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ORIGINAL PAPER

Recovery of Water-Soluble Fertilizers from Biomass Boiler Ash Via Acid Leaching: Evaluation of Primary and Residual Effects on Maize Growth and Nutrient Uptake

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Abstract

This study evaluated the potential of water and acid-leached boiler ash (BA) as fertilizers by analyzing the elemental contents, recovery rates, and their effects on maize growth and soil nutrient dynamics. The resulting leachates were dried, and the molecular compositions of the materials were analyzed using XRD and FTIR. These materials were then applied to maize plants at a rate equivalent to 100 mg kg^{-1} of P. Subsequently, maize plants were grown again in the same pots without further application, and the P and other plant nutrient levels in the plants were determined. Despite variations in leach methods, over 5% P, 7% K, 16% Ca, and 3% Mg remained in the filter residues, while H_3PO_4 and HCl-leaching yielded the highest P concentrations in the leachates (7.45% and 5.95%, respectively). Water-leaching produced the highest K concentration (22%). As compared to control, the leachates significantly enhanced maize growth, with HNO_3-leached fertilizer producing the highest dry weight in the first crop and H_2SO_4 and H_3PO_4-leached fertilizers being most effective for the second crop. Phosphorus and K uptake increased across all treatments, with P uptake peaking in the first crop with H_2SO_4 and in the second crop with H_2SO_4 and H_3PO_4. Soil analysis revealed elevated plant-available P, K, and Mg levels after fertilizer applications, especially with H_2SO_4 and H_3PO_4, which persisted into the second crop. The results highlight the potential of BA-leachates as effective fertilizers for enhancing nutrient recovery and crop productivity, with tailored leaching treatments optimizing nutrient availability.

Keywords Circular economy · Incineration ash · Nutrient recovery · Waste management

1 Introduction

Agricultural byproducts, particularly organic wastes, can be significant sources of essential nutrients for plants, yet their effective recycling remains a major focus in sustainable farming practices (Shah et al. 2022). Rising global food demand increases organic waste generation, making biomass power generation increasingly important to meet expanding energy needs(Tripathi et al. 2019; Sudalai et al. 2024) Biomass power converts waste into energy and is considered carbon-neutral, as the CO_2 released equals the amount absorbed by plants during their growth cycle. In a world where environmental consciousness is paramount, biomass presents a valuable alternative. However, this approach is not without controversy, as many environmental groups raise concerns (Kataya et al. 2023).

In biomass power plants that use boiler bedding, approximately 10% of the biomass used as fuel is released as waste ash in the form of boiler ash, wet ash, and fly ash. The composition of these waste ashes reveals that all plant nutrients, except nitrogen (N), are present at concentrations approximately 10 times higher than before combustion (Fahimi et al. 2020; Gunes et al. 2024). However, because the combustion process occurs at temperatures between 800 and 1000 °C, the elements in the ash become calcined, reducing their solubility in water and, consequently, their availability to plants (Gunes et al. 2024; Kan et al. 2024). As fertilizer

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raw materials, particularly P, are becoming increasingly scarce, it is important to explore alternative sources for sustainable agriculture. Producing fertilizer from incineration ash contributes to a circular economy by recycling nutrients, reducing waste, and offering a sustainable alternative to traditional fertilizers. This approach not only enhances environmental sustainability but also supports economic and agricultural resilience.

The acidification of waste ashes is an effective strategy for making P and other nutrients in their composition available for plant use. Acidification, especially with sulfuric acid, yields highly successful results (Gunes et al. 2024; Kan et al. 2024). In this method, since the entire waste ash is converted into fertilizer, no residue is left behind. Another method for utilizing waste ashes is washing them with acids to obtain fertilizer. The leaching technique is particularly important for producing water-soluble fertilizers. However, factors such as the type of acid, concentration, and reaction time significantly impact the success of nutrient recovery when leaching plant nutrients from ash using acids. In this method, after washing the minerals in the ash, a small amount of non-soluble residue remains. Fertilizers obtained through acidification are suitable for field crop agriculture, whereas those obtained through leaching are suitable for drip irrigation systems. Thus, these methods, each with their own advantages and limitations, are important as they serve different areas in fertilization practices. Fertilizer recovery from BA incineration ash using acid leaching is an emerging technique aimed at extracting valuable nutrients, primarily P, for agricultural use. Poultry litter is rich in essential plant nutrients. When incinerated, these nutrients remain in the ash, making it a potential source for recovery. However, due to the mineral composition and insolubility of some of these compounds, direct use of the ash is limited. Acid leaching addresses this by dissolving these minerals, making the nutrients more bioavailable as fertilizers. There are studies on P recovery from BA using the acid-washing method (Kaikake et al. 2009; Cempa et al. 2022; Fahimi et al. 2022). These studies have primarily focused on mainly P recovery, and only a single type of acid was used; after the fertilizers were produced, their effects on plants and their reactions in the soil were not examined. Water-soluble fertilizers produced by acid leaching of BA contain plant-available macro- and micronutrients in sufficient quantities to enhance both the primary and residual growth and nutrient uptake of consecutively cultivated maize plants. This study investigates the potential of water-soluble fertilizers recovered from biomass boiler ash through acid leaching to enhance maize growth and nutrient uptake in both primary and residual cropping cycles. It is hypothesized that the type of acid used during leaching significantly affects nutrient solubility and fertilizer composition, thereby influencing maize growth performance and nutrient accumulation. Accordingly, the study aimed to develop water-soluble fertilizers by leaching biomass boiler ash with different acids and to evaluate their agronomic effectiveness by comparing the primary and residual effects of the macro- and micronutrients they provide on the growth and nutrient uptake of consecutively cultivated maize plants.

