

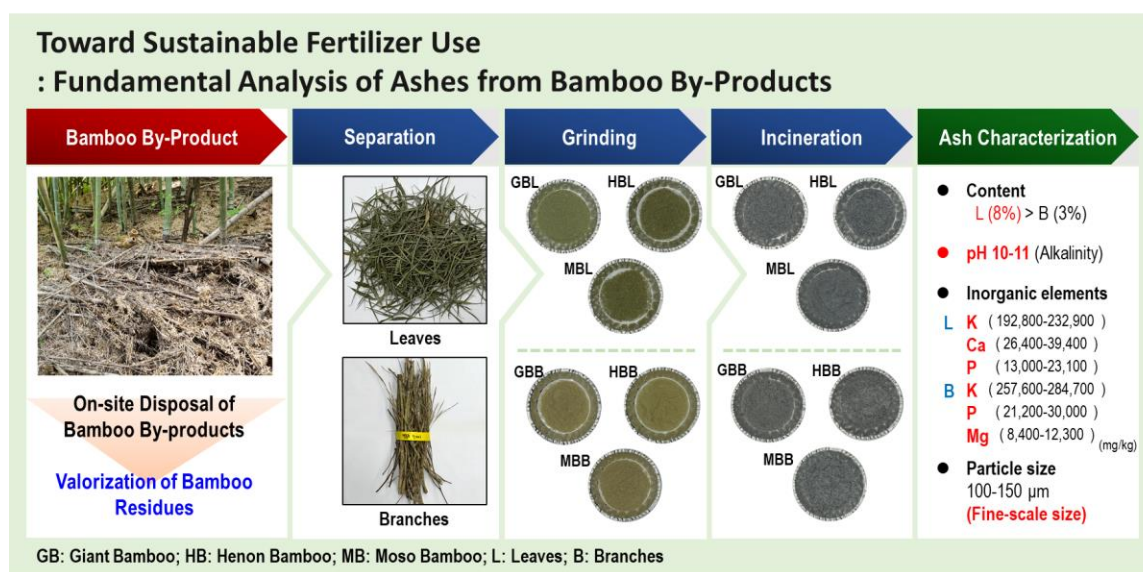
Toward Sustainable Fertilizer Use: Fundamental Analysis of Ashes from Bamboo By-Products

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GRAPHICAL ABSTRACT



Toward Sustainable Fertilizer Use: Fundamental Analysis of Ashes from Bamboo By-Products

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Bamboo is increasingly recognized as a sustainable biomass resource, supporting the global transition toward renewable raw materials for construction, landscaping, pulp and cellulose production, and high-performance bio-composites. However, intensive harvesting and processing leave behind substantial quantities of leaves, branches, and stem tips that are typically left in the field or incinerated, undermining the material's overall environmental benefits. Valorizing these by-products is therefore essential to closing the bamboo value loop, yet systematic data on their composition and reuse options remain limited. To address this gap, this work examined the chemical compositions of the by-products (*i.e.*, leaves and branches) of three bamboo species native to Korea —Giant Bamboo (*Phyllostachys bambusoides*), Henon Bamboo (*P. nigra*), and Moso Bamboo (*P. edulis*)—and characterized the ashes obtained after controlled combustion. All ashes were strongly alkaline (pH 10 to 11) and exceptionally rich in plant-essential nutrients (K, Ca, Mg and P). This is particularly significant, as it is the first study to demonstrate that bamboo by-product ash is a nutrient-dense material with inherent liming properties, making it suitable for use as a fertilizer or soil amendment. These findings lay an important foundation for the future agricultural and industrial utilization of bamboo residues.

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Keywords: Bamboo leaf ash; Bamboo branch ash; Korean bamboo by-products; Ash composition; *Phyllostachys*

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INTRODUCTION

Biomass has been widely recognized as a renewable energy source with significant potential to replace fossil fuels (Demirbas *et al.* 2009). Biomass resources include short-cycle wood, agricultural wastes, and herbaceous plants (Vassilev *et al.* 2010). Plants account for around 80% of the total biomass on Earth, and it is estimated that plants are the dominant kingdom in terms of biomass with a share of about 90% (Bar-On *et al.* 2018). Of these, wood-based biomass has limitations as a stable resource due to its higher demand (Ajani 2011), limited supply, high cost, and environmental regulations (Cubbage *et al.* 2010). Bamboo, a non-wood forest product, has recently gained global attention as an alternative and versatile biomass source.

Bamboo grows and develops rapidly (Xu *et al.* 2011), has a short harvesting cycle (Emamverdian *et al.* 2020), and exhibits excellent adaptability to a wide range of climate conditions, enabling it to be an appropriate renewable biomass source (Vogtländer *et al.* 2010). It is also low in cost compared with wood (Chaowana *et al.* 2013) and is regarded

as an alternative resource to wood owing to its high carbon sequestration capacity (Loreto *et al.* 2002). Because of these characteristics, research on bamboo utilization has gained momentum worldwide. Recently, a Kangwon National University research team has been accelerating research on the utilization of bamboo stems and by-products from the genus *Phyllostachys* (Kim *et al.* 2023, 2024; Kwon *et al.* 2025).

