Received: 24 June 2022 | Revised: 9 August 2022 | Accepted: 23 August 2022

DOI: 10.1111/gcbb.13002

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access

WILEY

RESEARCH ARTICLE

Effect of tree species on the elemental composition of wood ashes and their fertilizer values on agricultural soils

Michael O. Asare[1] | **Michal Hejcman**[2]

[1]Department of Agroenvironmental Chemistry and Plant Nutrition, Faculty of Agrobiology, Food, and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic

[2]Faculty of Environment, Jan Evangelista Purkyně University in Ústí nad Labem, Ústí nad Labem, Czech Republic

Correspondence
Michal Hejcman, Faculty of Environment, Jan Evangelista Purkyně University in Ústí nad Labem, Pasteurova 3544/1, CZ400 96, Ústí nad Labem, Czech Republic.
Email: michal.hejcman@ujep.cz

Funding information
MA was founded by European Regional Development project CZ.02.1.01/0.0/0.0/16_019/0000845, MH was founded by Czech Science Foundation by project GA21-25440S: CZ.02.1.01/0.0/0.0/16_019/0000845, GA21-25440S.

Abstract

Wood ashes obtained from household heating and cooking are often applied to home gardens and arable fields by farmers. The effect of tree species and their locations on the elemental composition of wood ashes derived from domestic cooking and heating is unknown. The study aimed to discover the fertilizer values of wood ashes obtained from *Betula pendula*, *Carpinus betulus*, *Fagus sylvatica*, *Larix decidua*, *Picea abies*, *Pinus sylvestris*, *Quercus robur*, and *Tilia cordata* from two different localities, Hlinsko and Mšec, Czech Republic. The total element content in the ashes of dry wood samples (wood and bark) burnt at 460°C with a wood stove interfaced with a thermometer was determined using portable x-ray spectrometry. The content (in g kg^{-1}) of P (3.23–20.53), K (26.79–136.22), Ca (94.89–295.56), and S (2.97–11.75) in the ashes varies according to the tree species, locality, parent rock, and anthropogenic activities in the location of trees. Additionally, trace element contents ranged from 0.63–32.07 g Mn kg^{-1}, 0.34–4.6 g Fe kg^{-1}, 32.4–2062 mg Zn kg^{-1}, 47.61–193.09 mg Cu kg^{-1}, 3.99–21.53 mg Mo kg^{-1}, and 1.50–6.62 mg Se kg^{-1}. The pH of the ashes ranged from 8.71 to 11.54, suitable to alleviate soil acidity and a condition satisfying soil additive. A significant positive correlation between the contents of Cu, Sr, and Pb with the ashes of *Picea abies*, *Larix decidua*, *Pinus sylvestris*, and *Betula pendula* at Hlinsko is indicative of ancient anthropogenic activities input in the soil. The combustion of wood under home heating temperatures resulted in the concentration of most risk metal(loid)s, below permissible limits in agricultural soils. Application of wood ashes on arable fields requires considerable caution due to potentially toxic elements (Zn and Pb).

KEYWORDS

arable field, combustion temperature, macro element, risk element, total element, trace element, X-ray fluorescence spectrometry

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2022 The Authors. GCB Bioenergy published by John Wiley & Sons Ltd.

1 | INTRODUCTION

Wood ashes are often treated as waste in many households, neglecting their relevance in recent crops and herbage production when applied as fertilizers. Meanwhile, wood ashes served as a source of potash production and nutrients for plants during prehistory (Hejcman et al., 2011, 2013; Šmejda et al., 2017). For example, locations with ashy deposits of current arable fields on ancient localities are well characterized by high element contents (Asare, Apoh, et al., 2020), biomass growth, and crop yields (Hejcman et al., 2011).

Many studies on the elemental composition of wood ashes demonstrated wide variability in their contents due to different plant species, parts, and combustion temperatures (Huang et al., 1992; Semelová et al., 2008; Smołka-Danielowska & Jabłońska, 2022). The contents of soil nutrients, for example, P, Ca, K, Cu, and Zn, are often reported in different wood ashes, providing a basis for the recent use of wood ashes in some agricultural fields (Semelová et al., 2008; Wierzbowska et al., 2020). The high contents of Ca and K and sometimes Na provide the characteristic alkaline nature (pH 7.8–13.5) of wood ashes from many tropical (Adekayode & Olojugba, 2010; Asare et al., 2022) and European plant species (Campbell, 1990; Okmanis et al., 2016); hence, they are used to alleviate soil acidity.

Notably, the elemental composition of wood ashes is directly dependent on the parent rock, plant species, and anthropogenic activities in the locations of species (Asare et al., 2022). Therefore, wood ashes of the same tree species but different locations can differ in elemental compositions, while such studies are so far not well known. Additionally, burnt plant parts, for example, bark, wood, leaf, and root (Saarela et al., 2005), and combustion temperature remain important factors that significantly affect the content of specific elements (Zhou et al., 2021). For example, C, H, O, and S may volatilize at high temperatures >500°C (Naylor & Schmidt, 1986; Serafimova et al., 2011). Mineral substitutes are, therefore, recommended during the management of arable fields. Again, wood samples need no moisture content during burning to avoid incomplete combustion and generation of smoke, which contains many chemical compounds, such as carbon monoxide (CO), methane (CH_4), and hydrocarbons (Curkeet, 2011). However, complete combustion of wood produces mainly CO_2 (absorbed by plants) and H_2O but under different temperatures.

Besides the possibility of losing vital nutrients during the combustion process, the use of biomass ashes as soil fertilizer can potentially release toxic elements (e.g., As, Cd, Ni, and Pb) above allowable limits in soils and may relate to locations with emissions from metal smelting, long-term intensive fertilizer application (Lane et al., 2020; Obernberger et al., 1997). For example, emissions from metal smelting, fossil fuel combustion, and the spread of phosphate fertilizers are considered the cause of high levels of Cd in wood ashes (Narodoslawsky & Obernberger, 1996). Meanwhile, contaminated wood–combustion ashes with high levels of regulated environmental contaminants generally require only a basic level of treatment for utilization on agricultural soils. Plants possess different mechanisms of soil nutrient uptake. For example, some plants exhibit restrictive root–shoot translocation, making wood ashes obtained from the shoot less toxic to risk elements. Hence, the elemental compositions of wood ashes are a direct function of the plant genotype, uptake, translocation, and accumulation of elements by plants. Determination of elemental composition in the ash of leaves and stems was carried out to well-correlated nutrient uptake by plants with the nutrient content of the soil (Misra et al., 1993).

To determine the effects of anthropogenic activities on element contents in soils and tree species, we tried to establish a relationship between the elements in soils and wood ashes. Other important factors influencing the accumulation and depletion of elements in wood ashes include the condition of wood combustion and the treatment before burning (Liodakis et al., 2005). For example, decomposition and volatilization of $CaCO_3$ and CaO may occur during combustion. Some studies have shown that at temperatures of 350–450°C and 500–600°C, Ca/Mg hydroxides, and $CaCO_3$, respectively, occur (e.g., Liodakis et al., 2005; Sanders & Andrén, 1997), which may decrease between 800 and 1000°C. Thus, the solubility of minerals during combustion can result in volatilization.

The question which is still unsatisfactorily resolved is, are wood ashes from domestic heating and cooking suitable enough as fertilizers? These household wood ashes often are obtained at different temperatures. Hence, empirical analyzes are needed to confirm the suitability of such wood ashes as fertilizers in arable fields from an extreme variety of tree species. Additionally, the effect of species on the elemental composition of wood ashes from different localities is not well known.

As x-ray fluorescence spectrometry (XRF) has been sparingly used (Chand et al., 2009; Misra et al., 1993), we adopted this analytical approach as a reliable and cost-effective approach to determine the total element content of wood ashes.

As the fertilizer values of the homemade wood ashes are not studied, we determined the elemental composition of the ashes of *Betula pendula*, *Carpinus betulus*, *Fagus sylvatica*, *Larix decidua*, *Picea abies*, *Pinus sylvestris*, *Quercus robur*, and *Tilia cordata* from different localities in the Czech Republic.

In this study, we aim to answer the following research questions: (a) To what extent can different localities

influence the elemental composition of wood ashes of the same tree species? (b) What is the fertilizer value of wood ashes obtained from the combustion of commonly used European tree species? (c) Are wood ashes generated from home combustion temperatures of wood species suitable fertilizers for agricultural soils?

2 | MATERIALS AND METHODS

Eight (8) solid biomass fuelwoods were selected from two sites (Hlinsko and Mšec, Czech Republic; Figure S1) for this study, as commonly used species for domestic heating. Hlinsko is characterized by Palaeozoic metamorphic rock and Histic Stagnosol soil (Czech Geological Survey, 2012; Němeček & Kozák, 2005). The site has an altitude ranging from 550 to 670 m a.s.l. At Mšec, the soil is Luvic Cambisol on a Marlstone geological substrate (Němeček & Kozák, 2005), with an altitude of 480 m a.s.l.

2.1 | Location and sample collection

2.1.1 | Wood sampling

The reference names adopted for the sample fuelwoods are in Table 1. We collected samples of branches (wood and bark) of *Betula*, *Carpinus*, *Fagus*, *Larix*, *Picea*, *Pinus*, *Quercus*, and *Tilia* for both sites in August 2018. All samples were cut as log discs during forest felling or from living trees at the sites. The location of *Betula* from Hlinsko represented a visible relic of an abandoned graveyard from an ancient settlement. We collected four branch wood from each tree species per individual localities. Each branch of wood measured about 100 cm long, with a diameter from 20 to 30 cm: as firewood size used for heating households in the Czech Republic.