2 Materials and methods

2.1 Synthesis and Characterizationof Acid Leaching Boiler Ash

The boiler ash used in this study was derived from chicken manure utilized as fuel for electricity generation by MAV Co. in Bolu, Ankara. The research aimed to produce fertilizer by dissolving the elements in the boiler ash using HCl (37%, Merck), H_2SO_4 (97%, Merck), HNO_3 (65%, Merck), H_3PO_4 (85%, Merck), and water. For this purpose, 200 g of BA was placed in five separate containers, and 500 ml of 1 M H_2SO_4 was added to each to facilitate nutrient dissolution. The mixtures were then filtered. After the initial, 200 mL of each leaching solution (1 M HCl, 1 M H_2SO_4, 1 M HNO_3, 1 M H_3PO_4 and tap water) was added to dissolve the remaining material on the filter and improve nutrient extraction in both the leachate (below the filter) and the filter cake (above the filter). After these processes, the residue remaining under and above the filter separated and dried at 65 °C. Water soluble (1 h extraction with distilled water, 1:100 w/v) and total (hotplate aqua regia digestion) element concentrations (P, K, Ca, Mg, Fe, Zn, Cu and Mn) of all BA leachate and filter cake were determined by ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry, Perkin Elmer Model DV 2100) (Boss and Fredeen 2004). The structural properties of boiler ash leachates treated with water and various acids were determined by an X-ray diffractometer (Rigaku, D/max-2200 Ultima) with Cu-Kα radiation (k:0.15406 nm) in the range of between 0 and 90° 2theta. The functional groups of leachates were characterized through Fourier transform infrared spectroscopy (FTIR). IR spectra ranging from 500 to 4000 cm^{-1} were collected using a FTIR Spectrometer (Thermo Scientific, Nicolet is10).

To explain the recovery rate of leachate with various acids, the leaching recovery (LR) was used as defined in Eq. (1):

$$LR\,(\%) = \frac{Con.\ of\ Filter\ Cake + Con.\ of\ Leachate}{Cont.\ of\ Leache} \times 100 \qquad (1)$$

*Con. Concentration, (mg kg^{-1})

2.2 Plant Growth Conditions and Treatments of Leachates

The first maize (*Zea Mays L*. cv. Pioneer 2088) experiment was conducted under greenhouse conditions with natural lighting at the Faculty of Agriculture, Ankara University (39°57′44.51″ N; 32°51′46.95″ E), from June 2 to July 7, 2024. The experimental soil was taken from the plow depth of the experimental area (0–20 cm), dried and sieved through 2 mm and subjected to the necessary chemical analysis (Page et al. 1982). Some physical and chemical properties of soil were given in Table 1. To evaluate the residual effects of the leachates, a second maize (*Zea Mays L*. cv. Pioneer 2088) crop was grown in the same pots used in the first experiment, conducted from July 12 to August 16, 2024. First and second maize plants were grown in pots containing 2 kg of air-dried soil. The experiment was conducted with four replications and comprised the following treatments: control (Unfertilized soil), tap water leachate, HCl leachate, H_2SO_4 leachate, HNO_3 leachate, and H_3PO_4 leachate. All leachate materials were dried, ground into powder, and applied to the soil at a rate of 2.5 g kg^{-1}. Fertilizers were mixed homogeneously into the soil and eight homogeneous maize seeds were planted per pot. In the second week, the number of plants was thinned to three in all pots. In both experiments, no basal fertilization was applied. Instead, N was supplied as a top dressing at a rate of 100 mg N kg^{-1} soil per pot using NH_4NO_3 (33.5% N). During the experiments, randomly selected pots were weighed daily and irrigated with the required volume of water to reach 70% of the field capacity.

After all experiments, the plants were harvested by cutting them at the soil surface, thoroughly washed with tap water followed by distilled water, and dried at 65 °C until all moisture was removed. The dry weight of the samples was determined using a precision balance (accuracy: 0.001 g). The dried samples were ground using a static grinder, sieved through a 0.20 mm mesh, and prepared for plant analysis. Additionally, 100 g of soil samples were collected after harvesting for the soil analysis.

2.3 Determination of Macro and Microelement Concentrations of Maize Plants and Post-harvesting Soil

Dried plant samples were digested with HNO_3-$HClO_4$ acid mixture (Kalra 1997). Total P, K, Ca, Mg, Zn, Fe, Cu, and Mn concentrations were determined by ICP-OES (Perkin Elmer Optima 2100 DV, Waltham, MA, USA). The peach leaves received from the National Institute of Standards and Technology were used as the standard reference material with the code 1547. Plant available P concentration of soil was determined according to Olsen et al. (1960). Exchangeable K, Ca and Mg were extracted with NH_4OAc (Pratt 1965) and Fe, Zn, Cu and Mn were extracted with DTPA (Lindsay and Norvell 1978) and macro and micronutrients were determined by ICP-OES.

2.4 Statistical and Multivariate Analysis

The significance of treatments was determined with one-way ANOVA (MINITAB 17 software) and the significant differences among the treatment means were determined using Duncan's Multiple Range Test (MSTAT-C software), with significance set at $p < 0.05$. Bar charts, FTIR spectra, and principal component analysis (PCA) were generated using OriginPro 2021 (OriginLab, Northampton, MA, USA).