Currently, 19 bamboo species across five genera are distributed throughout approximately 24,111 ha of bamboo forests in South Korea. Among these, the species with high industrial utilization value are the giant bamboo (*Phyllostachys bambusoides*, occupying 6,023 ha), Henon bamboo (*Phyllostachys nigra*, 6,175 ha), and moso bamboo (*Phyllostachys edulis*, 291 ha) (Jeon *et al.* 2018). In South Korea, bamboo stems are applied for various purposes such as landscaping and as building materials, pulp, and charcoal, and they are also used in traditional food culture, such as for steaming rice and refining liquor (Gan *et al.* 2022). In other countries, bamboo is being utilized in industries related to textiles, building materials, and boards (Nguyen *et al.* 2012), and recent applications of bamboo stems and fibers as biocomposites (Khalil *et al.* 2012; Xu *et al.* 2023) and reinforcements have been reported (Jayanetti *et al.* 2008; Yadav *et al.* 2021). In the USA, a bicycle made of bamboo stems has even been demonstrated (Emamverdian *et al.* 2020).

However, as mentioned above, most industries mainly use bamboo stems, resulting in the generation of a large amount of bamboo by-products, including barks, leaves, branches, and tips (Lin *et al.* 2016). Among these, bamboo leaves in particular contain an abundance of various bioactive substances, including flavonoids, polysaccharides, amino acids, and phenolic acids, which have been researched for their potential applications in pharmacology and medicine (Shen *et al.* 2022). Recent studies have reported that bamboo leaves and shoots have antioxidative, anti-osteoporosis, antiviral, antibacterial, and anti-inflammatory effects, making them highly applicable as herbal medicines and functional food ingredients (Cheng *et al.* 2023; Huang *et al.* 2024). Bamboo leaf extract has also been reported to exhibit antidiabetic activity through its protective effect on pancreatic β -cells (Xu *et al.* 2017). Zhang *et al.* (2022) produced carboxymethyl cellulose from bamboo branches and tips. Additionally, research on the industrial applicability of bamboo by-products has been growing.

In a previous study, the authors' research group incinerated some of the by-products collected from a bamboo forest site (Geoje in Gyeongsangnam-do, South Korea) and analyzed their ashes, wherein various types of inorganic elements were found (Kwon *et al.* 2025). Bamboo has an approximately 2 to 3 times higher mineral content than that in wood (Huang *et al.* 2014). De Moraes *et al.* (2024) suggested that bamboo leaf ash could serve as a pozzolanic material to enhance mechanical performance of fiber cement for construction use. Furthermore, utilizing the ash from these by-products reduces the need for commercial fertilizers, counteracts acidification, and provides a solution to potential waste disposal issues (Zhang *et al.* 2002). With the high potential applicability of bamboo ashes suggested by these studies, basic research on the ash characteristics is warranted to verify the high value of bamboo by-products for further applications.

Therefore, in this study, the elemental compositions and particle sizes of the ashes of by-products (leaves and branches) from three representative bamboo species native to Korea were analyzed to establish basic data that will serve as a reference source for future exploration of the applicability of under-utilized bamboo by-products. In particular, this study focused on analyzing the characteristics of ash with an emphasis on its on plant growth promotion and its potential agricultural applicability.

EXPERIMENTAL

Materials

Giant bamboo (*Phyllostachys bambusoides*), Henon bamboo (*Phyllostachys nigra*), and moso bamboo (*Phyllostachys edulis*), all native to Korea, were used in this study. Samples were collected from 2- or 3-year-old trees grown at the Gajwa Forest experimental plot of the Forest Biomaterials Research Center in Jinju (Gyeongsangnam-do, South Korea; 35° 10' 1" north latitude, 128° 6' 23" east longitude). The leaves and branches were first sufficiently dried at ambient temperature and then separately ground to a 40-mesh size using a grinder (Pulverisette 15 Cutting Mill, Fritsch, Idar-Oberstein, Germany) (Fig. 1).