2.1.2 | Soil sampling

We collected soil samples in the surroundings of *Picea*, *Larix*, *Pinus*, and *Betula* at Hlinsko: locations marked with evidence of ancient human activities. To cover the variability of soil, we randomly collected four samples around each selected tree species. Each soil sample represented 10 sub-samples randomly collected and mixed into one representative sample per tree species. Soil samples from each stand were collected from the upper 10 cm depth using a soil probe (Purchhauer type, core diameter: 30 mm).

We collected 32 wood samples for each locality (Table 1), in addition to 16 soil samples only from the Hlinsko site.

TABLE 1 Names, distribution, and number of samples of selected tree species

Local name	Scientific name	Reference name	Distribution	Branch wood per site
Silver birch	*Betula pendula*	*Betula*	It occurs naturally throughout most of Europe up to central Siberia	4
European hornbeam	*Carpinus betulus*	*Carpinus*	The natural range extends from the Pyrenees to southern Sweden and eastwards to Iran. Widespread in central Europe	4
European beech	*Fagus sylvatica*	*Fagus*	The natural range extends from southern Scandinavia to Sicily, from Spain in the west to northwest Turkey in the east	4
European larch	*Larix decidua*	*Larix*	It occurs in the central and eastern mountains of Europe	4
Norway spruce	*Picea abies*	*Picea*	Dominates the Boreal forests in Northern Europe and the subalpine areas of the Alps and the Carpathian Mountains	4
Scots pine	*Pinus sylvestris*	*Pinus*	Found across Eurasia. The huge pine forests of Siberia are the largest stands	4
European oak	*Quercus robur*	*Quercus*	In Europe, found from Scandinavia to the Iberian Peninsula	4
Small-leaved lime	Tilia cordata	*Tilia*	Native to Europe	4
Total samples				32

2.2 | Sample preparation

Each branch wood sample was washed thoroughly with Ultrapure-deionized H_2O (18 Ω) to prevent dust and soil contact. The fresh wood samples were first dried in the open air in summer (avrg. temp. of 31°C and 44% air humidity) for 72 h.

Individual branch wood samples were chopped into small slides of 0.5 cm thick and then oven-dried for 3 days at 60°C to total desiccation: this contributes to complete and fast combustion. After, 500 g of each dried sample per species was burnt independently in a wood stove interfaced with a thermometer (manufactured by Mingle Development, Shen Zhen Co., Ltd. China) until complete combustion. The combustion temperature did not exceed 460°C. The ash samples were homogenized through a 0.1-mm sieve and put into labeled plastic bags.

All the soil samples were initially oven-dried for 48 h. After removal of plant materials and other debris, samples were ground and homogenized through a 2-mm sieve.

2.3 | Analytical methods

The total element compositions of the wood ashes and soil samples were determined with a portable ED-XRF (pXRF) analyzer manufactured by Delta Professional Olympus, Waltham, MA (USA). In both cases, the pXRF device was in mining mode (for wood ashes) and Geochem-mode for soils.

The pXRF was previously successfully used for the elemental analysis of wood ashes (Xing et al., 2016) and different types of soils (Canti & Huisman, 2015; Šmejda et al., 2017). The device measures the total or near-total contents of magnesium to uranium in different matrices.

Each sample measurement was in triplicate, the final value as the arithmetic average of the three results. The quality of the pXRF results was tested successfully by BAS Rudice Ltd. Company, Czech Republic (https://www.bas.cz/) on 55 reference materials (e.g., SRM 2709a, 2710a, 2711a, OREAS 161,164, 166, RTC 405, 408). The content of P, K, Ca, Mn, Fe, Zn, Cu, Sr, Rb, Al, Si, Mo, Zr, Se, As, Ni, and Pb were pertinent in this study as elements above the detection limit by the pXRF in all the samples. The contents of some elements were omitted from further analysis for either not detected or above the detection limit only in a few cases (e.g., Ag, Cd, Sn, Sb, Ni, and Ti).

We determined the pH (H_2O) in two replicates for all ash samples at a ratio (ash-water) of 1:2 using a Voltcraft PH-100 ATC pH meter (pH 212) manufactured by I & CS spol. sr. o. (Czech Republic).

2.4 | Quality control

The precision of the pXRF was assessed by comparing the data with the elemental composition obtained by standard analyses. The contents of the total elements of certified reference material (CRM, BCR—176R-fly ash) were extracted using the USEPA 3052 extraction procedure (International Organization for Standardization, USEPA, 1996) with an extraction mixture of 65% HNO_3, 36% HCl, and 38% HF.

Procedure: A mass of 0.25 g of fly ash was mineralized in a mixture of 9 ml HNO_3, 3 ml HCl and 1 ml HF and heated in a sealed 60 ml VWR® PTFE Jar on a hot plate at 150°C for 24 h. After 24 h, 1 ml of 30% of H_2O_2 again added to the sample and evaporated on a hot plate at 50°C for 24 h. The evaporated sample was diluted to 20 ml by 2% HNO_3 for 2 h and filtrated. Next, the content of elements was determined with an inductively coupled plasma–optical emission spectrometry (ICP–OES; 720 Series, Agilent Technologies Inc., USA) and obtained in triplicates. We analyzed with an emphasis on the total contents of P, K, Ca, Mn, Fe, Zn, Cu, As, and Pb. The elements were also determined using the pXRF, and a calibration curve was made for each element.

2.5 | Reliability of analytical methods

The overall recovery of Ni, Co, Fe, Cu, Zn, As, and Pb from the CRM using Aqua regia ICP-OES and the pXRF was >90% (Table 2a). Moreover, the comparison of the data obtained from the pXRF and *Aqua regia* ICP-OES revealed a strong linear correlation for P, K, Ca, Mn, Fe, Cu, Zn, Pb ($r = 0.60–0.99$, $p < 0.01$) except for As, with a negative correlation ($r = -0.25$, $p = 0.547$) (Table 2). The control test indicates that the pXRF has adequate precision for this study and offers a cost-effective approach for the elemental analysis of wood ashes.

2.6 | Data analysis

There was relatively homogeneity of variance among obtained data for the contents of elements in studied ashes and soils. Data for elemental contents of ashes and soil were tested with the Shapiro–Wilk W-test for normality and met the assumption for the use of parametric tests. Factorial ANOVA followed by post hoc comparison using the Turkey HSD test was applied to identify significant differences among elements in wood ashes from different localities. The relationship between obtained dataset by pXRF and *Aqua regia* ICP-OES and the content of elements in selected ashes and soils furthermore was evaluated using Pearson's correlation. We performed all

TABLE 2 (a) The recovery efficiency using pXRF and aqua regia ICP-OES of certified reference material (CRM-fly ash) relationship. (b) Correlation (Pearson's) between data obtained by aqua regia ICP-OES and pXRF

(a)

	Ni	Co	Fe	Cu	Zn	As	Pb
pXRF	119 ± 2.1	24.5 ± 1.41	13,414 ± 161	1088 ± 70.7	16,709 ± 140.7	56 ± 3.6	4954 ± 76.6
A.R. ICP-OES	117 ± 6	26.7 ± 1.6	13,100 ± 420	1050 ± 70	16,800 ± 200	54 ± 5	5000 ± 100
Recovery (%)	101	91.8	102.4	103.6	99.5	103.7	99.1

The recovery (mean value of element ÷ reference value) × 100 according to the Eurachem guide (Magnusson & Örnemark, 2014)

(b)

Parameter	P	K	Ca	Mn	Fe	Cu	Zn	As	Pb
Regression equation	$y = 0.9 + 0.9^*x$	$y = -3.08 + 1.05^*x$	$y = -33.32 + 1.09^*x$	$y = 1.99 + 0.89^*x$	$y = 0.28 + 0.91^*x$	$Y = 128 + 0.44^*x$	$y = 43.05 + 1.05^*x$	$y = 20.7 + 0.27^*x$	$y = 3.89 + 0.98^*x$
Correlation coefficient (r)	0.97	0.99	0.98	0.99	0.99	0.60	0.75	−0.25	0.96
p-value	<0.001	<0.001	<0.001	0.026	<0.001	0.011	0.03	0.547	<0.001

statistical analyses using STATISTICA 13.4 (www.statsoft.io).

3 | RESULTS

3.1 | Chemical composition of wood ashes

The statistical description of the pH[H_2O] and elemental composition of the studied ashes are in Table 3 and Figures 1–5. The pH value of the ashes under analysis was defined as alkaline, ranging from 8.71 to 11.54 (Table 3), indicating their suitability for highly acidic soils. There was a significantly negative relationship between pH and the content of S ($r = -0.27$, $p = 0.027$; Figure S2a) and vice versa with Ca ($r = 0.67$, $p < 0.001$; Figure S2b), which indicate that an increase S and Ca content reduces and increases pH of wood ashes.

There was a significant effect among the contents of macro (P, K, Ca, and S; Figure 1), trace (Mn, Fe, Zn, Cu, Al, Si, Rb, Sr, Mo, Zr, and Se; Figures 2–4), and risk (As and Pb; Figure 5) elements in the ashes of all the species among the localities. The contents of macro-elements in the ashes were significantly different among the species from the localities except for a few cases where the ashes from *Betula* (K), *Picea* (K), *Larix* (Ca), and *Tilia* (Ca) were similar in both sites (Figure 1). The contents of P in Hlinsko ranged from 6.85 to 20.53 g kg^{-1} and in Mšec, 3.23 to 7.62 g kg^{-1} (Figure 1a). The highest P content (20.53 g kg^{-1}) was in *Pinus* ash and the lowest, 3.23 g kg^{-1} in *Fagus*. The content of K was from 46.85 to 136.22 g kg^{-1} in Hlinsko and 26.75 to 66.94 g kg^{-1} in Mšec (Figure 1b). The highest content of K (136.22 g kg^{-1}) was in the ash of *Quercus* and the lowest (26.75 g kg^{-1}) was in *Tilia*. The Ca content ranged from 94.89 to 280 g kg^{-1} in Hlinsko and Mšec, 207.36 to 295.56 g kg^{-1} (Figure 1c). The highest Ca content (295.56 g kg^{-1}) was in *Carpinus* with the lowest (94.89 g kg^{-1}) in *Quercus*. The content of Ca was the highest compared to all the macro elements, which contributed to the high pH of the wood ashes. Among the macro elements, S recorded the least- 3.74 – 8.64 g kg^{-1} in Hlinsko and 3.7–12 g kg^{-1} in Mšec (Figure 1d). We recorded 11.75 g S kg^{-1} in *Pinus* and the lowest (2.97 g kg^{-1}) contents in *Quercus* from Mšec.