Table 1 Some physical and chemical properties of experiment soil

Properties (Method)	Soil
Texture (Bouyoucos)	Sandy clay loam
pH (1:2.5 water)	7.88
EC (1:2.5 water), dS m^{-1}	0.38
$CaCO_3$ (Scheibler), g kg^{-1}	74.1
Organic matter (Walkley-Black), g kg^{-1}	1.50
P ($NaHCO_3$-extractable), mg kg^{-1}	1.55
Total-N (Kjeldahl), g kg^{-1}	0.60
K (NH_4OAc-extractable), mg kg^{-1}	178
Ca (NH_4OAc-extractable) mg kg^{-1}	4900
Mg (NH_4OAc-extractable), mg kg^{-1}	500
Zn (DTPA-extractable), mg kg^{-1}	0.54
Fe (DTPA-extractable), mg kg-¹	4.39
Cu (DTPA-extractable), mg kg^{-1}	1.75
Mn (DTPA-extractable), mg kg^{-1}	3.09

3 Results

3.1 Characterization of Leached Materials

Fourier transform infrared spectroscopy analysis was conducted to identify functional group differences in leachates obtained from biomass ash treated with water and various acids (HCl, H_2SO_4, HNO_3, and H_3PO_4) (Fig. 1). The spectra around 1100 cm^{-1} indicate phosphate groups formed by the dissolution of phosphates or carbonates, along with silicate or sulfate vibrations from the ash matrix. Peaks near 600 cm^{-1} correspond to metal oxides and phosphate groups, while those at around 1300 cm^{-1} in HNO_3 and H_3PO_4 leachates represent asymmetric stretching of nitrate and phosphate ions, respectively. Carbonate stretching bands around 1300 cm^{-1} likely result from acid–carbonate reactions. Absorptions near 1625 cm^{-1} in all acid leachates reflect hydration, whereas peaks around 800 cm^{-1}, particularly in HNO_3 and H_3PO_4 treatments, indicate Si-O-Si or Si-O-Al bonds, confirming the partial dissolution of silicate and phosphate species.

X-ray diffraction (XRD) was used to determine the mineral phases in leachates obtained from biomass ash treated with water and different acids. The water leachate exhibited peaks at 13°- 44° 2θ, indicating the presence of $CaCO_3$/$CaSO_4$ (13°−15°), silicates (21°), phosphate minerals such as $Ca_3(PO_4)_2$ or hydroxyapatite (HAP) (24°−32°), and oxides like CaO and MgO (38°−44°) (Fig. 2). The HCl-leached sample showed peaks at 20°−45° 2θ corresponding to $CaH_2PO_4 \cdot 2H_2O$ (20°), HAP (28°), SiO_2 (29°−30°), calcium phosphate (32°), and CaO/MgO (40°- 45°) (Fig. 3A). For H_2SO_4 leachates, peaks at 15°–44° 2θ indicated $MgNH_4PO_4 \cdot 6H_2O$ (15°), mono- and dicalcium phosphates (18°–32°), $CaSO_4 \cdot 2H_2O$ (33°), and CaO/MgO (44°) (Fig. 3B). The HNO_3 leachate displayed peaks at 11°−47° 2θ, signifying hydrated phosphates (11°), monocalcium and magnesium phosphates (19°–26°), dicalcium phosphate and its dihydrate forms (29°−33°), $Ca(NO_3)_2 \cdot 4\ H_2O$ (34°), and Ca/Mg oxides (44°−47°) (Fig. 3C). The H_3PO_4 leachate showed peaks at 21°–44° 2θ attributed to monocalcium phosphate (21°, 29°−32°), HAP (24°), $CaSO_4$ (39°), and CaO/MgO (44°) (Fig. 3D). Our, XRD results confirm that acid leaching transformed the mineral composition of the ash, promoting the formation of soluble phosphate and sulfate phases and thereby enhancing nutrient availability in the leachates.

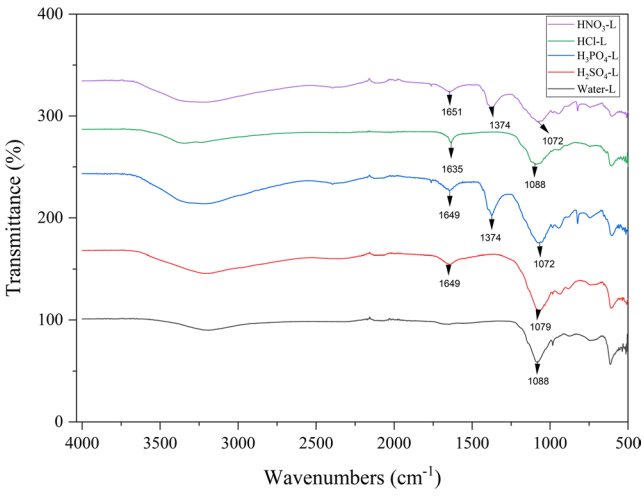


Fig. 1 Fourier Transform Infrared (FTIR) spectroscopy analysis of boiler ash leachates treated with water (Water-L) and different acids HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L)

3.2 Element Concentration and Recovery Rate of Leachate with Various Acids

The elemental contents and recovery rates of the materials remaining on the filter (filter cake) and in the leachates are presented in Figs. 4 and 5. It was determined that, despite different extraction methods, more than 5% of P, 7% of K, 16% of Ca, and 3% of Mg remained in the material on the filter (Fig. 4A, B, C, D). In contrast, the lowest P concentration in the leachates was obtained with the water leach treatment, followed by HCl, HNO_3, H_2SO_4, and H_3PO_4, respectively. Potassium (K) concentrations in the leachates exceeded 16%, with the highest value (22%) obtained from the water leachate. The Ca concentration in the leachates was significantly lower compared to the material on the filter. Magnesium (Mg) extraction was around 3.5% in the leachates obtained with water and the other acids.