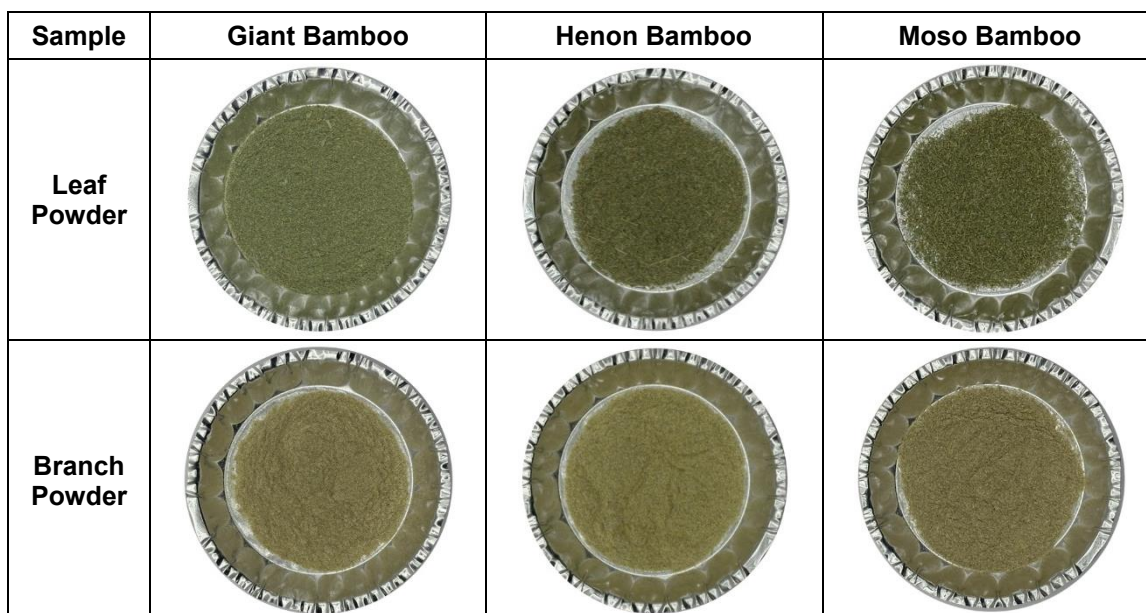


Fig. 1. Leaf and branch powders of three bamboo species

Chemical Compositional Analysis of the Bamboo By-Products

The chemical compositions of the bamboo leaves and branches were analyzed according to the procedures of the National Renewable Energy Laboratory Analytical (Sluiter *et al.* 2005a, 2005b, 2008). The percentage moisture content of each by-product was calculated based on its dry moisture content.

Ash content

The ash of each by-product was obtained by burning 3 g of the specific plant part at 575 °C for 15 h in an electrical muffle furnace (DMF-4.5, Lab House, Pocheon, South Korea)(Fig. 2). The ash remaining in the crucible after burning was weighed, and the ash content was then calculated using Eq. 1.

$$\text{Ash content (\%)} = \frac{\text{Weight of the residue in the crucible}}{\text{Weight of the dry sample}} \times 100 \quad (1)$$

Extractive contents

In brief, 3 g each of the leaf and branch powders of the three *Phyllostachys* species was separately extracted with ethanol–benzene (1:2, v/v) for more than 6 h in a Soxhlet extractor. The extract was then concentrated using a rotary evaporator. Subsequently, the

extractives were dried at 105 °C in a drying oven to a constant weight and then weighed to determine their content.

Lignin content

Extractive-free samples of leaves and branches (3 g each) were used for determining their lignin contents. For analysis of Klason lignin, 3 mL of 72% sulfuric acid was added to each degreased sample, and the mixture was incubated at 30 °C in a constant-temperature water tank for 1.0 h. Subsequently, after the sulfuric acid concentration had been adjusted to 4% using distilled water, the mixture was incubated in an autoclave at 121 °C for 1.0 h and then subjected to vacuum filtration using a glass filter. The Klason lignin obtained by filtration was dried thoroughly in a 105 °C desiccator and then weighed. The acid-insoluble lignin content was calculated using Eq. 2.

$$\text{Acid-insoluble lignin content (\%)} = \frac{\text{Weight of the residue on the glass filter}}{\text{Weight of the dry sample}} \times 100 \quad (2)$$

To analyze the content of acid-soluble lignin, the absorbance of the filtrate was measured with a UV-visible spectrometer (Optizen Pop-S spectrometer, KLab, Daejeon, South Korea). The sample was diluted so that the absorbance at 205 nm wavelength can be in the range of 0.2 to 0.7. The acid-soluble lignin content was calculated using Eq. 3.

$$\text{Acid-soluble lignin content (\%)} = \frac{A_{UV} \times V_{\text{filtrate}} \times \text{Dilution}}{\epsilon \times W_{\text{OD sample}}} \times 100 \quad (3)$$

where A_{UV} is the average absorbance of the filtrate at 205 nm wavelength, V_{filtrate} is the volume of the filtrate (mL), ϵ is the absorbance coefficient (110 L/g·cm), and $W_{\text{OD sample}}$ is the weight of the oven-dried sample (g).

Holocellulose content

Holocellulose was obtained according to the Wise method using sodium chlorite and glacial acetic acid (Du *et al.* 2016; Park *et al.* 2017; Álvarez *et al.* 2018). The extractive-free sample was treated with distilled water, sodium chlorite, and glacial acetic acid, and the mixture was stirred in a water bath at 80 °C. After the reaction, the residue was filtered through a glass filter to collect the holocellulose, and its content was calculated using Eq. 4.

$$\text{Holocellulose content (\%)} = \frac{\text{Weight of the residue on the glass filter}}{\text{Weight of the dry sample}} \times 100 \quad (4)$$

Elemental analysis

The elemental carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) contents in the samples were analyzed using the Dumas method. In brief, the samples were combusted in the presence of O₂ to ionize the constituent elements, which were then oxidized to H₂O, CO, CO₂, N₂, NO, NO₂, SO₂, and SO₃ in an oxidation reactor. Subsequently, NO and NO₂ were reduced to N₂ and likewise SO₃ to SO₂ in a reduction reactor, and CO was oxidized back to CO₂. Finally, the generated gases were separated on a gas chromatography column under a carrier gas (helium), and the thermal conductivity difference was calculated (Lee *et al.* 2012). Additionally, the content of organic elements was analyzed by injecting approximately 1.0 mg of the sample into an elemental analyzer (EA3000, Eurovector, Redavalle, Italy).

Characterization of the Bamboo By-Product Ashes

Figure 2 depicts the ashes obtained in the experiment described above. These ashes were characterized to determine their agricultural applicability.