There was a significant effect on the content of Mn, Fe, Zn, and Cu among the ashes of the species in the localities (Figure 2). The Mn content ranged from 1.09 to 21.05 g kg^{-1} in Hlinsko and 0.63 to 32.07 g kg^{-1} in Mšec (Figure 2a). The highest Mn content (32.07 g kg^{-1}) was in the ashes of *Larix* and the lowest (0.63 g kg^{-1}) in *Tilia*.

Moreover, the Fe content ranged from 0.66 to 4.60 g kg^{-1} in Hlinsko and 0.34 to 4.09 g kg^{-1} in Mšec

TABLE 3 The pH of wood ashes of studied tree species

Locality	*Betula*	*Carpinus*	*Fagus*	*Larix*	*Picea*	*Pinus*	*Quercus*	*Tilia*
Hlinsko	10.3 ± 0.1	10.25 ± 0.2	9.63 ± 0.3	10.41 ± 0.4	10.01 ± 0.1	9.28 ± 0.1	8.51 ± 0.3	10.38 ± 0.03
Mšec	11.13 ± 0.3	11.03 ± 0.1	10.91 ± 0.2	10.07 ± 0.1	9.96 ± 0.1	9.52 ± 0.1	10.11 ± 0.1	10.23 ± 0.04

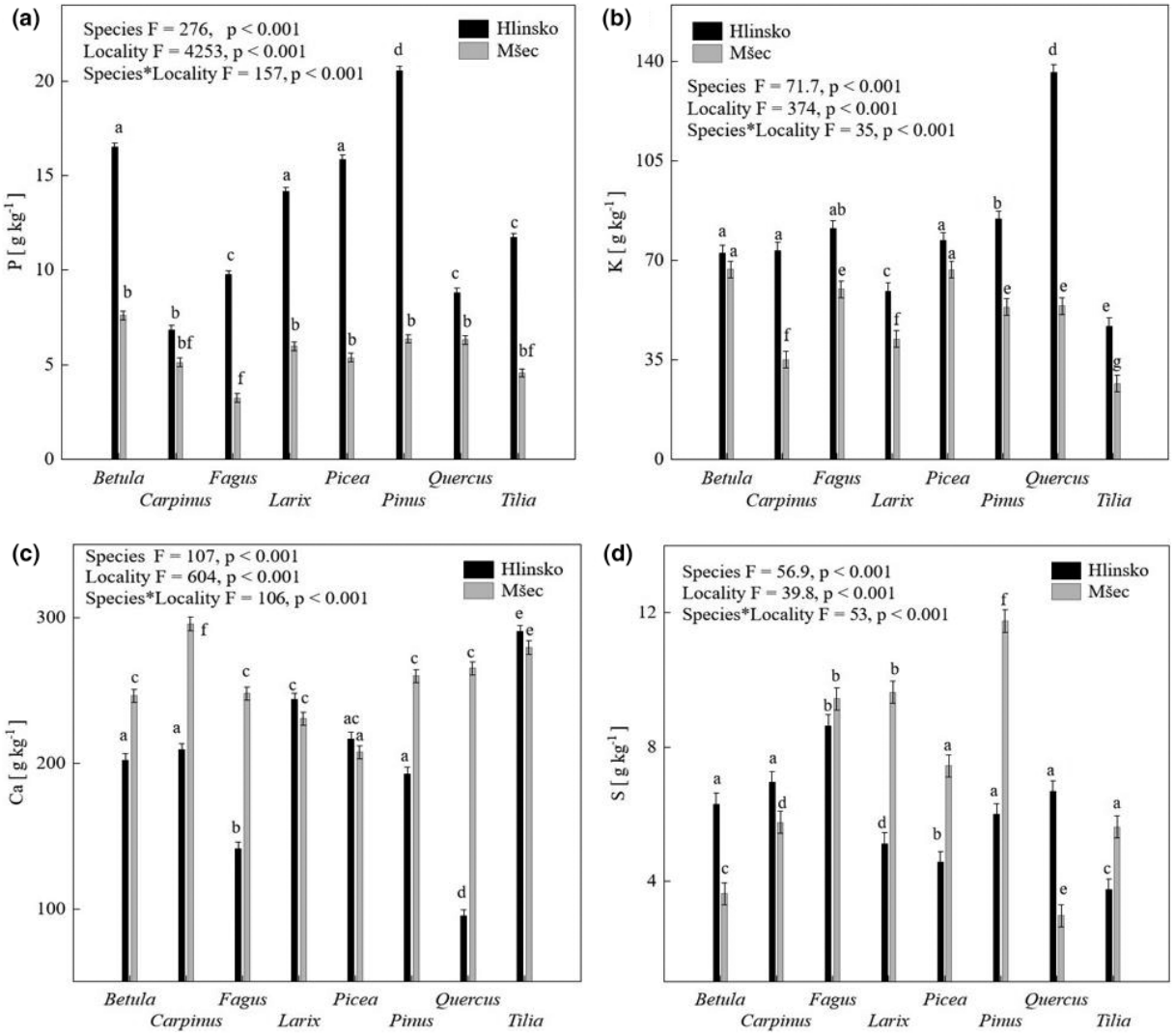


FIGURE 1 Effect of species on the total concentration of (macro elements) (a) P, (b) K, (c) Ca, and (d) S in the wood ashes from Hlinsko and Mšec, Czech Republic. The *F* and *p*-values were obtained from factorial ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean.

(Figure 2b). The highest (4.60 g kg^{-1}) content of Fe was in the ash of *Fagus* with the lowest (0.339 g kg^{-1}) in *Carpinus* from Mšec. The content of Zn (in mg kg^{-1}) ranged from 32 to 2062 in Hlinsko and 65.93 to 1044.68 in Mšec (Figure 2c). Zinc content was highest (2062 mg kg^{-1}) and lowest (89 mg kg^{-1}) in the ash of *Betula* and *Carpinus*, respectively, from Hlinsko. The content of Cu ranged from (in mg kg^{-1}) to 58.31–193.09 in Hlinsko and 47.61–146.51 in Mšec (Figure 2d). Copper content was highest in the ashes of *Fagus* from Hlinsko and the lowest in *Carpinus*, Mšec.

Additionally, there was a significant effect on the content of Al, Si, Rb, Sr, Mo, Zr, and Se in the ashes from the different species among the localities (Figures 3 and 4). Except for the ash of *Fagus* in Hlinsko (14 g kg^{-1}), the content of Al was relatively similar (approx. 5 g kg^{-1}) for all the species from both sites (Figure 3a). Si content ranged from 7.2 to 18 g kg^{-1} in Hlinsko and 6.3 to 21.2 g kg^{-1} in Mšec (Figure 3b). Rubidium content in Hlinsko was from 0.2 to 1.6 g kg^{-1} and 0.2 g kg^{-1} in the ashes from Mšec (Figure 3c). The Sr content was from 1000 to 3225 mg kg^{-1} in Hlinsko and 500 to 1467 mg kg^{-1} in Mšec (Figure 3d).