The lowest Fe concentration in the filter residue was observed with the HNO_3 treatment, while the lowest Zn and Cu contents were found with the water and HNO_3 leach treatments. The lowest Mn content was observed with the water leach treatment. In the leachates (under the filter), the concentrations of Fe, Zn, Cu, and Mn were approximately 5000 mg kg^{-1}, 2500 mg kg^{-1}, 600 mg kg^{-1}, and 4000 mg kg^{-1}, respectively (Fig. 5A, B, C, D).

When the recovery rates (%) of elements with water and acid treatments were calculated, the highest P recovery was achieved with H_3PO_4, and H_2SO_4, at 55.3%, and 52.5%, respectively. Potassium recovery was quite high (over 69.4%), with the highest K recovery (75.9%) obtained with the water leach treatment. Calcium (Ca) recovery remained below 6.60% across all treatments. The highest Mg recovery was obtained with HCl leach (89.8%), while in other treatments, this rate was slightly above 50%. The recovery rates for Fe, Zn, Cu, and Mn exceeded 90% in almost all treatments.

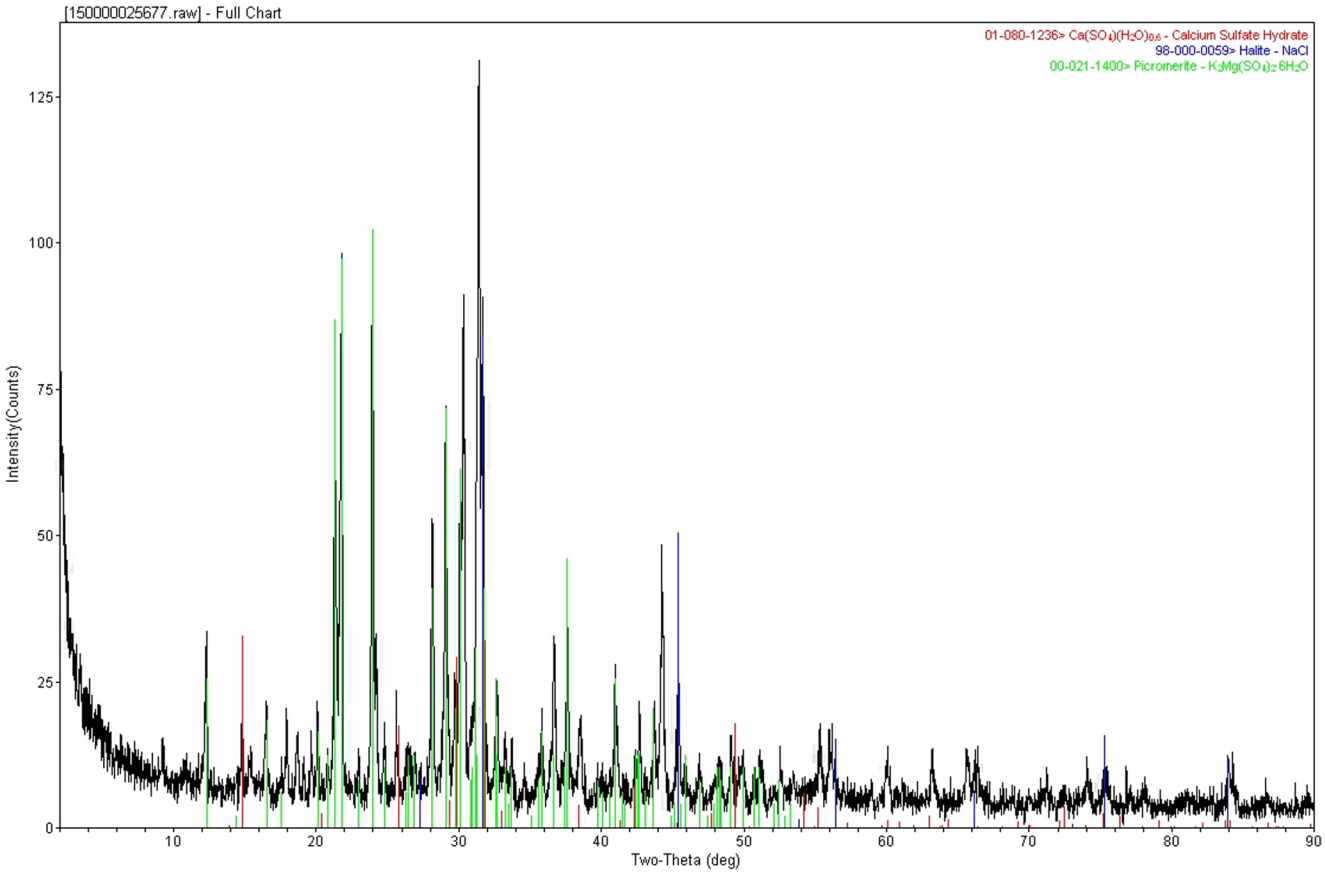


Fig. 2 X-ray diffraction (XRD) pattern of boiler ash leachate treated with water (Water-L)

3.3 Dry Weights of Plants

The effects of fertilizers obtained by dissolving with water and various acids on the dry weight of the first and second maize plants were significant. In first maize plant, the highest dry weight as compared to control was observed in the HNO_3-leached fertilizer. In the second maize plants grown without additional fertilizer after the harvest of the first plants, the highest dry weight was found in the H_2SO_4 and H_3PO_4-leached fertilizer treatments (Table 2).