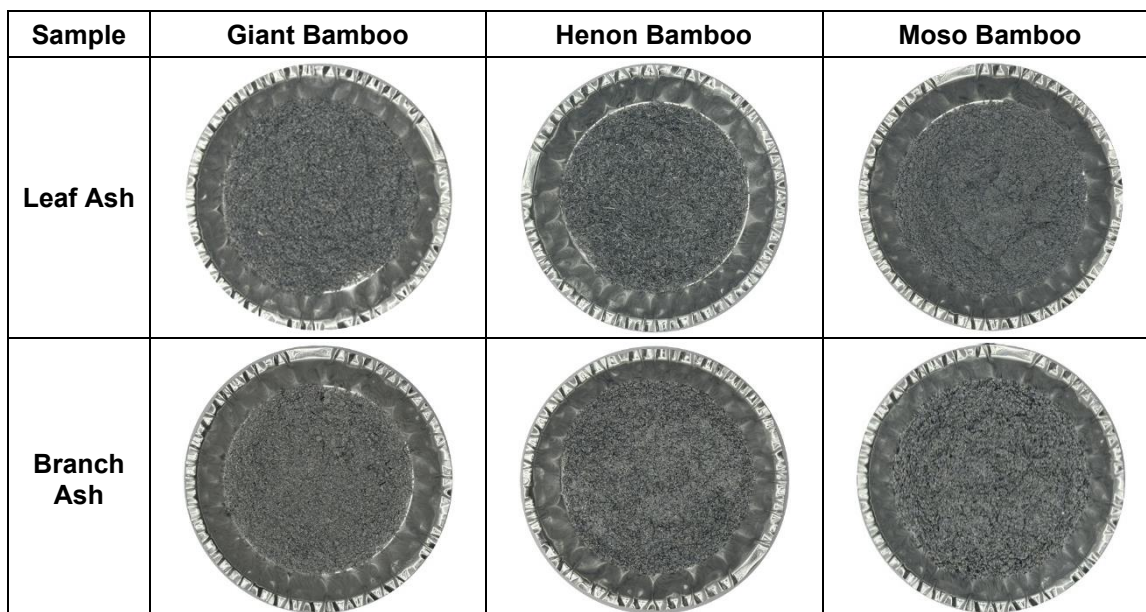


Fig. 2. Leaf and branch ashes of three bamboo species

pH

The ash samples from leaf and branch were separately diluted with distilled water at mixing ratios (ash:water, w:w) of 1:500, 1:1000, and 1:10,000. After filtering each solution to prevent ash particles from affecting the measurement, the pH of each solution was measured at 25 °C using a pH meter (Orion Star A211, Thermo Fisher Scientific, Waltham, MA, USA).

Inorganic elements

The composition of inorganic elements such as potassium (K), calcium (Ca), iron (Fe), manganese (Mn), magnesium (Mg), and sodium (Na) in the leaf and branch ashes were determined using inductively coupled plasma mass spectrometry (PlasmaQuant MS Elite, Analytik Jena, Germany).

Particle size distribution

To determine whether the different ashes can be utilized in various fields, an analysis of their particle size distribution is essential. This was accomplished using a particle size distribution meter (Mastersizer 3000, Malvern Pananalytical, Malvern, UK). The particle size distribution was measured in the range of 0.01 to 3500 µm using the wet method by dispersing the ash sample in ethanol.

RESULTS

Chemical Composition

Table 1 shows the chemical composition and contents of the by-products of the three *Phyllostachys* species, which are the basis for determining how they can be utilized. The Analysis of Variance (ANOVA) on the chemical composition and contents (Table 1) showed significant differences on the chemical composition and contents content within the *Phyllostachys* species. The ash content of the leaves was more than twice that of the branches, regardless of the *Phyllostachys* species, likely because leaves absorb a large amount of nutrients during growth and therefore have a much higher ash content than stems and branches do (Vassilev *et al.* 2010). Additionally, the proportions of ash in giant bamboo and Henon bamboo were higher than that in moso bamboo.

The extractive content of the leaves was also more than twice that of the branches, with no difference between the *Phyllostachys* species. Kim *et al.* (2001) reported a higher content of extractives in leaves than in stems, which was consistent with the findings of this study. Based on these results for the leaves, one can assume that a stepwise approach of ashing the residue after pre-extraction of the effective active ingredients of leaves is necessary for ash utilization.

By contrast, the Klason lignin content was relatively higher in the branches than in the leaves. The acid-soluble lignin content in bamboo stems is generally between 0.9% and 2% (Jiang *et al.* 2015; Maulana *et al.* 2020) but was particularly high in the leaves in this study.

The holocellulose content ranged from 60% to 70%, with the highest values observed in biant bamboo: 65.7% in the leaves and 70.3% in the branches. Regardless of bamboo species, the holocellulose content was consistently higher in the branches. This may be attributed to the structural role of the branches which similar to the culms, contain a higher proportion of fibrous tissues due to their function in supporting the plant body.

