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Influence of biomass ash fertilization on soil pH, $CaCO_3$, K_2O and P_2O_5 under *Miscanthus x giganteus*

Utjecaj primjene pepela na reakciju tla, sadržaj $CaCO_3$, K_2O i P_2O_5 pod kulturom *Miscanthus x giganteus*

Dija BHANDARI[1], Stella ARLOVIĆ[2], Marija GALIĆ[3], Nikola BILANDŽIJA[4], Josip LETO[5], Darija BILANDŽIJA[3] (✉)

[1] University of Zagreb Faculty of Agriculture, Graduate Study programme in "Sustainability in Agriculture, Food Production and Food Technology in the Danube Region" (DAFM), Svetošimunska cesta 25, Zagreb, Croatia
[2] University of Zagreb Faculty of Agriculture, Graduate Study programme in "Agroecology", Svetošimunska cesta 25, Zagreb, Croatia
[3] University of Zagreb Faculty of Agriculture (AGR), Division for Agroecology, Svetošimunska cesta 25, Zagreb, Croatia
[4] University of Zagreb Faculty of Agriculture, Division for Agricultural Engineering and Technology, Svetošimunska cesta 25, 10000 Zagreb, Croatia
[5] University of Zagreb Faculty of Agriculture, Division for Plant Sciences, Svetošimunska cesta 25, Zagreb, Croatia

✉ Corresponding author: dbilandzija@agr.hr

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ABSTRACT

The cultivation of energy crops and the use of biomass ash are part of a sustainable energy economy and have a major impact on the environment. Biomass ash can be used as a soil conditioner due to its chemical composition with essential micro- and macronutrients and has a proven positive effect on the physicochemical properties of soils. With the increasing interest and use of bioenergy species, the production of biomass ash is also increasing and is expected to increase further in the future. Therefore, the correct use of this product is important. Ensuring its use to enrich soils will strengthen the ecological aspect and close the gaps in the circular economy. In this context, investigating the influence of biomass ash on individual soil properties under different agro-ecological conditions is important to determine its possible uses and limitations. The aim of the study was therefore to determine the influence of different ash dosages (2 and 5 t/ha) on soil pH, carbonate content ($CaCO_3$), the content of plant-available phosphorus (P_2O_5) and plant-available potassium (K_2O) under the perennial energy crop *Miscanthus x giganteus*. The study was conducted in the years 2016-2019 in the continental part of Croatia near Zagreb city. The study showed that the application of ash had no significant effect on soil pH, but did have an effect on $CaCO_3$, P_2O_5 and K_2O. At both ash doses studied, there was a significant decrease in P_2O_5 and a significant increase in $CaCO_3$, while the K_2O content only increased significantly at the higher ash dose compared to the control treatment. Biomass ash proved to be a good soil conditioner in terms of $CaCO_3$ and K_2O content under the agroecological conditions studied. Further studies on various agroecological conditions such as soil types, vegetation and climate will provide further insights into the effective use of biomass ash. Likewise, research on the influence of biomass ash on other important soil properties in combination with studies on plant uptake is necessary to understand the complex interaction of biomass ash.

Keywords: forest biomass ash, chemical soil properties, perennial energy grass, sustainability, circular economy

SAŽETAK

Uzgoj energetskih kultura i primjena pepela iz biomase dio su održivog energetskog gospodarenja i imaju značajan utjecaj na okoliš. Pepeo iz biomase može se koristiti kao gnojivo ili poboljšivač tla zbog svog kemijskog sastava odnosno sadržaja važnih mikro i makro hranjiva, kao i pozitivnog učinka na fizikalno-kemijska svojstva tla. Sa sve većim interesom i korištenjem bioenergetskih kultura, proizvodnja pepela iz biomase također raste i očekuje se da će se u budućnosti dodatno povećati. Stoga je važna pravilna primjena ovog proizvoda. Osiguravanje njegove primjene kao poboljšivača tla ojačati će ekološki aspekt i zatvoriti praznine u kružnom gospodarstvu. U tom kontekstu, istraživanje utjecaja pepela iz biomase na pojedinačna svojstva tla u različitim agroekološkim uvjetima važno je za određivanje njegove moguće primjene i ograničenja. Stoga je cilj istraživanja bio utvrditi utjecaj različitih doza pepela (2 i 5 t/ha) na pH vrijednost tla, sadržaj karbonata ($CaCO_3$) u tlu, sadržaj biljkama dostupnog fosfora (P_2O_5) i kalija (K_2O) u tlu pod višegodišnjom energetskom kulturom *Miscanthus x giganteus*. Istraživanje je provedeno tijekom razdoblja 2016.-2019. u kontinentalnom dijelu Hrvatske u blizini grada Zagreba. Istraživanjem je utvrđeno da primjena pepela nije značajno utjecala na pH tla, ali je imala značajan utjecaj na sadržaj $CaCO_3$, P_2O_5 i K_2O u tlu. Kod obje istraživane doze pepela došlo je do značajnog smanjenja sadržaja P_2O_5 i značajnog povećanja sadržaja $CaCO_3$, dok se sadržaj K_2O u tlu značajno povećao samo pri većoj dozi pepela u usporedbi s kontrolnim tretmanom. Pepeo iz biomase pokazao se kao dobar kondicioner tla u pogledu sadržaja $CaCO_3$ i K_2O u proučavanim agroekološkim uvjetima. Daljnja istraživanja o primjeni pepla u različitim agroekološkim uvjetima poput različitih tipova tala, vegetacijskog pokrova i klimatskih uvjeta pružit će detaljniji uvid u učinkovito korištenje pepela iz biomase. Također, istraživanje o utjecaju pepela iz biomase na druga važna svojstva tla u kombinaciji s istraživanjima o biljnom usvajanju hranjiva potrebno je za razumijevanje složenog ponašanja pepela iz biomase.