3.4 Total Phosphorus and Potassium Concentration and Uptake of Plants

All fertilizer applications significantly increased the phosphorus (P) concentration in plants compared to the control, both in the first and second maize plants. In the control treatment, the P concentration of the plants was around 1.0 g kg^{-1}. In the first maize plant, the highest P concentration, 2.72 g kg^{-1}, was obtained from the H_2SO_4-leached fertilizer. In the second maize plant, P concentrations increased to 1.73 g kg^{-1} and 1.67 g kg^{-1} with the H_3PO_4 and H_2SO_4-leached fertilizer applications, respectively. The P uptake of plants, similar to the P concentration, increased with the applied ash leachates. The highest P uptake was observed in the first maize plant with the H_2SO_4 leach treatment and in the second maize plant with both H_2SO_4 and H_3PO_4 leach treatments (Table 2).

In the first maize crop, the K concentrations of the plants was decreased by the HCl, HNO_3, H_3PO_4-leached fertilizer treatments as compared to control plants. In the first maize crop, K concentrations decreased with the application of HCl, HNO_3, and H_3PO_4-leached fertilizers compared to the control. While the K concentrations of the second maize plants were decreased by H_2SO_4, HNO_3, H_3PO_4-leached fertilizer treatments. However, when evaluating the effects of ash leach treatments on K uptake by the plants, it was observed that K uptake in both maize plants increased by at least twofold compared to the control in all treatments (Table 2).

3.5 Calcium and Magnesium Concentrations and Uptake of Plants

In the both experiments, the Ca concentrations of the plants significantly decreased with all fertilizer treatments.

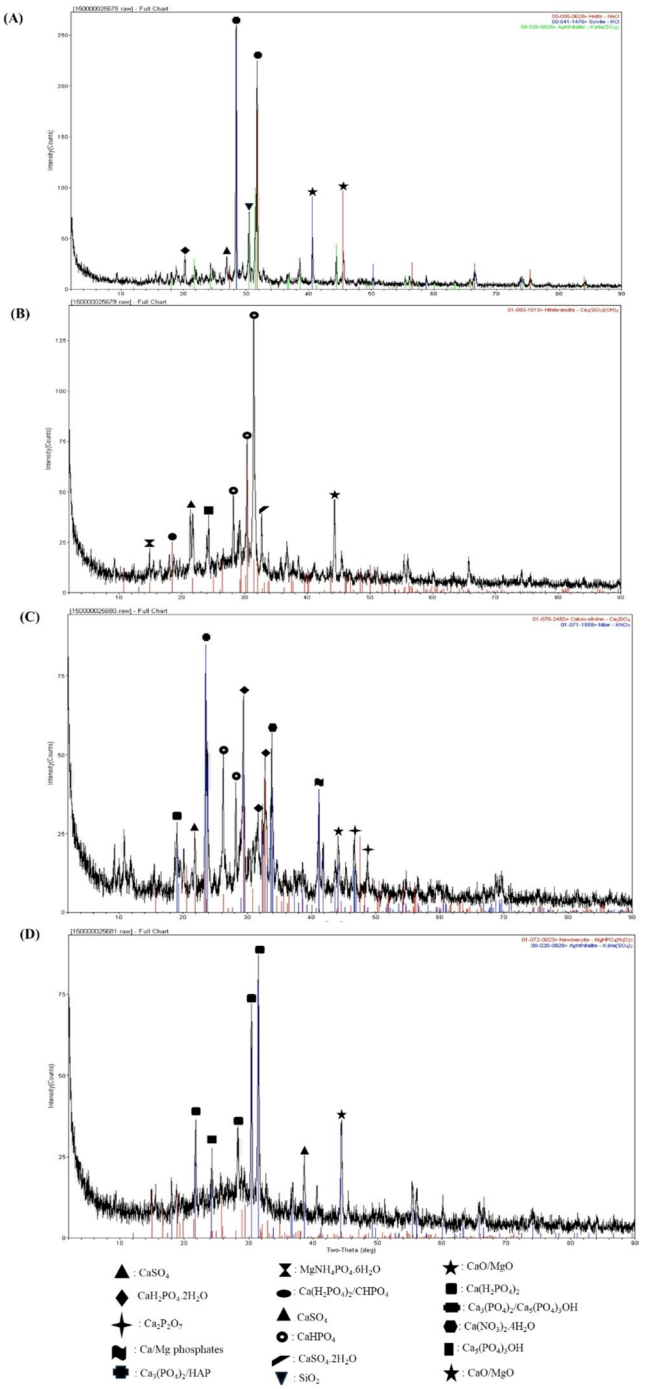


Fig. 3 X-ray diffraction (XRD) patterns of boiler ash leachates treated with HCl (B), H_2SO_4 (C), HNO_3 (D), and H_3PO_4 (E)

However, except for the first maize crop, the Ca uptake of the plants significantly increased with all ash-leach treatments compared to the control (Table 3).