Table 1. Chemical Compositions of the By-Products of Three Bamboo Species

(%)	Giant Bamboo		Henon Bamboo		Moso Bamboo	
	L	B	L	B	L	B
Ash	8.05 ^a ± 0.06	3.43 ^c ± 0.07	8.08 ^a ± 0.05	3.07 ^d ± 0.12	5.70 ^b ± 0.01	2.51 ^e ± 0.02
Extractives	6.69 ^a ± 0.86	3.12 ^b ± 0.19	6.64 ^a ± 0.98	3.25 ^b ± 0.26	7.34 ^a ± 0.52	3.04 ^b ± 0.36
Total Lignin	25.32 ± 1.24	23.65 ± 2.27	26.82 ± 0.61	27.49 ± 1.05	27.20 ± 1.81	29.56 ± 1.83
Klason Lignin	19.63 ^b ± 0.70	22.28 ^a ± 2.27	21.47 ^b ± 0.57	25.76 ^a ± 0.97	20.86 ^b ± 1.77	28.11 ^a ± 1.83
Soluble Lignin	5.68 ^{ab} ± 1.01	1.37 ^c ± 0.11	5.35 ^b ± 0.21	1.72 ^c ± 0.40	6.35 ^a ± 0.39	1.45 ^c ± 0.05
Holocellulose	65.73 ^b ± 1.44	70.32 ^a ± 0.72	61.03 ^d ± 1.14	64.76 ^{cd} ± 0.26	62.88 ^c ± 1.71	65.35 ^{cd} ± 0.59
L: Leaves; B: Branches; Values were expressed as mean ± standard deviation (n=3). Values bearing different superscripts in the same line are significantly different at p<0.05 by Duncan's multiple range test (a>b>c>d>e).						

The results of the organic elemental analysis are summarized in Table 2. All samples contained C, N, H, and O elements. Regardless of the bamboo species, the N-content in the leaves was approximately two times higher than that in the branches. The N-content of typical biomass ranges from 0.1% to 12% (Vargas-Moreno *et al.* 2012) and that of wood is approximately 0.3%, thus the content in bamboo by-products is confirmed to be relatively higher (Rusch *et al.* 2021).

By contrast, the O-content was lower in the leaves than that in the branches. In particular, the branches of moso bamboo showed the highest O-content (48.24%) and C-content (46.67%), whereas the leaves of giant bamboo showed the lowest O-content (40.14%) and C-content of 42.03%. Organic S was not detected because its content in the by-products was less than 1%.

Table 2. Organic Elemental Compositions of the By-Products of Three Bamboo Species

Element (%)	Giant Bamboo		Henon Bamboo		Moso Bamboo	
	L	B	L	B	L	B
C	42.03	43.96	43.98	45.89	44.28	46.67
N	2.72	0.85	2.78	0.88	3.11	0.91
H	5.44	5.67	5.65	5.64	6.07	5.69
O	40.14	45.69	41.82	46.21	42.42	48.24
L: Leaves; B: Branches						

No significant differences among the three bamboo species were found in terms of their chemical compositions, with all generally exhibiting high sugar contents in the branches, and high extractive and ash contents in the leaves. Furthermore, all three species were found to be rich in C- and O-contents. Based on these results, one can assume that potential usage and applications of the active ingredients can be found by confirming the compositions of the specific by-products of the three species.

Characterization of the Ashes of the Bamboo By-Products

pH

The average pH of the ashes was measured after mixing 0.1 g of the sample with distilled water at dilution ratios of 1:500, 1:1000, and 1:10,000 (w:w) (Table 3). On average, moso bamboo showed the highest pH value (~pH 11) in its branch ash compared with the other samples. No significant differences in pH values were found regardless of bamboo species and plant parts. Overall, the pH of the ashes derived from by-products ranged between 10.1 and 11.4, indicating their alkalinity. Kaima *et al.* (2023) reported that when the dilution ratio of wood ash and distilled water was 1:1900, the pH of the ash was 12.2, and when the ratio was 1:900, the pH was 12.5, which was higher than the pH values obtained in this study.

Table 3. pH Values of the By-Product Ashes from Three Bamboo Species

pH	Giant Bamboo		Henon Bamboo		Moso Bamboo	
	L	B	L	B	L	B
1:500	11.35	10.85	11.10	10.92	10.81	11.42
1:1000	11.05	10.71	10.90	10.87	10.74	11.13
1:10,000	10.08	10.25	10.16	10.13	10.36	10.44
L: Leaves; B: Branches						

Contents of inorganic elements

Because the inorganic elemental compositions of ashes derived from biomass varies greatly from material to material and even within a particular material type, the characterization and evaluation of their inorganic contents are necessary to determine their applicability in the agricultural sector. The inorganic elemental compositions of the by-product ashes are listed in Table 4.