Ključne riječi: pepeo šumske biomase, kemijska svojstva tla, višegodišnje energetske kulture, održivost, kružno gospodarstvo

INTRODUCTION

The cultivation of energy crops and the use of biomass ash are part of a sustainable energy economy and have a major positive impact on the environment. Energy from renewable sources like biomass has the potential to replace fossil fuels as they are considered carbon neutral. Biomass as a renewable source is being intensively researched and it is predicted that its use will increase significantly in the future. Biomass burning produces biomass ash. It is estimated that the combustion of biomass for energy currently produces a total of around 170 million tons of ash per year worldwide, and in the future, this figure could rise to as much as 1000 million tons per year (Zhai et al., 2021).

One of the main concerns in the field of bioenergy is therefore the most innovative, economical and sustainable use and/or environmentally sound disposal of this large amount of biomass ash. Vassilev et al. (2013b) states in the review that the main applications of biomass ash include soil improvement and fertilization, followed by building materials and sorbents, and occasionally the synthesis and production of minerals, ceramics and other materials. Among the options for ash utilization, the use of biomass ash as a secondary raw material for soil improvement measures on agricultural and forestry land (direct or indirect application) falls under sustainable ash utilization among other utilization options (Obernberger and Supancic, 2009). For sustainable use of biomass, both domestically and on an industrial scale, it is important to recognize that ash can largely be returned to the soil, renewing and replacing the nutrients removed (Ilyushechkin et al., 2012).

The solid residue that is produced when biomass is burned is biomass ash. This combustion residue is a complex inorganic-organic mixture with multicomponent, heterogeneous and variable composition and contains closely interconnected solid, liquid and gaseous phases of different origins (Vassilev et al., 2013a). The composition, content and origin of the biomass components as well as the ash yield are important when it comes to the use of biomass ash. Ash content varies among different types of biomass and can be as low as 0.5% on a dry basis for some types of pulpwood or as high as 20% for some cereals or forest and agricultural wastes (Garba et al., 2013). The composition of biomass ash is influenced by a variety of factors. The combustion process (fuel preparation, combustion technology and conditions, collection and cleaning facilities), as well as the biomass resources (type of biomass, plant species or plant part, cultivation processes and conditions, age of plants, application of agrochemicals, type of harvesting) and also a number of processes such as transportation, storage, contamination, processing, etc., affect the properties and composition of biomass (Vassilev et al., 2010, 2013a). The chemical composition of biomass ash varies greatly depending on the composition of the biomass. The most common components of ash are CaO, K_2O and SiO_2 (Zhai et al., 2021), two of which are essential macroelements for plants. In addition, the elements in biomass ash can be generally divided into micro, macro and trace elements based on their elemental concentration. Based on the chemical data on the composition of 86 types of biomass, their groups and subgroups, the macro and micro elements in decreasing order are usually O > Ca > K > Si > Mg > Al > Fe > P > Na > S > Mn > Ti and some Cl, C, H, N and trace elements (Vassilev et al., 2010). In addition to the alkali (Na, K) and alkaline (Ca, Mg) earth metals typical of biomass, ash can also contain metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn) that limit the direct use of ash in the soil i.e. environment (Kalembkiewicz et al., 2018). The ash resulting from industrial incineration can be divided into two different types: bottom ash and fly ash, which also have different compositions. This distinction must be taken into account, as fly ash has a higher concentration of heavy metals (Obernberger and Supancic, 2009).

Forest residue biomass is a relatively abundant renewable resource, mostly originating from forestry activities and forest management practices (e.g. forest fire prevention), and is ideally suited for thermochemical processing into energy vectors (Silva et al., 2019). The resulting biomass ash must be used effectively, and recycling the ash on agricultural land can help reduce the use of artificial fertilizers and close the natural mineral cycle. The estimates of biomass ash derived from forestry are dominated by wood fuel ash (Zhai et al., 2021). The aim of this paper is to evaluate the effects of using forestry-derived biomass ash on soil chemical properties and the possibility of using biomass ash as a soil conditioner during cultivation of giant miscanthus (*Miscanthus x giganteus*). The soil chemical properties to be investigated are i) soil pH, ii) calcium carbonate content, iii) plant-available potassium content and iii) plant-available phosphorus content.