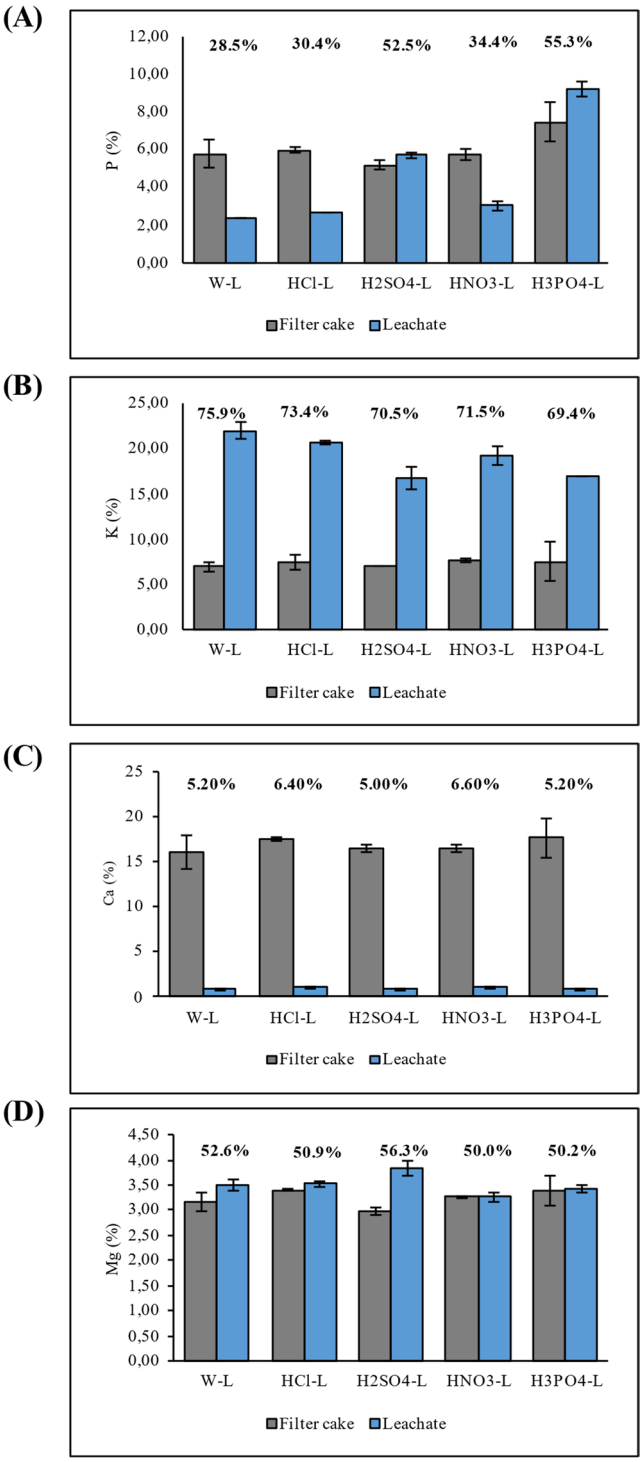


Fig. 4 Concentrations of total phosphorus (**A**), potassium (**B**), calcium (**C**), and magnesium (**D**) in the filter cake and leachates treated with water (W-L) and various HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L). The percentage values displayed above each column represent the recovery rates of the macronutrients

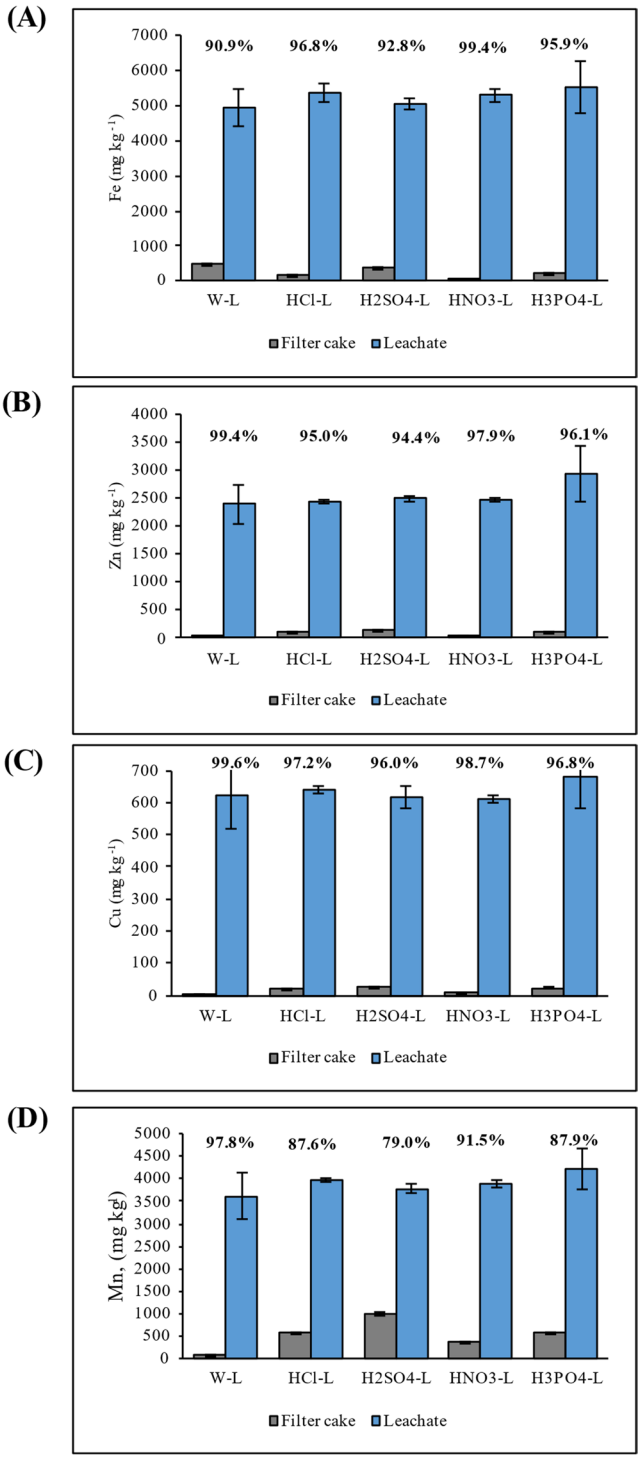


Fig. 5 Concentrations of total iron (**A**), zinc (**B**), copper (**C**), and manganese (**D**) in the filter cake and leachates treated with water (W-L) and various acids HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L). The percentage values above each column indicate the recovery rates of the micronutrients

In the first maize crop, Mg concentrations significantly decreased with all fertilizer treatments. Similarly, in the second maize crop, Mg concentrations decreased with the water and HCl-leached treatments. However, Mg uptake in the plants increased in all treatments compared to the control, with the highest Mg uptake observed in the first crop under the HNO_3-leach treatment. In the second maize crop, Mg uptake increased in all treatments except for the water-leach treatment (Table 3).