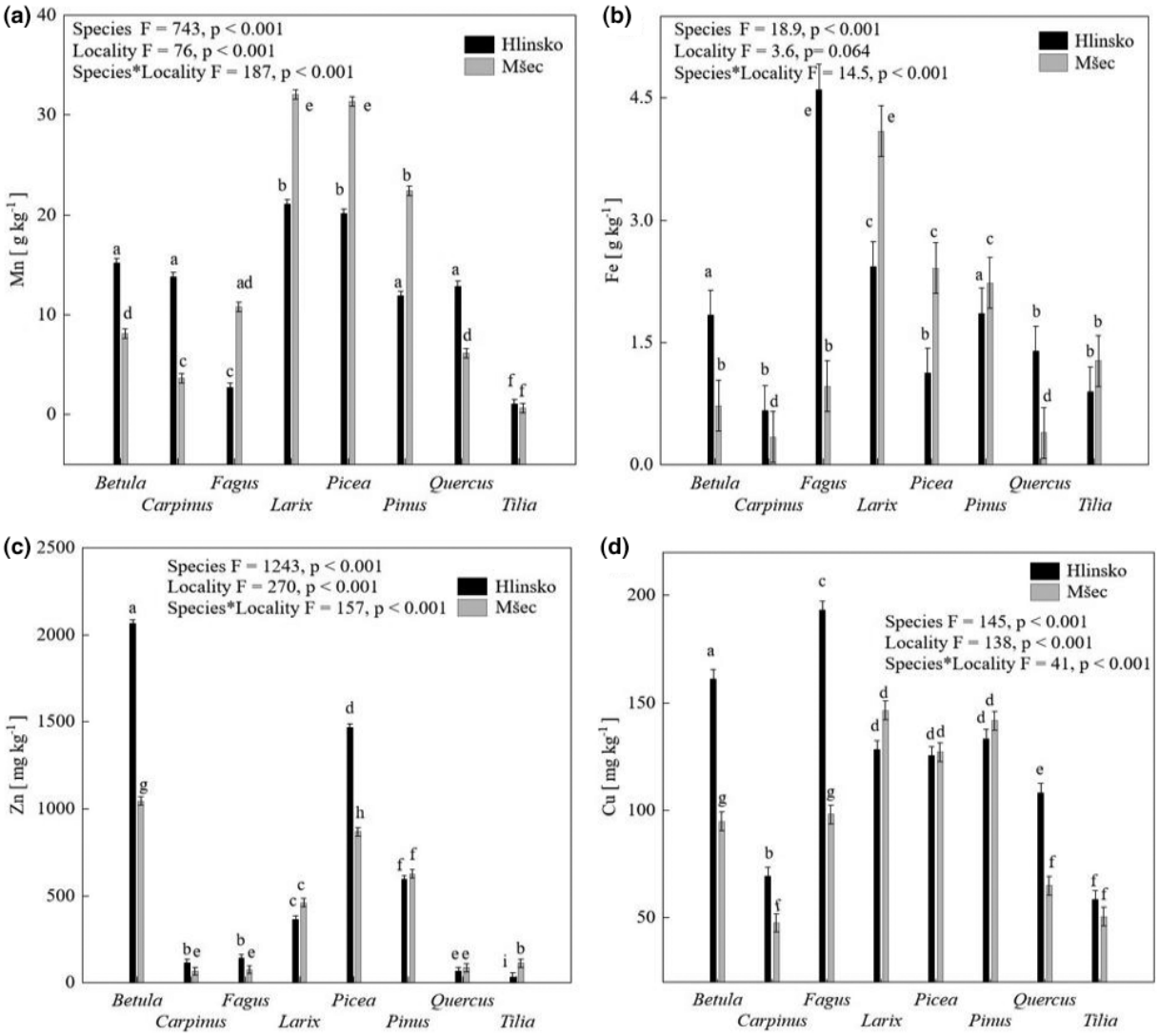


FIGURE 2 Effect of species on the total concentration of (microelements) (a) Mn, (b) Fe, (c) Zn, and (d) Cu in the wood ashes from Hlinsko and Mšec, Czech Republic. The *F* and *p*-values were obtained from factorial ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean.

In the case of risk elements (As and Ni), there was a relatively higher content in Hlinsko among all the ashes compared to Mšec (Figure 5). Except for Pb content ($132\,mg\,kg^{-1}$) in the ash of *Larix* from Mšec, other risk elements were below permissible limits for agricultural soils according to Decree No. 13/1994 Sb. of Ministry of Environment in the Czech Republic ($mg\,kg^{-1}$) 20 for As and 60 for Pb (Figure 5c; Carlon, 2007) and European Commission (Brandón et al., 2017; Table 5).

3.2 | Chemical composition of soils and the relationship with wood ashes

The content of elements in the soils around the selected tree species is in Table 4. The content of P, K, Cu, Zn, Mo, and Pb was significantly higher in the soils around the *Betula* compared to the other sample locations. There was a significant positive correlation among Cu, Sr, and Pb contents in soils and ashes of *Betula*, *Pinus*, *Larix*, and *Picea* ($r = 0.56–0.90$, $p < 0.05$) (Figure 6a–c). Conversely, there was no significant relationship between the content of Ca, Fe, Mn, Zn, Rb, Zr, and Mo in the soil and the ashes of all the species (Figures S2 and S3).

4 | DISCUSSION

Even though the wood ashes were of the same tree species, the content of many elements differed with localities. The contents of macro (P, K, Ca, and S) and trace (Mn, Fe, Zn, Cu, Mo, and Se) nutrients pertinent to

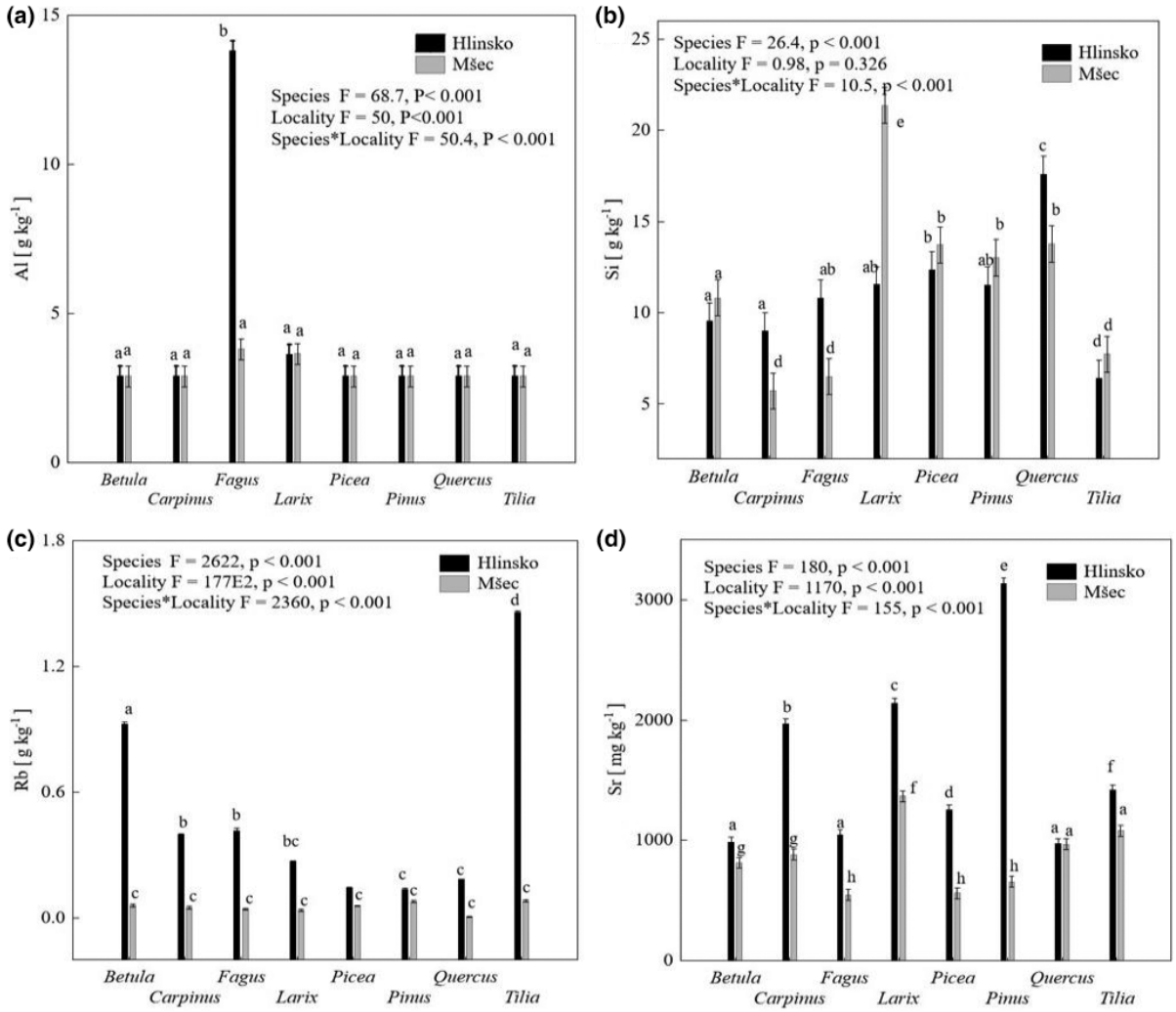


FIGURE 3 Effect of species on the total concentration of (trace elements) (a) Al, (b) Si, (c) Rb, and (d) Sr in the wood ashes from Hlinsko and Mšec, Czech Republic. The *F* and *p*-values were obtained from factorial ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean.

plants were sufficiently enough compared to other ashes from European tree species, for example, pine, aspen, alder, poplar, spruce, hornbeam, hazel (Dibdiakova et al., 2015; Górecka et al., 2006; Okmanis et al., 2016; Someshwar, 1996), and renders them suitable for deficient arable soils. Positive plant growth after wood ashes application is well documented (Demeyer et al., 2001). Additionally, different plant species possess diverse mechanisms in the uptake, translocation and accumulation of elements evident from the content of the individual wood ashes. The wide distribution of the content of elements in the wood ashes of the tree species provides an opportunity to select the most suitable ashes according to soil needs. For example, the ashes of *Tilia* are more suitable for Ca deficient soils regardless of the locality (Figure 2c). The study supports the use of wood ashes to alleviate soil acidity according to the basic pH. Additionally, the influence of high Ca content from the Marl parent rock from Mšec contributed to higher pH than Hlinsko (Figure S2b).

The effects of mineral properties of soils are well shown according to the elemental contents. For example, the influence of the Marl parent rock at Mšec in the high content of Ca in the ashes of *Betula*, *Carpinus*, *Fagus*, *Pinus*, and *Quercus* compared to Hlinsko (Table S1). Other minerals found in wood ashes, including hematite (Fe_2O_3), albite (Ca, Ca)Al (Si, Al)$_3O_8$, and dolomite (CaMg $[CO_3]_2$) are either in small quantities in the wood or bark or absent, with mostly higher calcite due to the high concentration of Ca (Ndlovu, 2007; Symanowicz et al., 2018). These relate to the mineralogical composition of parent bedrocks, while the crystalline phase of minerals in wood ash changes as combustion temperature increases (Olanders & Steenari, 1995). The influence of anthropogenic sources of elements in the ashes of *Picea*, *Larix*, *Pinus*, and *Betula* was well reflected in the significant positive correlation