Soil pH is referred to as the "main soil variable" that influences biological, chemical and physical properties and processes in the soil that affect plant growth and biomass yield (Neina, 2019). Neutral soil pH is considered the most favorable pH for plant growth and the problem of soil acidification has been identified as the main threat to soil quality (Caon and Vargas, 2017). It is estimated that up to 30% of the Earth's ice-free land area is occupied by acidic soils, which corresponds to about 4,000 Mha (Von Uexküll and Mutert, 1995). In agricultural practice, soil acidification is usually corrected by the application of calcareous calcium carbonate ($CaCO_3$) to increase the pH of the soil. Due to the alkaline nature of biomass ash, it can be used as a soil-liming material (Qin et al., 2017). $CaCO_3$ is the main source of calcium (Ca) in soil. It is not only an essential plant nutrient, but also a major component of soil and forms the main exchangeable base of clay minerals. Although Ca is present as a natural mineral in the soil, Ca is lost from minerals over time through weathering and is completely lost as a structural component in mature soils (Barker and Pilbeam, 2015). In more mature soils, the Ca present is bound to cation exchange sites, where it usually makes up a high proportion of the total exchangeable cations, so the amounts present depend on the cation exchange capacity (CEC) of the soil. Biomass ash application can provide Ca and also prevent Ca leaching by increasing the pH and site of ion absorption. Potassium (K) is an essential nutrient required by plants and is routinely added to the soil as fertilizer. K is one of the major constituents of biomass ash. The study conducted by Samadhi et al. (2019) on the feasibility of K recovery from biomass ash and its use as a raw material for the production of fertilizer solutions highlights the importance of biomass ash as a K additive. The direct or indirect application of biomass ash can therefore replace artificial mineral fertilizers. Like nitrogen and potassium, phosphorus (P) is also an important macronutrient for plants, which is required for important life functions. It is also one of the most limited nutrients in the soil. Extensive cultivation of vegetables and other crops, as well as natural hazards, deplete the natural phosphate content in the soil (De Silva et al., 2015). If the soil is unable to supply sufficient P, this leads to deficiency symptoms and crop yield losses. Farmers have used phosphate fertilizers to supplement the plants' needs. The phosphorus taken up by plants from the soil comes from the soil solution, where it is present as the inorganic orthophosphate ion $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}, with 'orthophosphate' being the most available (Vidyapeetham, 2013). This inorganic form, which occurs in the soil solution, is therefore the available P for the plants. Together with other macronutrients, biomass ash contains P and can serve as an important supplement in the soil. Although much research has been conducted on the production and properties of biomass ash, there are still gaps in knowledge and research opportunities, particularly with regard to the beneficial reuse of ash (Zhai et al., 2021). Considering the context and importance of biomass ash for agricultural use and to address the gaps in the circular economy, the following research questions were formulated: What are the effects of biomass ash (forest biomass) on soil chemical properties? How well can biomass ash be used as a potential soil conditioner?

MATERIALS AND METHODS

Site Description

The study was conducted at the experimental station "Šašinovec" of the Faculty of Agriculture University of Zagreb (FAUZ), located in the continental part of northwestern Croatia, near the Zagreb city (N 45°51'01.32"; E 16°10'35.85", at the elevation of 123 m above sea level). The experimental field with giant miscanthus (*Miscanthus x giganteus* Greef et Deu) was established in 2016.

Climate

The research area has a temperate continental climate. According to the Köppen classification, the research area has a "Cfwbx" climate (a temperate precipitation climate). The area has an average annual air temperature of 11.8 °C, an average annual precipitation amount of 867 mm, evapotranspiration is 618 mm, the growing degree days for the growing season are 1616 mm and a rain factor is 73.3, indicating a semi-humid climate in the period 1991 – 2018 (Bilandžija, 2019). Temporal variation of average annual air temperature and precipitation amount are presented at Figure 1.

Soil

Soil sampling to determine the chemical soil properties at the research site was carried out in 2016 before the field was established. Sampling was carried out in three repetitions using an Eijkelkamp soil probe in the surface soil layer of 0-30 cm soil depth. The soil at the research site has alkaline reaction (pH_{KCl} = 7.26), contained 0.11% total nitrogen and 1.88% humus, the carbonate content was low (7.6%), it was well supplied with plant-available potassium (18.7 mg K_2O/100 mg soil) and very well supplied with plant-available phosphorus (43 mg P_2O_5/100 g soil). In order to determine the changes in chemical soil properties due to the application of ash, further soil sampling was carried out in three repetitions in 2020 using the Eijkelkamp soil probe in the surface soil layer of 0-30 cm soil depth.