3.6 Iron, Zinc, Copper and Manganese Concentration and Uptake of Plants

The effects of fertilizer applications on the Fe concentration of plants were not significant. However, Fe uptake by the plants increased with ash-leach treatments, and this increase was particularly significant in the first maize crop with the H_2SO4 and HNO_3-leach treatments (Table 4).

In the first maize crop, the Zn concentration of the plants decreased with water and HCl-leached fertilizer applications, while other leached fertilizers did not affect Zn concentrations. In contrast, in the second maize crop, Zn concentrations decreased with all leached fertilizer applications compared to the control, but these differences were statistically insignificant. However, Zn uptake by the plants showed significant increases in the first maize crop with the H_2SO_4, HNO_3, and H_3PO_4 treatments compared to the control (Table 4).

The Cu concentration in the first maize plants decreased with all fertilizer applications compared to the control, while no change was observed in the second maize crop. In the first maize plants, Cu uptake increased with water and HCl-leach applications, whereas in other treatments, it was either the same as the control or showed a decrease compared to the control. In the second maize plants, Cu uptake was higher than the control with the HCl, H_2SO_4, and H_3PO_4-leach treatments (Table 5).

Fertilizer applications, particularly in the first maize crop, significantly reduced the Mn concentration in the plants. In contrast, in the second maize plants, Mn concentration decreased in all treatments except for HCl and HNO_3-leach applications. However, Mn uptake in the first maize plant increased significantly in all treatments compared to the control, especially with the HNO_3-leach application. Similarly, in the second maize crop, Mn uptake significantly increased in all treatments except for the water-leach application (Table 5).

Table 2 Impact of boiler Ash leachates obtained using water (Water-L), HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L) on dry weight, phosphorus (P) concentration, phosphorus uptake, potassium (K) concentration, and potassium uptake of first and second crop maize

Treatments	First Crop Maize				
	DW g pot^{-1}	*P* g kg^{-1}	*P* uptake, mg pot^{-1}	K g kg^{-1}	K uptake mg pot^{-1}
Control	6.46 ± 0.21 d	0.94 ± 0.03 e	6.11 ± 0.36 d	44.6 ± 1.80 a	287 ± 5.69 c
Water-L	14.5 ± 0.08 b	1.91 ± 0.05 c	27.8 ± 0.57 bc	40.8 ± 2.12 ab	592 ± 28.0 a
HCl-L	14.5 ± 0.33 b	1.78 ± 0.08 c	25.7 ± 1.40 bc	38.8 ± 1.14 b	560 ± 19.3 a
H_2SO_4-L	14.1 ± 0.26 bc	2.72 ± 0.14 a	38.5 ± 2.29 a	39.5 ± 1.42 ab	557 ± 22.2 a
HNO_3-L	17.6 ± 0.42 a	1.36 ± 0.07 d	24.0 ± 1.69 c	36.6 ± 1.85 bc	646 ± 46.8 a
H_3PO_4-L	13.2 ± 0.41 c	2.25 ± 0.11 b	29.7 ± 1.57 b	32.9 ± 1.82 c	437 ± 36.2 b
F value	144**	52.05**	52.67**	5.22**	19.7**
LSD	0.92	0.26	4.37	5.11	87.3
Second Crop Maize					
Control	3.71 ± 0.53 c	1.01 ± 0.06 b	3.82 ± 0.72 c	39.2 ± 1.69 a	145 ± 20.8 d
Water-L	7.33 ± 0.79 b	1.36 ± 0.23 ab	9.48 ± 0.73 b	36.3 ± 1.33 ab	267 ± 32.9 c
HCl-L	8.59 ± 1.34 b	1.48 ± 0.36 ab	11.8 ± 1.62 b	38.7 ± 2.43 a	324 ± 34.7 abc
H_2SO_4-L	11.4 ± 0.70 a	1.67 ± 0.18 a	18.7 ± 1.20 a	31.1 ± 1.09 b	353 ± 18.0 ab
HNO_3-L	9.12 ± 0.93 ab	1.23 ± 0.06 ab	11.1 ± 0.92 b	32.0 ± 1.85 b	287 ± 16.7 bc
H_3PO_4-L	11.5 ± 0.53 a	1.73 ± 0.08 a	19.9 ± 0.86 a	31.8 ± 0.77 b	365 ± 9.54 a
F value	11.6**	2.01*	32.2**	5.11**	11.3**
LSD	2.53	0.57	3.14	4.81	70.9

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan Multiple Range Test. ns: not significant; *: $p < 0.05$; **: $p < 0.01$. (Uptake = Dry weight x Element concentration)

Table 3 Impact of boiler Ash leachates obtained using water (Water-L), HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L) on calcium (Ca) concentration, calcium uptake, magnesium (Mg) concentration, and magnesium uptake of first and second crop maize

