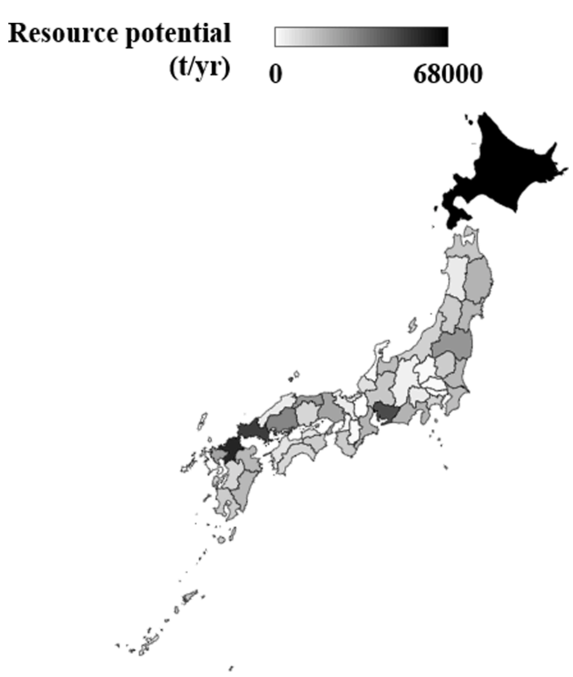


**Fig. 6.** Geological distribution of recoverable WBA for fertilizer material.

## 4. Conclusion

A questionnaire survey aimed at obtaining information on WBA generation was conducted. The survey results were used to estimate the amount of ash potentially useful as K fertilizer material in Japan.

The distribution of the ash content in woody biomass fuels was more similar to a log-normal distribution than to a normal distribution. More ash was contained in WC with than without BR. The data allowed the successful development of an estimation model for ash generation. The slopes in estimation model of $A_G$ versus $A_C$ were largest for G, followed by stoker furnaces and fluidized bed boilers. Ash generation in Japan in 2026 was estimated to be in the range of 6.9–12 $\times 10^5$ t, with BA accounting for 2.7–4.7 $\times 10^5$t, of which the contribution of CFB-derived ash was determined as > 60 %. In addition, PKS comprised 21 % of total consumed fuel. As discharged ash contains moisture, sand, and impurities, the average amount of annually generated ash suitable for fertilizer use was estimated to be $7.6 \times 10^5$ (SD: 6.2–11 $\times 10^5$) t, with the largest share from Hokkaido prefecture. The average amount of K in the generated WBA exceeded the amount of K in annually imported fertilizer by 1.8-fold. The domestic K resource in WBA should be fully exploited, through the efficient use of K extraction residue in WBA to improve Japan's circular economy.

The estimation model developed in this work can be applied to ash estimations from different fuel types and furnace types in other countries. It enables prediction of ash generation by considering the changing trends in fuel and furnace choice. Determination of the relationship between ash recycling potential and production parameters, such as fuel type, ash type, and furnace type, will provide the information needed to assess the amount of recoverable ash available for various objectives, leading to more effective recycling. The complete use of recoverable

WBA requires collection and stock systems for ash and guaranteed demand. Better estimates of WBA components with applications other than as fertilizer, such as cementitious materials and geopolymers, are needed to make full use of benefits of WBA.

## CRediT authorship contribution statement

**Minori Ike:** Writing – original draft, Methodology, Investigation, Formal analysis. **Hiroyuki Kawagoe:** Investigation, Data curation. **Kazuyuki Oshita:** Writing – review & editing, Project administration. **Masaki Takaoka:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.02.009.

## Data availability

Data will be made available on request.

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