Experimental Design

In a 3-year-old Miscanthus plantation, an additional experiment was set up in 2019 with 2 different doses of ash as a soil conditioner in 3 repetitions (Table 1). The ash was applied in spring, before the beginning of vegetation period, i.e. the sprouting of miscanthus shoots.

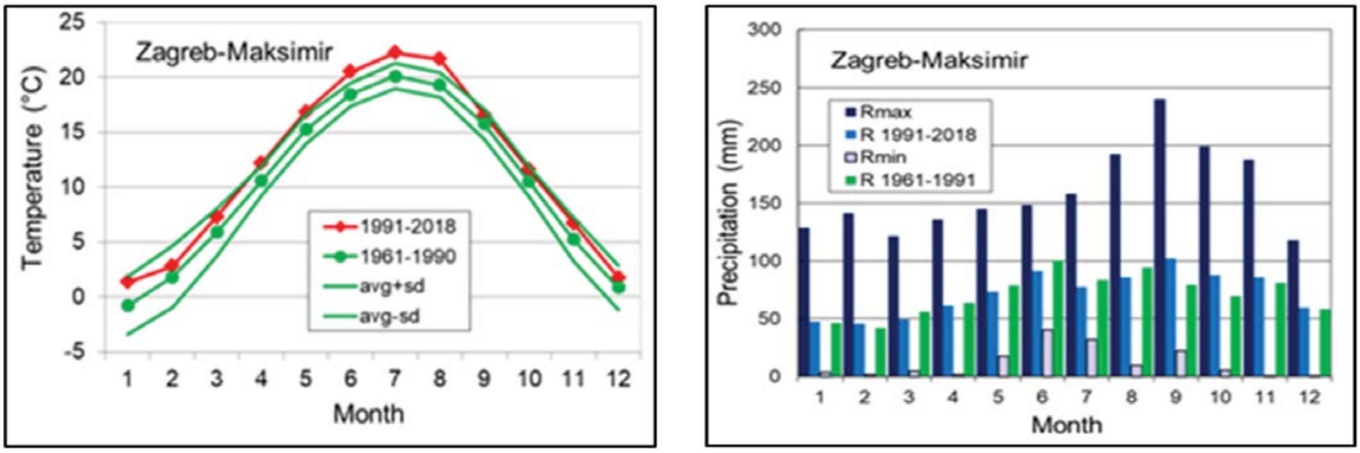

Figure 1. Average annual air temperature, precipitation amount and water balance at the site (source: Bilandžija, 2019)

Table 1. The experiment treatments

Treatment	Doses of applied ash
P0	0 t/ha
P2	2 t/ha
P5	5 t/ha

The ash applied is obtained from forest biomass and has an alkaline reaction, a low humus content, a medium carbonate content, well supplied with plant-available phosphorus and very well supplied with plant-available potassium (Table 2).

Laboratory analysis

The analysis of the soil samples sampled at the experimental field in 2020 was carried out in the analytical laboratory of the Department of General Agronomy, Faculty of Agriculture, University of Zagreb. Analyzed soil properties are: the soil reaction (pH), plant-available phosphorus (P_2O_5) and plant-available potassium (K_2O), and calcium carbonate ($CaCO_3$) content. The soil reaction was determined by potentiometric measurement in a suspension of soil and extractant (1 M KCl) in a ratio of 1:2.5 in accordance with the HRN ISO 10390:2005 standard. The plant-available phosphorus and potassium were extracted with an ammonium-lactate-acetic acid solution (Egner et al. 1960). Potassium was then determined using the chemical flame photometry method and phosphorus using the colorimetric method. The $CaCO_3$ content was determined according to the volumetric method.

Statistical Analysis

Data analysis was performed using STATISTICA 12 software (StatSoft Inc, 2014). The variability between the treatments studied was analyzed using analysis of variance (ANOVA) and, if necessary, tested using the Tukey test. The significance threshold for all analyses was 5%. The prescribed quality control procedures are carried out in the analytical laboratory of the Department of General Agronomy, Faculty of Agriculture, University of Zagreb.

Table 2. Properties of applied biomass ash

	pH_{KCl}	Carbon (%)	Nitrogen (%)	P_2O_5 (mg/100 g)	K_2O (mg/100 g)	$CaCO_3$ (mg/100 g)	Humus (%)
Ash	12.84	3.398	0.005	25.1	<40.0	21.62	1.1

RESULTS AND DISCUSSION

The results of the statistical analysis show that no significant change in pH was observed. However, the $CaCO_3$ content, measured as a percentage (%), increased significantly with both two ash doses of 2 t/ha and 5 t/ha studied. There was a significant increase in the plant-available K_2O (mg/100 kg) of the soil at the higher dose of 5 t/ha applied. However, application with an ash dose of 2 t/ha did not result in a significant change in the measured plant-available K_2O content. With regard to the plant-available P_2O_5 content (mg/100 kg soil), the results showed a decreasing effect when both ash doses were applied. The results obtained in the research are presented in Figure 2.