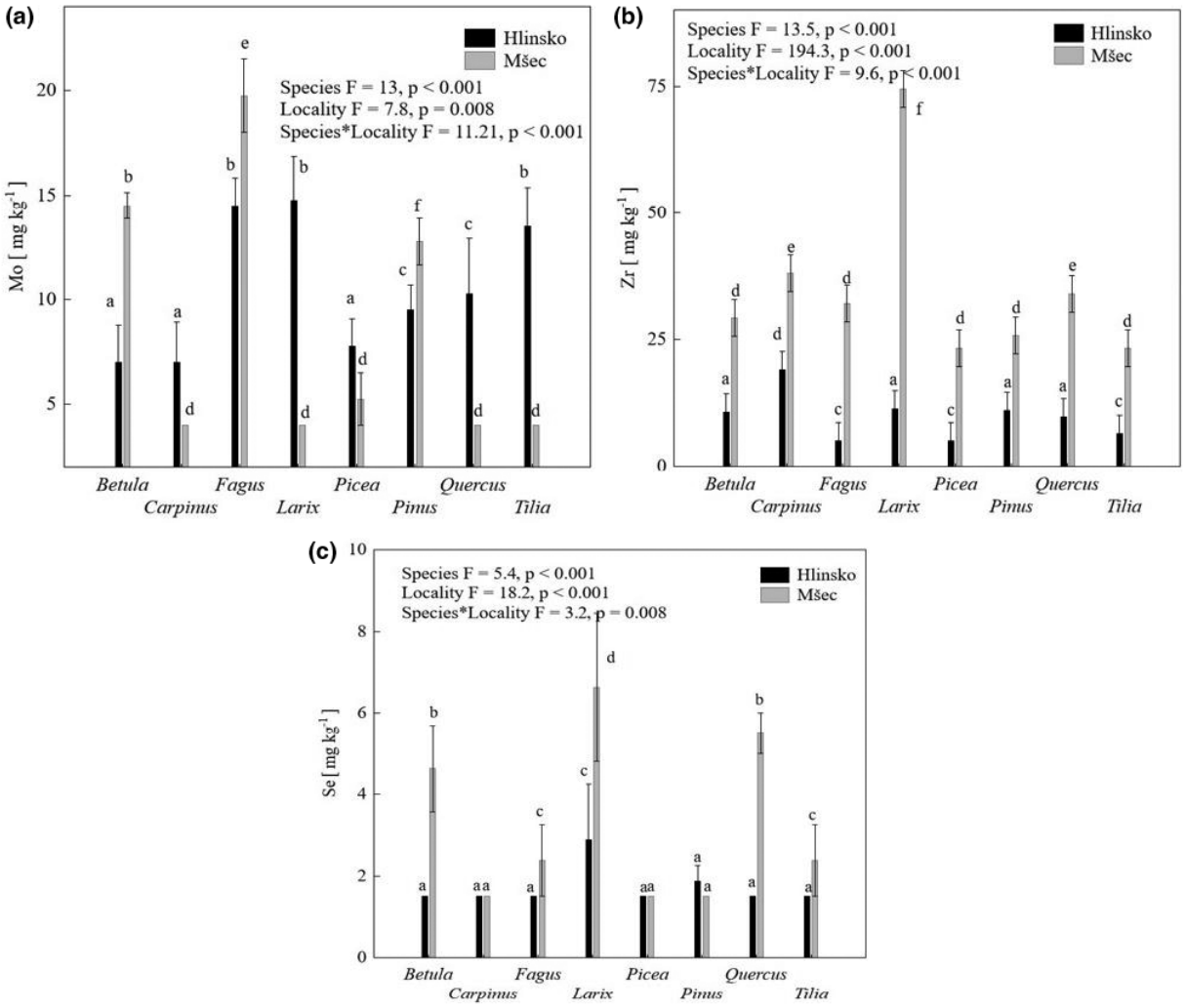


FIGURE 4 Effect of species on the total concentration of (trace elements) (a) Mo, (b) Zr, and (c) Se in the ashes of selected tree species from Hlinsko and Mšec, Czech Republic. The *F* and *p*-values were obtained from factorial ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean.

between the content of Cu, Sr, and Pb. Besides their comparatively higher content than the other trace elements, each species has different uptake and accumulation strategies (Mleczek et al., 2019) regardless of how abundant the elements are in the soil. The high content of P, K, Cu, Zn, Mo, and Pb in the ashes of *Betula* in Hlinsko was significantly higher than in the same species in Mšec, resulting from the high element content due to anthropogenic elements input. Although we expected a relatively similar ability of nutrient uptake by the plant. The exact location of the *Betula* had an ancient grave: decomposition of dead human bodies releases many elements (Asare, Šmejda, et al., 2020), where plants can take them up.

The content of Pb in the ashes of *Larix* at Mšec renders it risky to adopt as fertilizer according to the high level above permissible limits in arable fields and mostly connected with the species in proximity to automobile roads. However, there were low contents of Pb in Hlinsko, with some increases in the ashes of *Betula*. Locations with high organic matter sorb Pb and probably be taken up by the plant (Thompson & Goyne, 2012). Ashes generated from home may not be adversely affected, but the condition of the growing species can render them unsafe to apply on arable soils. Wood ashes generated from temperatures used in heating households are suitable to maximize element contents, while the pXRF offers a time-efficient and inexpensive approach to the geochemical exploration of wood ashes to determine their fertilizer value. However, this message is relevant for local farmers who apply household wood ashes on their arable fields without adequate elemental analysis.

The most suitable source of P was ash from *Pinus* in Hlinsko. However, ashes from a Hlinsko were more suitable P fertilizer compared to Mšec. The P contents in most of the ashes from Hlinsko were up to 21.9 g kg^{-1}, recorded for ashes of most European woody species (Etiégni &

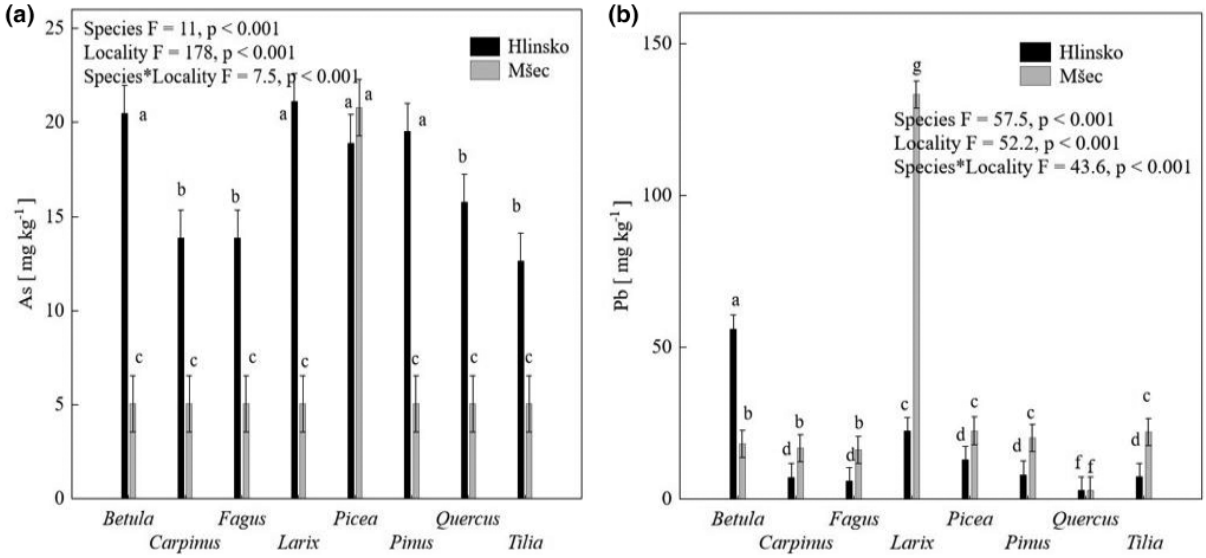


FIGURE 5 Effect of species on the total concentration of (risk elements) (a) As and (b) Pb in the wood ashes from Hlinsko and Mšec, Czech Republic. The *F* and *p*-values were obtained from factorial ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean.

Campbell, 1991; Górecka et al., 2006; Reimann et al., 2008; Vance, 1996). Comparatively, the ashes of *Quercus* in Hlinsko are more preferred fertilizer than the other species. K contents increase with the application of wood ashes attributed to the release of K by wood ash and the replacement of K on soil exchange sites by Ca and other exchangeable cations released into the soil suspension (Górecka et al., 2006). The solubility and potential availability of the macronutrients to plants in wood ashes are high, and K has the highest bioaccumulation compared to P, Ca, and S (Mandre, 2006). Since K fertilizers are usually expensive, the ashes from all the studied species can be good alternative sources of mineral K fertilizers for soils with K deficiency.

The wood ashes of the studied tree species are applicable for Ca-demanding soils according to their high contents. However, ashes from Mšec were more suitable, especially in the ash of *Carpinus*. The Ca contents in the ashes of all the species in this study were within the range (109–361 g mg^{-1}) of ashes of different woody species (Etiégni & Campbell, 1991; Huang et al., 1992; Górecka et al., 2006). Wood ashes have the same liming effects as commercial lime and comparatively provide better plant growth responses than limestone because of the supplementary nutrients in ashes (Adekayode & Olojugba, 2010). However, adding wood ashes which usually contain 25% $CaCO_3$, with a pH of 10–12, increases soil alkalinity and creates an adverse condition for growing plants (Lannotti, 2020). Hence, ashes above this Ca content are more suitable for acidic soils as many plants like a slightly acidic environment (pH <7.0) to absorb nutrients. Although wood ashes have a high effect on liming soils due to CaO (lime), their proportion during application needs proper attention to prevent leaching (Vassilev et al., 2013). However, the process of obtaining high CaO during wood combustion (calcination) can reduce at temperatures <800°C of totally dried wood (Kumar et al., 2007). When soil alkalinity increases and the pH rises, nutrients, for example, P, K, Fe, Mn, Cu, and Zn, can chemically adsorb to soil and become less available for plant uptake. The relatively lower contents of S compared to other macro elements are due to the high volatility during combustion, especially >500 °C (Dibdiakova et al., 2015). Consequently, if wood ash is applied to arable fields, S content, especially in ashes of *Pinus* from Mšec, is most suitable. However, the lowest macro element content in the studied ashes was S. At high pH, metal(loid)s in wood ashes often leach into soils. Meanwhile, a negative correlation between the pH and S indicates a decreasing effect on pH (Figure S2a), which can affect the solubility of metal(loid)s, thereby preventing extreme leaching. Hence, the application of this acid with a relatively low content of S will not result in high acidity after oxidation in the soil.