Table 4. Inorganic Elemental Compositions of the Ashes of Bamboo By-Products

Elemental Content (mg/kg)	Giant Bamboo		Henon Bamboo		Moso Bamboo	
	L	B	L	B	L	B
Potassium (K)	192,858.57	273,761.08	127,316.00	257,662.45	232,939.30	284,759.52
Calcium (Ca)	39,480.12	6,796.45	32,349.26	7,139.37	26,479.19	3,975.17
Phosphorus (P)	17,668.15	30,071.46	13,090.46	21,298.76	23,181.98	29,703.49
Magnesium (Mg)	13,692.44	8,487.82	13,415.19	12,335.94	13,496.14	12,062.06
Sulfur (S)	6,832.81	9,957.60	8,368.49	12,638.01	4,042.23	6,879.64
Manganese (Mn)	3,174.51	905.18	2,962.09	1,298.86	1,451.92	660.01
Iron (Fe)	879.54	495.28	948.40	553.68	1,221.49	532.23
Sodium (Na)	780.81	1,051.45	782.02	1,461.98	889.59	1,590.24
Silicon (Si)	584.80	1,647.22	239.31	515.38	365.50	1,165.81
Aluminum (Al)	495.59	880.91	452.54	1,222.81	415.42	1,034.18
Strontium (Sr)	135.23	32.22	136.87	54.93	219.57	42.63
Boron (B)	88.89	15.79	66.33	18.23	88.36	16.91
Titanium (Ti)	3.47	6.28	4.43	3.99	7.66	8.55
Molybdenum (Mo)	3.01	2.85	2.05	2.76	1.01	2.08
Cobalt (Co)	0.46	0.60	0.43	0.44	0.34	0.40
Gallium (Ga)	0.13	0.14	0.12	0.20	0.13	0.19
L: Leaves; B: Branches						

Annual or fast-growing crops (herbaceous plants, small branches, and leaves) contain relatively high levels of highly mobile K, P, and Mg contents compared with wood and large stems (Vassilev *et al.* 2010). This study revealed that the leaves of all three *Phyllostachys* species contained more than 100,000 mg/kg of K, whereas the branches contained more than 250,000 mg/kg of this element. The leaves contained an average of 32,800 mg/kg of Ca, which was higher than the amount found in the branches. The Mg content was on average 12,200 mg/kg. The inorganic S-content was lowest in moso

bamboo's leaves and highest in Henon bamboo's branches. According to Goyal *et al.* (2014), leaves have an abundant contents of Ca, Mg, and Mn but a low amount of P, K, and Na. Antonkiewicz *et al.* (2020) found that biomass ash contained the highest amounts of P, K, and Mg. In this study, high amounts of K, Ca, and P were found in the by-product ashes, suggesting that native soil and plant species could be highly affected by the contents of these elements.

The application of bamboo ash to promote plant growth is influenced by its heavy metal content. In this study, the analysis of heavy metals confirmed that concentrations did not exceed the established safety thresholds (Fertilizer legal standard guideline in Rural Development Administration).

Particle size distribution

The particle sizes of the ashe samples were measured to specifically determine the applicability of bamboo by-product ashes as fertilizers, since the particle size of fertilizers is one of the factors that influence the nutrient absorption between soil and plants (Saentho *et al.* 2022). Particle size was analyzed in the size range of 0.01 to 3500 μm .

In the by-product ashes of all three *Phyllostachys* species, particles larger than 1000 μm were not distributed. The leaf ash of moso bamboo exhibited a wider particle size distribution than those of the other *Phyllostachys* species (Fig. 3). With regard to the branch ashes, those of giant bamboo and moso bamboo had similar particle size distribution patterns, with the distribution of the approximately 100 μm particles being the highest (Fig. 4).

In Fig. 5, the particle size distribution is presented by dividing the size fractions into the following ranges: F1 (0 to 63 μm), F2 (63 to 125 μm), F3 (125 to 250 μm), F4 (250 to 500 μm), and F5 (500 to 1000 μm). This range classifications was based on the particle size range of volcanic ash (pyroclastic materials), which is 63 to 125 μm in size (Ersoy 2010). Values less than 5% were not indicated. In the by-product ashes of all *Phyllostachys* species, few particles belonging to F5 were found and less than 15% of the particles belonged to F4. However, the leaves of Henon bamboo had the highest proportion (~37%) of F4 particles. Giant bamboo had the highest proportion of F3 particle and moso bamboo showed the highest proportion of very fine-sized particles (F1). The ash of giant bamboo, Henon bamboo, and moso bamboo leaves contained 20.2%, 5.9%, and 45.9% of fine particles (less than 75 μm), respectively, while the twigs contained 34.6%, 58.8%, and 43.4% of fine particles, respectively. The highest concentration of fine particles was found in the ash of Henon bamboo branches (58.8%) which contained more than twice as many fine particles as wood ash (25.4%) (Grau *et al.* 2015).

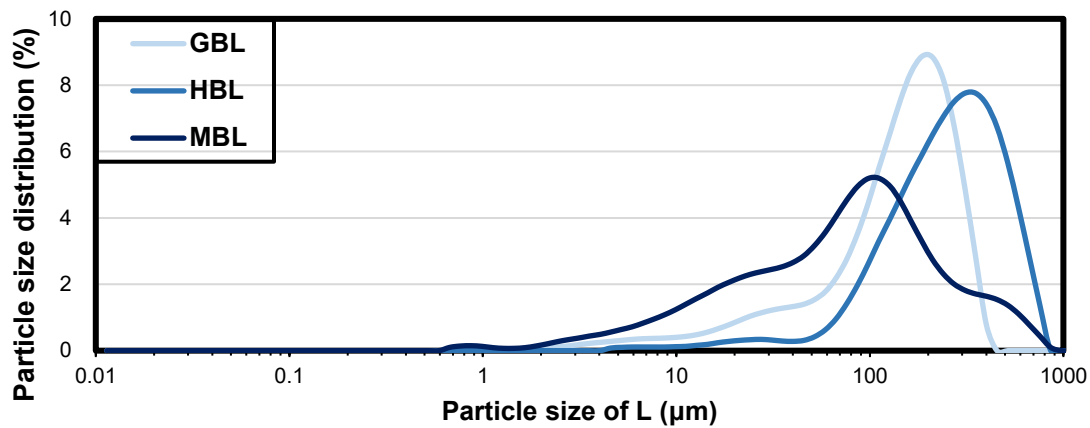


Fig. 3. Particle size distribution of the leaf (L) ashes of three bamboo species. GB: giant bamboo; HB: Henon bamboo; MB: moso bamboo