The alkaline nature of biomass ash plays a role in improving soil reaction by increasing the pH. Maintaining the proper soil pH is paramount to soil processes, including microbial functions, solubility of nutrients, and minimizing leaching and immobilization problems in agriculture. The effectiveness of applying biomass ash to increase soil pH has been successfully documented (Füzesi et al., 2015; Quirantes et al., 2016; Shi et al., 2017). Our analysis showed that the pH increased but not significantly with the applied doses. Gibczyńska et al. (2014) also found no significant increase in soil pH.

The alkalizing effect associated with the application of biochar to the soil environment is related to the content of alkaline compounds and the application rate (Saletnik et al., 2018). Significant effects on soil pH when applying biomass ash can be achieved by applying higher doses of 10-20 t/ha (Park et al., 2005; Saletnik et al., 2018). Füzesi et al. (2015) discovered that when ash was applied at 10 t/ha, the pH increased by about one unit. However, such high doses are not recommended as they could lead to excessive amounts of nutrients or heavy metals entering the soil. Another reason for the non-significant

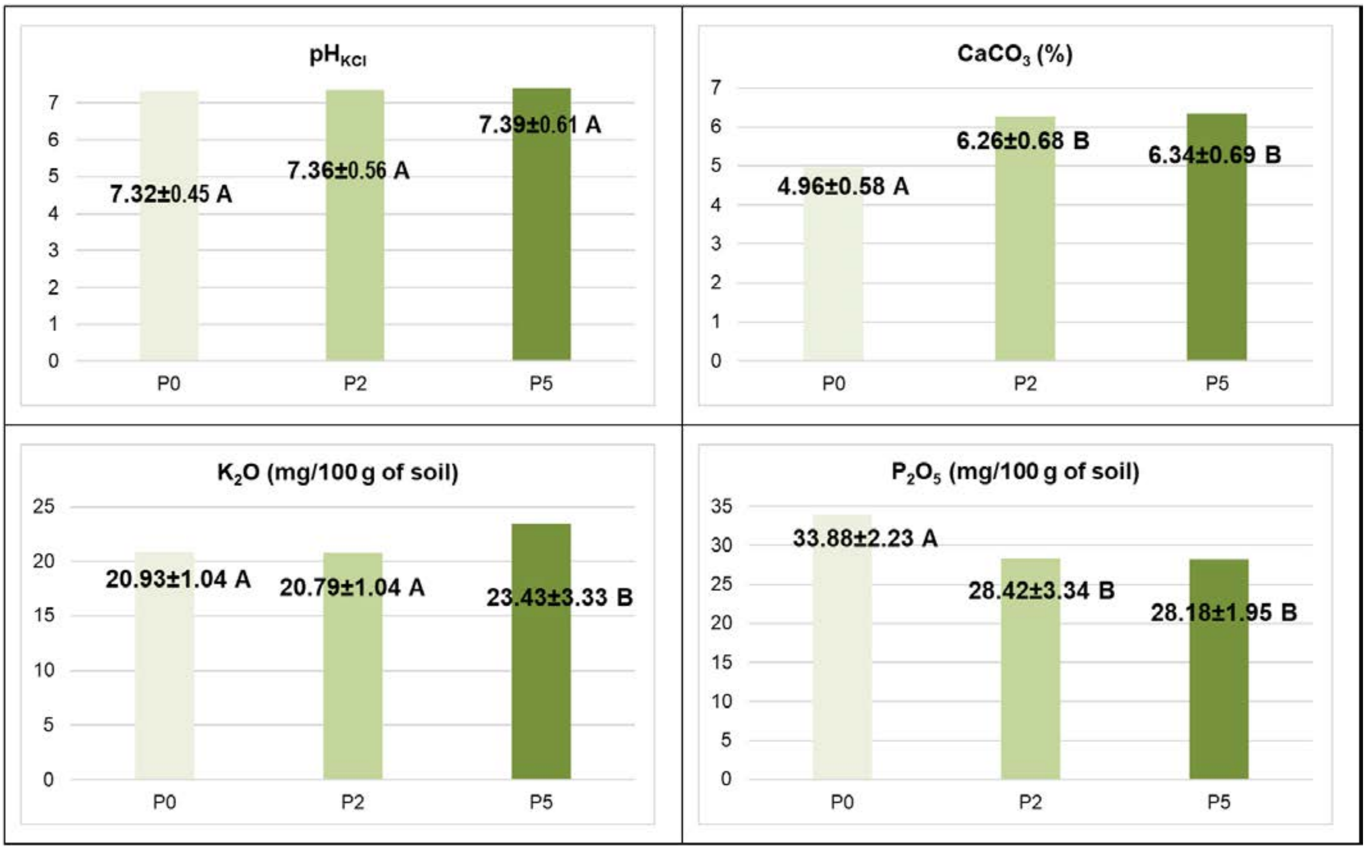

Figure 2. Effects of different ash doses applied on soil pH, $CaCO_3$ (%), K_2O (mg/100g), and P_2O_5 (mg/100g) during cultivation of *Miscanthus x giganteus*

increase could be the duration of the period after the ash application (one year) and the original pH of the soil, which was slightly alkaline. According to the existing literature, the most significant changes can be achieved in highly acidified soils, with a visible decrease in the proportion of H^+ and Al^{3+} (Zong et al., 2016).