The content of Fe in all the studied ashes was relatively within most recorded values (3–4 g kg^{-1}) for many different species and organs of plants (Vassilev et al., 2013). Furthermore, soil deficient in Mn and Fe can be fertilized by all the ashes of this study, especially from *Larix* and *Fagus* in Mšec and Hlinsko, respectively. The comparatively high content of Cu, especially in the case of the ash of *Betula* in Hlinsko, relates to the level in the soil.

TABLE 4 Mean content (±*SD*) of elements in the soils around selected tree species at Hlinsko

Species	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	S (g kg^{-1})	Mn (g kg^{-1})	Fe (g kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Mo (mg kg^{-1})	Pb (mg kg^{-1})
Picea	NA	15.02 ± 0.28^{b}	2.11 ± 1^{c}	NA	0.39 ± 0.02^{a}	20.48 ± 0.48^{b}	38.75 ± 2.0^{d}	26.5 ± 6.7^{b}	16 ± 2.94^{ab}	53 ± 4.5^{bc}
Larix	NA	10.9 ± 0.24^{c}	4.62 ± 0.6^{b}	0.25 ± 0.01^{a}	0.38 ± 0.03^{a}	20.54 ± 0.52^{b}	52.75 ± 4.58^{c}	25.25 ± 8.17^{b}	18 ± 1.82^{a}	56.75 ± 4.65^{b}
Pinus	NA	10.12 ± 0.21^{c}	0.55 ± 0^{d}	NA	0.45 ± 0.02^{a}	24.97 ± 0.83^{a}	75.25 ± 1.64^{b}	21.75 ± 6.42^{c}	15.5 ± 1.5^{bc}	42.25 ± 5.1^{d}
Betula	0.84 ± 0.02	19.86 ± 0.16^{a}	8.13 ± 0.55^{a}	0.28 ± 0.001^{a}	0.7 ± 0.04^{b}	25.47 ± 1.17^{a}	93.25 ± 1.54^{a}	34.25 ± 0.6^{a}	17.75 ± 2.99^{a}	109.75 ± 21.9^{a}

Note: Using the Tukey post-hoc HSD test, mean values with different letters were significantly different.
Abbreviation: ND, not detected.

The Zn content in the ash of *Betula* from Hlinsko was higher among all the species, with *Pinus* and *Quercus* above the allowable limit for arable soils. However, Zn content in the ashes of birch and spruce, according to Reimann et al. (2008), was as high as 14,300 and 5350 mg kg^{-1}, respectively (Reimann et al., 2008). Meanwhile, *Betula* spp. is also known as a Zn hyperaccumulator (Van Nevel et al., 2011). The content of Zn, especially in the *Betula* and *Picea* ashes, leaves concerns about their hyperaccumulation abilities in both sites, even though these localities are not contaminated. Thus, another pertinent aspect to consider during the selection of wood ashes for arable soil.

The composition of wood ashes varies because each tree species has its specific origin and formation conditions, which can cause enrichment or depletion of different elements (Pazalja et al., 2021; Vassilev et al., 2013, 2014). The element contents in wood ashes also depend on biomass resources, including types of biomass, plant species or parts, growing processes and conditions, plants' age, fertilizer/pesticide doses, collection technique, storage, and processing. The effect of species over the accumulation of Zn content (>500 ppm) per this study is visible in *Betula*, *Picea*, and *Pinus*. Meanwhile, the Zn contents besides *Betula* and *Picea* were within the mean range in the ashes of world reference plants (Cohen & Dunn, 2004). Zinc contents in all plants were within the limit values given by EU directives and regulations (Silva et al., 2019). Biomass combustion: fuel preparation, combustion technology, conditions, collection, and cleaning equipment can also contribute to a high content of trace elements above the permissible limits. However, it is necessary to consider the allowable limit of risk elements in soils before applying wood ashes to avoid further leaching. Leaching tests using common mineral and water fertilizers showed that ammonium sulfate and potassium nitrate mobilize Cu, Zn, and Pb in wood ashes. According to studies by Pędziwiatr et al. (2021), 30% of total Zn content in wood ashes from home can potentially leach into groundwater. It is of great concern to closely monitor the content of essential metal nutrients in wood ashes, for example, Cu and Zn, to remain within allowable limits in soils.

Mineral composition of soils and plant-mineral uptake can result in high trace element contents and subsequent accumulation in wood ashes (Vassilev et al., 2014). The presence of elements such as Sb in household wood ashes may also result from the co-combustion of plastics with wood, which contaminate ashes. Knowledge about the origin, abundance, and mode of element occurrences (including mineral composition) is among the factors to consider during the combustion and utilization of wood ash.

The effect of tree species on the contents of Al, Si, Rb, Sr, Mo, Zr, and Se in the wood ashes differed with the

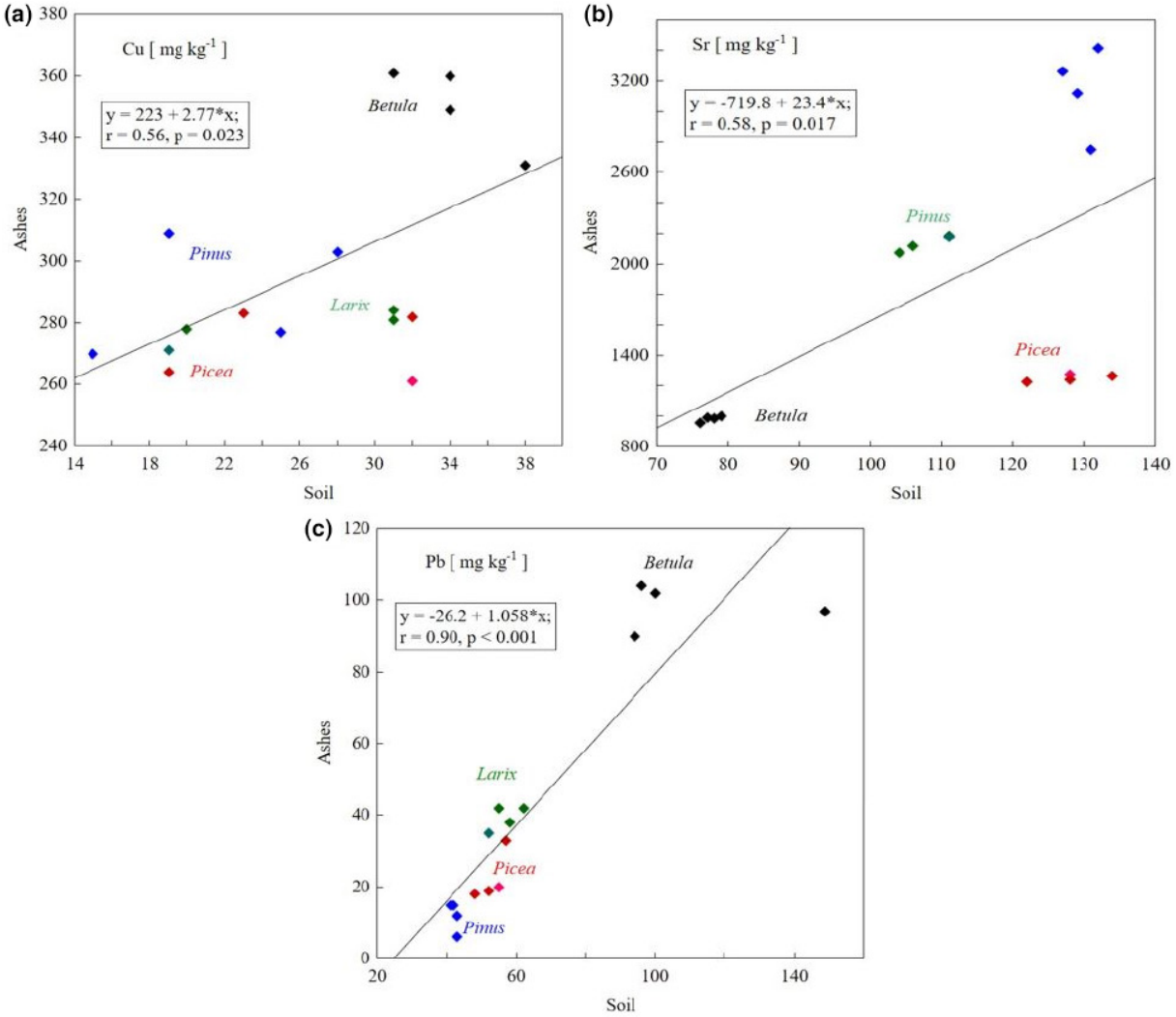


FIGURE 6 Relationship between the concentration of (a) Cu, (b) Sr, and (c) Pb in the soil and ashes of *Picea abies*, *Larix decidua*, *Pinus sylvestris*, and *Betula pendula* at Hlinsko.

TABLE 5 Content ($mg\,kg^{-1}$) of some trace elements in the studied sites and their regulatory limits

Trace element	Study site		EU directives and regulations (ash)[a]	Soil permissible limit	
	Hlinsko	Mšec		Finland[b] lower guideline limit / higher guideline limit	Czech Republic[c]
As	12.9–20.05	5.04	-	50[e] 100[e]	20
Cr			300	200[e] 300[e]	90
Cu	58.31–193.09	47.61–146.51	700	150[e] 200[e]	70
Pb	2.85–56	2.85–133.23	150	200[d] 750[e]	60
Zn	32.4–2062	65.93–1044.68	4500	250[e] 400[e]	150

[a]Silva et al. (2019)

[b]MEF (2007)

[c]Decree No. 13/1994 Sb. of Ministry of Environment in the Czech Republic.