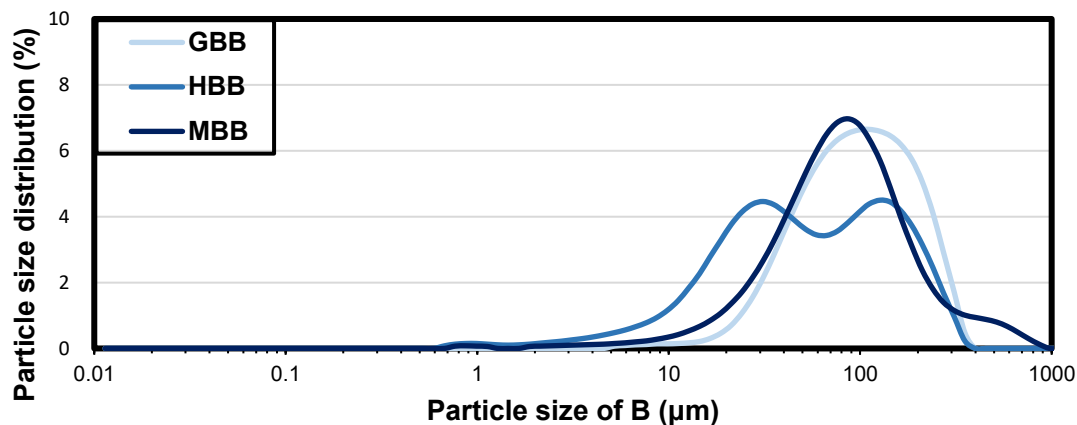


Fig. 4. Particle size distribution of the branch (B) ashes of three bamboo species. GB: giant bamboo; HB: Henon bamboo; MB: moso bamboo

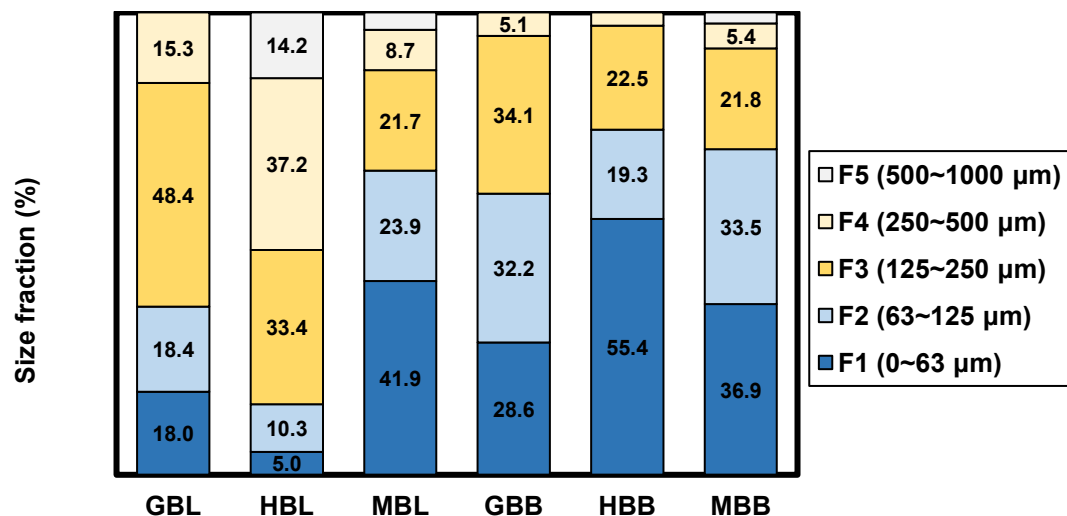


Fig. 5. Particle size distribution of leaf (L) and branch (B) ashes of three bamboo species. GB: giant bamboo; HB: Henon bamboo; MB: moso bamboo

Table 5. Physical and Mechanical Properties of the By-Product Ashes from Three Bamboo Species

	Giant Bamboo		Henon Bamboo		Moso Bamboo	
	L	B	L	B	L	B
d_{10} (μm)	32.9	39.1	101.0	13.7	12.1	28.9
d_{50} (μm)	161.0	102.0	278.0	56.6	84.7	85.9
d_{90} (μm)	289.0	233.0	567.0	209.0	320.0	229.0
Specific Surface Area (m^2/kg)	97.8	81.9	40.4	246.7	240.4	131.5
L: Leaves; B: Branches; d_{10} : grain diameter at 10%; d_{50} : grain diameter at 50%; d_{90} : grain diameter at 90%						

Table 5 further summarises the ashes' physical attributes. Ten percent of the particle volume of the giant bamboo leaf ash was greater than 32.9 μm , and 90% of it was less than 289 μm , with a median particle diameter of 161 μm . The median particle diameter of the leaf ash of Henon bamboo was 278 μm , whereas that of moso bamboo was 84.7 μm . The median particle diameter of bamboo leaf ash was 20.0 μm in a previous study (Moraes *et al.* 2019), whereas it was larger in this present study.