The results show that the plant-available phosphorus (P_2O_5) decrease after ash treatment, which is in contrast to the results of the literature (Wierzbowska et al., 2020; Füzesi et al., 2015; Li et al., 2016; Gibczyńska et al., 2014). However, Omil et al. (2011) also observed a low response of phosphorus to the different ash treatments. The reasons for this could be the comparatively low availability of P in the ash, the chemical and microbial immobilization of the element and also the rapid uptake by the plants. The ability of ash to supply macronutrients, including P, has been widely documented in the literature and Wierzbowska et al. (2020) also found that the fertilizing effect of P from ash is comparable to the effect of readily soluble phosphorus fertilizers. The dissolution of ash in soil is a complex process, as is the rate at which nutrients become available to plants, as each cation present in biomass ash is usually present in multiple forms such as oxides, hydroxides, carbonates and bicarbonates (Mercl et al., 2016). Similarly, the time factor after application also plays an important role in the presence of plant-available nutrients in the soil solution (Ochecova et al., 2016). The exact impact of ash application on the soil also depends on the type of cultivated crops on that soil (Wierzbowska et al., 2020). It was concluded that the behavior of biomass ash and nutrient dynamics in the soil is a complex phenomenon and can behave differently depending on several conditions.

The plant-available potassium (K_2O) content in the soil did not change significantly when the lower ash dose of 2 t/ha was applied, but increased significantly when 5 t/ha was applied, which could indicate the need for a higher dose. In an incubation experiment, a 1% ash addition was usually not sufficient to significantly increase the plant-available nutrient content, but a 5% ash addition resulted in a significant increase in the plant-available nutrient pool (Ochecova et al., 2016). Wierzbowska et al. (2020) found that soil concentrations of available forms of K_2O increased in parallel with increasing ash doses. Similarly, Gibczyńska et al. (2014) and Füzesi et al. (2015) found that the amounts of plant-available K in the soil increased with the application of biomass ash. However, Saletnik et al. (2018) analyzed the uptake of ions in miscanthus when fertilized with different combinations of biochar and biomass ash and found that among the analyzed ions, the highest concentration in the biomass of giant miscanthus was found for potassium – both after the first and after the second year of cultivation. Uptake by the plants could therefore be one of the main reasons for the change in contribution only at the higher dose applied.

$CaCO_3$ levels increased significantly with the application of ash doses, even at a lower ash dose of 2 t/ha. This effect could be due to the high $CaCO_3$ content in the applied ash as well as the high alkali content of the biomass ash with a pH_{KCl} of 12.84. Calcium is an important component of biomass ash and its release to the soil increases its availability in the soil (Shi et al., 2016). Mercl et al. (2016) found that the exchangeable Ca content in soil increased with the application of biomass ash. Omil et al. (2011) found that treatment with ash increased the content of carbonate lime in the soil. The increase in available Ca in the soil has an effect on the formation of calcium carbonate in the soil. With increasing pH and excess Ca, $CaCO_3$ (lime) is formed. Even if the change in soil pH was not significant, a higher calcium carbonate content in the soil contributes to the increase in soil pH.

Biomass ash has the potential to enrich the soil with important macronutrients and improve the pH value of the soil. In addition, the application of ash also improves other soil properties such as increasing available micronutrients (Gibczyńska et al., 2014), dehydrogenase activity, electrical conductivity (Quirantes et al., 2016) and CEC (Shi et al., 2016). However, the behaviour of biomass ash in soil is complex and depends on a variety of factors.