[d]Health risk.

[e]Ecological risk.

locality. The content of Al in all the ashes of this study may remain non-toxic even to sensitive plants in the soil owing to the alkaline nature (increased pH) of ash (Bojorquez et al., 2017). Meanwhile, monovalent ion impurities such as Rb^+ also were reported in natural apatite (Hughes et al., 1991; Simonetti et al., 2008). Rb can substitute for K in higher plants due to a similar monovalent charge. Thus, plants can take up Rb to replace K (Goldschmidt, 1954). However, this partly accounted for the high Rb contents in the ashes from all species. Strontium content in continental plants is 26 mg kg^{-1} (Pais, 1984), and their accumulation in biomass ashes was reported (Oroian et al., 2015). Species such as *Fagus sylvatica*, *Picea abies*, and *Pinus* spp contain elements including Sr and Rb (Simniškytė-Strimaitienė et al., 2017). The relatively high content of Se in the species (e.g., *Betula*, *Fagus*, *Larix*, *Quercus*, and *Tilia*) in Mšec relates to its content in the Marl parent rock, which may contain <0.1–7.4 mg kg^{-1} and the uptake potential ability (Connor & Schaklette, 1975).

Although the element contents of wood ashes can improve the nutrient needs of agricultural soils, the applications must follow agronomic rates (Symanowicz et al., 2018) and regulatory limits (Table 5). We can conclude that the studied ashes are suitable as fertilizers in agricultural soils. However, a thorough elemental analysis must be conducted as the content of elements can be influenced by anthropogenic activities.

5 | CONCLUSIONS

Comparative chemical analysis of homemade wood ashes from the same tree species from different localities revealed wide variability in the content of elements. The content of elements in wood ashes is a function of the type of soil, the parent rock, and the ability of the species to accumulate elements. Different localities have a significant effect on the fertilizer values of wood ashes.

The obtained ashes from *Betula*, *Carpinus*, *Fagus*, *Larix*, *Picea*, *Pinus*, *Quercus*, and *Tilia* were characterized by a high content of macro (P, K, Ca, and S) and trace (Mn, Fe, Zn, Cu, Al, Si, Rb, Sr, Mo, Zr, and Se) elements. The ashes of *Betula*, *Carpinus*, *Fagus*, *Picea*, *Pinus*, *Quercus*, and *Tilia* are suitable to be used as P, K, Ca, S, Mn, Fe, Cu, Zn, Mo, and Se fertilizers for agricultural soils according to their allowable limits. Wood ashes from the tree species have high pH, suitable to alleviate high soil acidity. The content of risk elements was below the regulatory limits for soils, except for Pb in the ash of *Larix* from Mšec and Zn in *Betula*, *Pinus*, and *Quercus* in both localities.

Differences in plant species, local parent rock, and anthropogenic interferences in the location of trees affect the content of elements in wood ashes. Many other environmental conditions, including the moisture content of wood, conditions during combustion, and soil chemical properties, at different geographical locations, affect the composition of wood ashes. A detailed chemical analysis of ashes is recommended, with strict adherence to permissible limits in soils.

ACKNOWLEDGMENTS

The authors would like to thank the scientific board of the Czech Science Foundation for the financial support of this project. We appreciate the human adaptability research team for their valuable contributions to previous versions of this manuscript.

FUNDING INFORMATION

MOA received support from the Nutrisk project (European Regional Development Fund—Project No. Wierzbowska).

CONFLICT OF INTEREST

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.69p8cz955.

ORCID

Michael O. Asare https://orcid.org/0000-0002-0008-1459
Michal Hejcman https://orcid.org/0000-0002-3513-2017

REFERENCES

Adekayode, F. O., & Olojugba, M. R. (2010). The utilization of wood ash as manure to reduce the use of mineral fertilizer for improved performance of maize (*Zea mays L.)* as measured in the chlorophyll content and grain yield. *Journal of Soil Science and Environmental Management*, *1*, 40–45.

Asare, M. O., Afriyie, J. O., Hejcman, M., & Jungová, M. K. (2022). Can wood ashes of commonly planted tree species in Ghana be applied as fertilizers? *Waste and Biomass Valorization*, *13*, 1043–1058. https://doi.org/10.1007/s12649-021-01588-7

Asare, M. O., Apoh, W., Afriyie, J. O., Horák, J., Šmejda, L., & Hejcman, M. (2020). Traces of German and British settlements in soils of the Volta region of Ghana. *Geoderma Regional*, *521*, e00270. https://doi.org/10.1016/j.geodrs.2020.e00270

Asare, M. O., Šmejda, L., Horák, J., Holodňák, P., Černý, M., Pavlů, V., & Hejcman, M. (2020). Human burials can affect soil elemental composition for millennia- analysis of necrosols from the corded ware culture graveyard in The Czech Republic. *Archaeological and Anthropological Science*, *12*, 255. https://doi.org/10.1007/s12520-020-01211-1

Bojorquez, Q. E., Escalante, C., & Martínez-Estevez, M. (2017). Aluminum, a friend or foe of higher plants in acid soils.

Frontiers in Plant Science, *8*, 1767. https://doi.org/10.3389/fpls.2017.01767

Brandón M.G., Juárez M.F-D., Insam H. (2017). Ash characterization. Report: Renewable residential heating with fast pyrolysis bio-oil, Residue2Heat Consortium. Retrieved from https://www.residue2heat.eu/wpcontent/uploads/2018/03/D6_3_Ash_characterization_1.0_UIBK_20151571219.pdf [Accessed in October 2020].

Campbell, A. G. (1990). Recycling and disposing of wood ash. *Tappi*, *73*, 141–145.

Canti, M., & Huisman, D. J. (2015). Scientific advances in geoarchaeology during the last twenty years. *Journal of Archaeological Science*, *56*, 96–108. https://doi.org/10.1016/j.jas.2015.02.024

Carlon C. (Ed.) (2007). Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonization. European Commission, Joint Research Centre, Ispra, EUR 22805-EN, 306 pp.

Chand, P., Kumar, A., Gaur, A., & Mahna, S. K. (2009). Elemental analysis of ash using X-ray fluorescence technique. *Asian Journal of Chemistry*, *21*, S220–S224.

Cohen D., Dunn, C.E. (2004). Form and distribution of trace elements in biomass for power generation. Research Report 48 of the Cooperative Research Centre for Coal in Sustainable Development, University of New South Wales, QCAT Technology Transfer Centre, Technology Court Pullenvale, Australia; p. 66.

Connor J.J., Schaklette H. (1975). Background geochemistry of some rocks, soils, plants, and vegetables in the conterminous United States, p. 168.

Curkeet R. (2011). Wood Combustion Basics https://is.muni.cz/el/1423/podzim2013/MEB423/um/Wood_Lesson_02.pdf. Accessed on 10/02/2022.

Czech Geological Survey (2012). Geological map of the Czech Republic. Retrieved from http://www.geology.cz/extranet-eng/publications. (assessed 20 October 2020).

Demeyer, A., Voundi Nkana, J. C., & Verloo, M. G. (2001). Characteristics of wood ash and influence on soil properties and nutrient uptake: An overview. *Bioresource Technology.*, *7*, 287–295. https://doi.org/10.1016/S0960-8524(00)00043-2

Dibdiakova, J., Wang, L., & Li, H. (2015). Characterization of ashes from Pinus sylvestris forest biomass. *Energy Procedia*, *75*, 186–191. https://doi.org/10.1016/j.egypro.2015.07.289

Etiégni, L., & Campbell, A. G. (1991). Physical and chemical characteristics of wood ash. *Bioresource Technology*, *37*, 173–178.

Goldschmidt, V. M. (1954). Geochemistry. In *Geochemistry* (p. 730). Oxford University.

Górecka, H. G., Chojnacka, K., & Orecki, H. G. (2006). The application of ICP-MS and ICP-OES in determination of micronutrients in wood ashes used as soil conditioners. *Talanta*, *70*, 950–956. https://doi.org/10.1016/j.talanta.2006.05.061

Hejcman, M., Ondráček, J., & Smrž, Z. (2011). Ancient waste pits with wood ash irreversibly increase crop production in Central Europe. *Plant and Soil*, *339*, 341–350. https://doi.org/10.1007/s11104-010-0585-x

Hejcman, M., Součková, K., & Gojda, M. (2013). Prehistoric settlement activities changed soil pH, nutrient availability, and growth of contemporary crops in Central Europe. *Plant and Soil*, *369*, 131–140. https://doi.org/10.1007/s11104-012-1559-y

Huang, H., Campbell, A. G., Folk, R., & Mahler, R. L. (1992). Wood ash as a soil additive and liming agent for wheat: Field studies. *Communications in Soil Science and Plant Analysis*, *23*, 25–33. https://doi.org/10.1080/00103629209368567

Hughes, J. M., Cameron, M., & Crowley, K. D. (1991). Ordering of divalent cations in the apatite structure: Crystal structure refinements of natural Mn- and Sr- bearing apatite. *Amereican Mineralogist*, *76*, 1857–1862.

Kumar, G. S., Ramakrishnan, A., & Hung, Y.-T. (2007). Lime Calcination. In L. K. Wang, Y.-T. Hung, & N. K. Shammas (Eds.), *Advanced physicochemical treatment technologies* (Vol. *5*, pp. 611–633). Humana Press. https://doi.org/10.1007/978-1-59745-173-414

Lane, D. J., Sippula, O., Peräniemi, S., & Jokiniemi, J. (2020). Detoxification of wood-combustion ashes containing Cr and cd by thermal treatment. *Journal of Hazardous Materials*, *400*, 123315. https://doi.org/10.1016/j.jhazmat.2020.123315

Lannotti M. (2020). Is wood ash good for garden soil? https://www.thespruce.com/is-wood-ash-good-for-garden-soil-1403126. Assessed on 18 October 2020.