High specific surface area values indicate a high degree of irregularity in particle shape and porosity of the surface (Cheah and Ramli 2011). The specific surface area value of bamboo ash was significantly lower than that of wood ash (12,000 to 14,000 m^2/kg), indicating that it is easy to disperse and has low viscosity, making it easy to process (Grau *et al.* 2015).

DISCUSSION

The high nitrogen (N) content observed in bamboo leaves provides compelling evidence for their utility as composting feedstocks. Nitrogen, a key element driving microbial activity during organic matter decomposition, directly influences the speed and efficiency of the composting process (Zhang *et al.* 2016). In this study, the N content in bamboo leaves was found to be two to three times higher than that in branches, a pattern consistent across all three *Phyllostachys* species examined. This consistent leaf > branch trend suggests an evolutionarily conserved nutrient allocation pattern in bamboo, possibly linked to leaf function in photosynthesis and metabolic activity. Such findings support the targeted use of bamboo leaves in compost formulations, particularly in nitrogen-deficient agricultural regions. Furthermore, the integration of bamboo leaf biomass into composting systems could reduce the reliance on synthetic nitrogen additives, aligning with low-input and organic farming principles.

In addition to composting applications, the chemical characteristics of bamboo ash strongly support its function as a soil amendment. The ashes exhibited high pH values (between 10 and 11), confirming their alkaline nature. This is a critical property when considering soil amelioration in acid-prone regions, such as tropical and subtropical areas with high rainfall and leaching (Zajac *et al.* 2018). Unlike synthetic lime materials (*e.g.*, calcium carbonate), bamboo ash offers the dual function of de-acidification and nutrient supply. This multifunctionality positions bamboo ash as a circular solution that not only

disposes of biomass waste but also regenerates degraded soils. Importantly, previous research has cautioned against the over-application of highly alkaline amendments due to potential disruption of soil microbial communities and nutrient imbalances (Bramryd and Fransman 1995; Park *et al.* 2005). However, the moderate pH range of bamboo ash, as compared to wood ash (pH > 12), may offer a safer, more balanced alternative with minimal risk of over-liming.

From a plant nutrition standpoint, the high concentrations of macronutrients in bamboo ashes—particularly potassium (K), calcium (Ca), phosphorus (P), and magnesium (Mg)—are noteworthy. These elements play synergistic roles in cell wall integrity, osmotic regulation, root development, and energy transfer within plants (Marschner 2012). In particular, the exceptional K content (>250,000 mg/kg in branches) far exceeds levels reported for many agricultural residues and may serve as an alternative to commercial potash-based fertilizers. Notably, the high P content in bamboo ash is especially relevant in regions where phosphate rock reserves are limited or geopolitically constrained (Antonkiewicz *et al.* 2020). Thus, valorizing bamboo ash as a phosphorus source can contribute to long-term fertilizer security and reduce dependency on finite mineral resources.

The relevance of particle size distribution to ash functionality is another critical aspect. As demonstrated in this study, most bamboo ashes fell within the particle size range of 25 to 1000 μm , which overlaps with the optimal range for fertilizer efficiency identified in prior agronomic studies (Sander *et al.* 1988; Schiemenz and Eichler-Löbermann 2010). Fine particles (<75 μm), which were particularly abundant in moso and Henon bamboo ashes, are more readily absorbed into soil micro-pores, facilitating faster dissolution and ion exchange. However, these same fine particles may pose handling challenges, such as airborne dust or uneven field application. Future work may consider granulation or pelletization technologies to improve ash manageability and reduce environmental dispersal risks, while maintaining or enhancing its agronomic performance.

Furthermore, the ecological implications of bamboo ash application warrant deeper consideration. Returning mineral-rich ash to the soil can be viewed as closing the nutrient loop in bamboo production systems, particularly in agroforestry or intercropping contexts. In addition to enhancing soil fertility, such circular strategies reduce the need for external inputs, mitigate nutrient runoff, and promote long-term soil health. There is also emerging evidence that the application of biomass ashes can alter rhizosphere microbial composition and function, opening new avenues for integrated nutrient–microbe management strategies.

CONCLUSIONS

1. This study has provided fundamental insights into the physicochemical characteristics of bamboo by-product ashes and their potential for agricultural applications. The ashes exhibited fine particle sizes, high alkalinity (pH 10 to 11), and abundant concentrations of essential inorganic nutrients such as K, Ca, Mg, and P.
2. These properties suggest that bamboo ashes could serve a dual role as both liming agents and nutrient carriers, particularly beneficial for acidic or nutrient-deficient soils. However, the introduction of such materials into forest or agricultural ecosystems must be approached with caution, as they may also alter soil microbiota or ecological functioning. Therefore, further research is needed to assess their actual effects on plant

growth, soil health, and long-term sustainability.

3. The integrated valorization of bamboo by-products—composting of leaves and ash-based soil amendments—represents a promising pathway for low-carbon, regenerative agriculture.
4. Future studies should focus on field-scale trials, microbial interaction analyses, and techno-economic evaluations of formulation methods such as pelletization to ensure safe, scalable, and effective implementation within circular bioeconomy frameworks.

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