CONCLUSION

Although biomass ashes are currently classified as waste, they can provide valuable resources as alternative raw materials in the circular economy, provided that their utilization is regulated by an appropriate legal framework. The study found that the application of biomass ash led to a significant increase in $CaCO_3$ and K_2O content. An increase in pH was found although it was no significant. The effects on the content of plant-available phosphorus in the soil decreased after ash application. It was concluded that the behavior of biomass ash is a complex phenomenon and requires further investigation. Research can continue with monitoring other soil properties along with crop yield assessment for plant uptake. It can also be extended to monitoring the unfavorable aspect of applying higher doses of ash as these could lead to excessive amounts of nutrients or heavy metals entering the soil to better understand the nutrient dynamics and behavior of biomass ash. Similarly, research can be coupled under different agroecological conditions, including different soil and vegetation types. Such research will help to develop practices for utilization and provide specific recommendations for practical use. Appropriate use of biomass ash would fit into the spheres of the circular economy and contribute to better environmental health. The research is only preliminary in terms of the duration of ash application to the soil. However, the role of biomass ash use in enhancing economic and environmental value is recognized. In the future, research can be extended to the growth parameters and yield of bioenergy crops to understand nutrient uptake and accurately predict the behavior of biomass ash. Extending the research to different agro-ecological conditions, soil and vegetation types with a cost-benefit analysis may be beneficial to provide recommendations for practical use. Investigating biomass ash in combination with nature-friendly products could also further improve its effectiveness as a substitute for artificial fertilizers and as a soil conditioner, which needs to be investigated in more detail in the future.

REFERENCES

Barker, A.V., Pilbeam, D.J. (2015) Handbook of Plant Nutrition. CRC Press eBooks. DOI: https://doi.org/10.1201/b18458

Bilandžija, D. (2019) Spatio-Temporal Climate and Agroclimate Diversities over the Zagreb City Area. Geographica Pannonica, 23 (4), 385-397. DOI: https://doi.org/10.5937/gp23-24253

Caon, L., Vargas, R. (2017) Threats to soils: Global trends and perpectives. A Contribution from the Intergovernmental Technical Panel on Soils, Global Soil Partnership Food and Agriculture Organization of the United Nations. In G. Pierzynski & Brajendra (Eds.), Global land outlook working paper, 28 p.

De Silva, C.S., Koralage, I.S.A., Weerasinghe, P., Silva, N.R.N. (2015) The Determination of Available Phosphorus in Soil: A Quick and Simple Method. OUSL Journal, 8 (0). DOI: https://doi.org/10.4038/ouslj.v8i0.7315

Egner, H., Riehm, H., Domingo, W.R. (1960) Untersuchung über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nahrstoffzustanden der Boden. II, Chemische Extraktionsmethoden zur Phosphor und Kaliumbestimmung. Kungliga Lantbrukshögskolans Annaler, 26, 199-215

Füzesi, I., Heil, B., Kovács, G. (2015) Effects of wood ash on the chemical properties of soil and crop vitality in small plot experiments. Acta Silvatica et Lignaria Hungarica, 11 (1), 55–64. DOI: https://doi.org/10.1515/aslh-2015-0004

Garba, M.U., Ingham, D.B., Ma, L., Degereji, M.U., Pourkashanian, M., Williams, A. (2013) Modelling of deposit formation and sintering for the co-combustion of coal with biomass. Fuel, 113, 863–872. DOI: https://doi.org/10.1016/j.fuel.2012.12.065

Gibczyńska, M., Stankowski, S.ł., Hury, G., Kuglarz, K. (2014) Effects of limestone, ash from biomass and compost use on chemical properties of soil. Soil Science Annual, 65 (2), 59–64. DOI: https://doi.org/10.2478/ssa-2014-0009

HRN ISO 10390:2005 Kakvoća tla - Određivanje pH-vrijednosti. Hrvatski zavod za norme.

Ilyushechkin, A.Y., Roberts, D.G., French, D., Harris, D.J. (2012) IGCC Solids Disposal and Utilisation, Final Report for ANLEC Project 5-0710-0065. CSIRO, Australia.

Kalembkiewicz, J., Galas, D., Sitarz-Palczak, E. (2018) The physicochemical properties and composition of biomass ash and evaluating directions of its applications. Polish Journal of Environmental Studies, 27 (6), 2593–2604. DOI: https://doi.org/10.15244/pjoes/80870

Li, X., Rubæk, G.H., Sørensen, P. (2016) High plant availability of phosphorus and low availability of cadmium in four biomass combustion ashes. Science of the Total Environment, 557–558, 851–860. DOI: https://doi.org/10.1016/j.scitotenv.2016.03.077

Mercl, F., Tejnecký, V., Száková, J., Tlustoš, P. (2016) Nutrient dynamics in soil solution and wheat response after biomass ash amendments. Agronomy Journal, 108 (6), 2222–2234. DOI: https://doi.org/10.2134/agronj2016.03.0176

Neina, D. (2019) The Role of Soil pH in Plant Nutrition and Soil Remediation. Applied and Environmental Soil Science, 1–9. DOI: https://doi.org/10.1155/2019/5794869

Obernberger, I., Supancic, K. (2009) Possibilities of Ash Utilisation from Biomass Combustion Plants. Proceedings of the 17th European Biomass Conference and Exhibition, pp. 2373–2384. Available at: https://graz.pure.elsevier.com/de/publications/possibilities-of-ash-utilisation-from-biomass-combustion-plants [Accessed 15 November 2022]