Liodakis, S., Katsigiannis, G., & Kakali, G. (2005). Ash properties of some dominant Greek forest species. *Thermochimica Acta*, *437*, 158–167. https://doi.org/10.1016/j.tca.2005.06.041

Magnusson, B. & Örnemark, U. (2014). *Eurachem guide: The fitness for purpose of analytical methods – A laboratory guide to method validation and related topics*, (2nd ed.). Retrieved from https://www.eurachem.org/images/stories/Guides/pdf/MV_guide_2nd_ed_EN.pdf

Mandre, M. (2006). Influence of wood ash on soil chemical composition and biochemical parameters of young scots pine. Proceedings of the Estonian Academy of Sciences. *Biology, Ecology*, *55*, 91–107.

Ministry of the Environment, Finland 2007. Government decree on the assessment of soil contamination and remediation needs.

Misra, M. K., Ragland, K. W., & Baker, A. J. (1993). Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy*, *4*, 103–116. https://doi.org/10.1016/0961-9534(93)90032-Y

Mleczek, M., Rutkowski, P., Kaniuczak, J., Szostek, M., Budka, A., Magdziak, Z., Budzyńska, S., Kuczyńska-Kippen, N., & Niedzielski, P. (2019). The significance of selected tree species age in their efficiency in elements phytoextraction from wastes mixture. *International Journal Environmental Science Technology.*, *16*, 3579–3594. https://doi.org/10.1007/s13762-018-1996-0

Narodoslawsky, M., & Obernberger, I. (1996). From waste to raw material—The route from biomass to wood ash for cadmium and other heavy metals. *Journal of Hazardous Materials*, *50*, 157–168. https://doi.org/10.1016/0304-3894(96)01785-2

Naylor, L. M., & Schmidt, E. J. (1986). Agricultural use of wood ash as a fertilizer and liming material. *Tappi*, *10*, 114–119.

Ndlovu H. (2007). Ash from homestead fireplaces and wood as possible sources of minerals for livestock. M.Inst. (Agrar.) dissertation, University of Pretoria, Pretoria, South Africa.

Němeček, J., & Kozák, J. (2005). Status of soil surveys, inventory, and soil monitoring in The Czech Republic. In R. J. Jones, A. B. Houšková, P. Bullock, & L. Montanarella (Eds.), *Soil resources of Europe (2nd ed.). European soil bureau research report no. 9* (pp. 103–109). Ispra.

Obernberger, I., Biedermann, F., Widmann, W., & Riedl, R. (1997). Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. *Biomass and Bioenergy*, *12*, 211–224. https://doi.org/10.1016/S0961-9534(96)00051-7

Okmanis, M., Skranda, I., Lazdiņš, A., & Lazdiņa, D. (2016). Impact of wood ash and potassium sulfate fertilization on growth of Norway spruce stand on organic soil. *Research for Rural Development International Scientific Conference Proceedings*, *2*, 62–66.

Olanders, B., & Steenari, B.-M. (1995). Characteristics of ashes from wood and straw. *Biomass & Bioenergy*, *8*, 105–115.

Oroian, I., Predescu, C., Odagiu, A., Covrig, I., Bordeanu, B., Mihaiescu, T., & Proorocu, M. (2015). Analyzing the properties as fertilizer of ash from oak wood combustion. *Environmental Engineering and Management Journal*, *14*, 2617–2624.

Pais, I. (1984). Importance of macroelements in agricultural production and position of the research on the world Budapest. In *Hungarian*. Academic publishers.

Pazalja, M., Salihović, M., Sulejmanović, J., Smajović, A., Begić, S., Špirtović-Halilović, S., & Sher, F. (2021). Heavy metals content in ashes of wood pellets and the health risk assessment related to their presence in the environment. *Scientific Reports*, *11*, 17952. https://doi.org/10.1038/s41598-021-97305-4

Pędziwiatr, A., Potysz, A., & Uzarowicz, Ł. (2021). Combustion wastes from thermal power stations and household stoves: A comparison of properties, mineralogical and chemical composition, and element mobilization by water and fertilizers. *Waste Management*, *131*, 136–146. https://doi.org/10.1016/j.wasman.2021.05.035

Reimann, C., Ottesen, R. T., Andersson, M., Arnoldussen, A., Koller, F., & Englmaier, P. (2008). Element levels in birch and spruce wood ashes — Green energy? *Science of Total Environment.*, *393*, 191–197. https://doi.org/10.1016/j.scitotenv.2008.01.015

Saarela, K. E., Harjua, L., Lillb, J.-O., Heseliusb, S.-J., Rajandera, J., & Lindroosd, A. (2005). Quantitative elemental analysis of dry-ashed bark and wood samples of birch, spruce, and pine from South-Western Finland using PIXE. *Acta Academiae Aboensis, Series B*, *64*, 1–27.

Sanders, M.-L., & Andrén, O. (1997). Ash from cereal and rape straw used for heat production: Liming effects and contents of plant nutrients and heavy metals. *Water Air Soil Pollution*, *93*, 93–108.

Semelová, V., Hejcman, M., Pavlů, V., Vacek, S., & Podrázský, V. (2008). The grass garden in the Giant mts. (Czech Republic): Residual effect of long-term fertilization after 62 years. *Agriculture Ecosystem and Environment*, *123*, 337–342. https://doi.org/10.1016/j.agee.2007.07.005

Serafimova, E., Mladenov, M., Mihailova, I., & Pelovski, Y. (2011). Study on the characteristics of waste wood ash. *Journal of the University of Chemical Technology and Metallurgy*, *46*, 31–34.

Silva, F. C., Cruz, N. C., Tarelho, L. A., & Rodrigues, S. M. (2019). Use of biomass ash-based materials as soil fertilizers: Critical review of the existing regulatory framework. *Journal of Cleaner Production*, *214*, 112–124. https://doi.org/10.1016/j.jclepro.2018.12.268

Simniškytė-Strimaitienė, A., Selskienė, A., Vaičiūnienėb, J., Pakštas, V., & Šmigelskasa, R. (2017). Tracing archaeology through geochemistry: An example of a disturbed prehistoric hilltop settlement site in south-eastern Lithuania. *Interdisciplinaria Archaeologica Natural Sciences in Archaeology*, *8*, 17–33.

Simonetti, A., Buzon, M. R., & Creaser, R. A. (2008). In-situ elemental, and Sr isotope investigation of human tooth enamel by laser ablation-(MC)-ICP-MS: Successes and pitfalls. *Archaeometry*, *50*, 371–385.

Šmejda, L., Hejcman, M., Horák, J., & Shai, I. (2017). Ancient settlement activities as important sources of nutrients (P, K, S, Zn, and cu) in eastern Mediterranean ecosystems – The case of biblical Tel Burna, Israel. *Catena*, *156*, 62–73. https://doi.org/10.1016/j.catena.2017.03.024

Smołka-Danielowska, D., & Jabłońska, M. (2022). Chemical and mineral composition of ashes from wood biomass combustion in domestic wood-fired furnaces. *International Journal of Environmental Sciences and Technology*, *19*, 5359–5372. https://doi.org/10.1007/s13762-021-03506-9

Someshwar, A. V. (1996). Wood ash and combination wood-fired boiler ash characterization. *Journal of Environmental Quality*, *25*, 962–972.

Symanowicz, B., Becher, B., Jaremko, D., & Skwarek, K. (2018). Possibilities for the use of wood ashes in agriculture. *Journal of Ecological Engineering*, *19*, 91–196. https://doi.org/10.12911/22998993/86156

Thompson, A., & Goyne, K. W. (2012). Introduction to the sorption of chemical constituents in soils. *Nature Education Knowledge*, *4*, 7.

USEPA Method 3052 (1996). Microwave-assisted acid digestion of siliceous and organically based matrices https://www.epa.gov/sites/production/files/2015-12/documents/3052.pdf.

Van Nevel, L., Mertens, J., Staelens, J., De Schrijver, A., Tack, F., De Neve, S., Meers, E., & Verheyen, K. (2011). Elevated cd and Zn uptake by aspen limit the phytostabilization potential compared to five other tree species. *Ecological Engineering*, *37*, 1072–1080. https://doi.org/10.1016/j.ecoleng.2010.07.010

Vance, E. D. (1996). Land application of wood-fired and combination boiler ashes: An overview. *Journal of Environmental Quality*, *25*, 937–944.

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2013). An overview of the composition and application of biomass ash. Part 1. Phase-mineral and chemical composition and classification. *Fuel*, *105*, 40–76.

Vassilev, S. V., Vassileva, C. G., & Baxter, D. (2014). Trace element concentrations and associations in some biomass ashes. *Fuel*, *129*, 292–313. https://doi.org/10.1016/j.fuel.2014.04.001

Wierzbowska, J., Sienkiewicz, S., Żarczyński, P., & Krzebietke, S. (2020). Environmental application of ash from incinerated. *Biomass Agronomy*, *10*, 482. https://doi.org/10.3390/agronomy10040482

Xing, P., Mason, P. E., Chilton, S., Lloyd, S., Jones, J. M., Williams, A., Nimmo, W., & Pourkashanian, M. (2016). A comparative assessment of biomass ash preparation methods using X-ray fluorescence and wet chemical analysis. *Fuel*, *182*, 161–165. https://doi.org/10.1016/j.fuel.2016.05.081

Zhou, S., Chen, X., Zhang, H., & Liu, H. (2021). The influence of combustion temperature on alkali content of cattle manure ash. *Case Studies in Construction Materials*, *14*, e00519. https://doi.org/10.1016/j.cscm.2021.e00519

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Asare, M. O., & Hejcman, M. (2022). Effect of tree species on the elemental composition of wood ashes and their fertilizer values on agricultural soils. *GCB Bioenergy*, *14*, 1321–1335. https://doi.org/10.1111/gcbb.13002