Ochecova, P., Tlustos, P., Szakova, J., Mercl, F., Maciak, M. (2016) Changes in nutrient plant availability in loam and sandy clay loam soils after wood fly and bottom ash amendment. Agronomy Journal, 108 (2), 487–497. DOI: https://doi.org/10.2134/agronj2015.0143

Omil, B., Sánchez-Rodríguez, F., Merino, A. (2011) Effects of Ash Applications on Soil Status, Nutrition, and Growth of Pinus radiata D. Don Plantations. In: Recycling of Biomass Ashes. Berlin Heidelberg: Springer, pp. 69–86. DOI: https://doi.org/10.1007/978-3-642-19354-5_6

Park, B.B., Yanai, R.D., Sahm, J.M., Lee, D.K., Abrahamson, L.P. (2005) Wood ash effects on plant and soil in a willow bioenergy plantation. Biomass and Bioenergy, 28 (4), 355–365. DOI: https://doi.org/10.1016/j.biombioe.2004.09.001

Qin, J., Hovmand, M.F., Ekelund, F., Rønn, R., Christensen, S., Groot, G.A., de Mortensen, L.H., Skov, S., Krogh, P.H. (2017) Wood ash application increases pH but does not harm the soil mesofauna. Environmental Pollution, 224, 581–589. DOI: https://doi.org/10.1016/j.envpol.2017.02.041

Quirantes, M., Calvo, F., Romero, E., Nogales, R. (2016) Soil-nutrient availability affected by different biomass-ash applications. Journal of Soil Science and Plant Nutrition, 16 (1), 159–163. DOI: https://doi.org/10.4067/S0718-95162016005000012

Saletnik, B., Zagula, G., Bajcar, M., Czernicka, M., Puchalski, C. (2018) Biochar and biomass ash as a soil ameliorant: The effect on selected soil properties and yield of giant miscanthus (*Miscanthus x giganteus*). Energies, 11 (10). DOI: https://doi.org/10.3390/en11102535

Samadhi, T.W., Wulandari, W., Amalia, R.A., Khairunnisah, R. (2019) Potassium recovery from tropical biomass ash. AIP Conference Proceedings, 2085. DOI: https://doi.org/10.1063/1.5094981

Shi, R.Y., Li, J.Y., Ni, N., Mehmood, K., Xu, R., Qian, W. (2017) Effects of biomass ash, bone meal, and alkaline slag applied alone and combined on soil acidity and wheat growth. Journal of Soils and Sediments, 17 (8), 2116–2126. DOI: https://doi.org/10.1007/s11368-017-1673-9

Shi, R.Y., Li, J.Y., Xu, R.K., Qian, W. (2016) Ameliorating effects of individual and combined application of biomass ash, bone meal and alkaline slag on acid soils. Soil and Tillage Research, 162, 41–45. DOI: https://doi.org/10.1016/j.still.2016.04.017

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

StatSoft, Inc. (2014) STATISTICA Data Analysis Software System, version 12; StatSoft Inc: Tulsa, OK, USA.

Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G. (2010) An overview of the chemical composition of biomass. Fuel, 89 (5), 913–933. DOI: https://doi.org/10.1016/j.fuel.2009.10.022

Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G. (2013a) An overview of the composition and application of biomass ash. Part 1. Phase-mineral and chemical composition and classification. Fuel, 105, 40–76. DOI: https://doi.org/10.1016/j.fuel.2012.09.041

Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G. (2013b) An overview of the composition and application of biomass ash.: Part 2. Potential utilisation, technological and ecological advantages and challenges. Fuel, 105, 19–39. DOI: https://doi.org/10.1016/j.fuel.2012.10.001

Vidyapeetham, A.V. (2013) Soil Analysis-Determination of Available Phosphorus Content in the Soil by Bray's Method. Advanced Analytical Chemistry Virtual Lab: Chemical Sciences. Available at: https://vlab.amrita.edu/?sub=2&brch=294&sim=1550&cnt=1 [Accessed 22 March 2024]

Von Uexküll, H.R., Mutert, E. (1995) Global extent, development and economic impact of acid soils. Plant and Soil, 171 (1), 1–15.

Wierzbowska, J., Sienkiewicz, S., Zarczyński, P., Krzebietke, S. (2020) Environmental application of ash from incinerated biomass. Agronomy, 10 (4), 482. DOI: https://doi.org/10.3390/agronomy10040482

Zhai, J., Burke, I.T., Stewart, D.I. (2021) Beneficial management of biomass combustion ashes. Renewable and Sustainable Energy Reviews, 151, 111555. DOI: https://doi.org/10.1016/j.rser.2021.111555

Zong, Y., Xiao, Q., Lu, S. (2016) Acidity, water retention, and mechanical physical quality of a strongly acidic Ultisol amended with biochars derived from different feedstocks. Journal of Soils and Sediments, 16 (1), 177–190. DOI: https://doi.org/10.1007/s11368-015-1187-2