Treatments	First Crop Maize			
	Ca g kg^{-1}	Ca uptake mg pot^{-1}	Mg g kg^{-1}	Mg uptake mg pot^{-1}
Control	7.17 ± 0.11 a	46.2 ± 0.93 d	3.56 ± 0.02 a	23.0 ± 0.88 d
Water-L	3.89 ± 0.11 c	56.5 ± 1.63 c	2.18 ± 0.07 c	31.6 ± 1.12 b
HCl-L	4.55 ± 0.21 b	65.6 ± 2.46 b	2.27 ± 0.09 c	32.7 ± 0.84 b
H_2SO_4-L	4.73 ± 0.36 b	66.6 ± 4.77 b	2.29 ± 0.09 c	32.3 ± 1.26 b
HNO_3-L	5.06 ± 0.05 b	89.0 ± 2.32 a	2.66 ± 0.07 b	46.9 ± 2.20 a
H_3PO_4-L	4.85 ± 0.19 b	63.9 ± 1.87 bc	2.09 ± 0.06 c	27.6 ± 0.99 c
F value	32.1**	29.3**	57.98**	38.1**
LSD	0.58	7.78	0.22	3.86
Second Crop Maize				
Control	7.99 ± 0.88 a	28.5 ± 2.70 c	5.41 ± 0.31 a	20.0 ± 3.04 c
Water-L	4.47 ± 0.20 b	32.4 ± 2.83 c	3.67 ± 2.24 c	26.4 ± 2.13 bc
HCl-L	5.69 ± 0.75 b	46.0 ± 1.46 b	3.95 ± 0.58 bc	32.4 ± 3.30 b
H_2SO_4-L	5.63 ± 0.88 b	62.4 ± 5.48 a	4.89 ± 0.47 ab	54.8 ± 2.27 a
HNO_3-L	5.72 ± 0.54 b	51.1 ± 4.46 ab	4.93 ± 0.22 ab	46.6 ± 3.83 a
H_3PO_4-L	4.88 ± 0.22 b	56.1 ± 3.46 ab	4.51 ± 0.20 abc	51.7 ± 2.70 a
F value	3.59*	13.4**	3.21*	23.3**
LSD	1.91	10.8	1.08	8.73

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan Multiple Range Test. *: $p < 0.05$; **: $p < 0.01$. (Uptake = Dry weight x Element concentration)

Table 4 Impact of boiler Ash leachates obtained using water (Water-L), HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L) on iron (Fe) and zinc (Zn) concentrations and their uptake in first and second crop maize

Treatments	First Crop Maize			
	Fe mg kg^{-1}	Fe Uptake µg pot^{-1}	Zn mg kg^{-1}	Zn Uptake µg pot^{-1}
Control	133 ± 31.2	873 ± 229 b	19.9 ± 2.86 a	128 ± 18.7 c
Water-L	76.8 ± 13.8	1116 ± 203 b	11.0 ± 2.03 b	160 ± 29.9 c
HCl-L	81.8 ± 13.7	1173 ± 178 b	5.35 ± 0.91 b	77.7 ± 14.3 c
H_2SO_4-L	96.7 ± 7.94	1364 ± 112 ab	19.5 ± 1.86 a	275 ± 24.7 b
HNO_3-L	125 ± 32.8	2164 ± 510 a	23.0 ± 3.49 a	404 ± 60.3 a
H_3PO_4-L	66.0 ± 20.0	857 ± 235 b	20.0 ± 0.75 a	263 ± 7.58 b
F value	1.53^{ns}	3.09^{*}	9.35^{**}	14.8^{**}
LSD	-	817	6.57	92.0
Second Crop Maize				
Control	155 ± 20.5	558 ± 92.9	12.4 ± 1.61	48.2 ± 12.0
Water-L	296 ± 163	1799 ± 748	5.10 ± 0.42	36.8 ± 3.86
HCl-L	121 ± 17.6	1075 ± 280	9.85 ± 3.75	72.4 ± 19.3
H_2SO_4-L	120 ± 11.6	1352 ± 124	7.25 ± 1.65	79.2 ± 12.7
HNO_3-L	201 ± 35.4	1909 ± 441	5.75 ± 0.88	52.0 ± 8.98
H_3PO_4-L	167 ± 42.1	1963 ± 564	4.90 ± 0.97	57.3 ± 12.9
F value	0.85^{ns}	1.57^{ns}	2.52^{ns}	1.58^{ns}
LSD	-	-	-	-

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan Multiple Range Test. ns: not significant; *: $p < 0.05$; **: $p < 0.01$. (Uptake = Dry weight x Element concentration)

Table 5 Impact of boiler Ash leachates obtained using water (Water-L), HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L) on copper (Cu) and manganese (Mn) concentrations and their uptake in first and second crop maize

Treatments	First Crop Maize			
	Cu mg kg^{-1}	Cu Uptake µg pot^{-1}	Mn mg kg^{-1}	Mn Uptake µg pot^{-1}
Control	7.60 ± 1.57 a	49.8 ± 11.2 ab	114 ± 8.83 a	736 ± 49.1 c
Water-L	4.60 ± 1.00 b	66.9 ± 14.7 a	71.7 ± 2.89 b	1041 ± 46.6 b
HCl-L	3.40 ± 0.94 bc	49.1 ± 14.0 ab	74.4 ± 2.36 b	1074 ± 32.0 b
H_2SO_4-L	1.50 ± 0.71 c	21.2 ± 9.90 bc	74.0 ± 4.35 b	1043 ± 54.9 b
HNO_3-L	1.40 ± 0.08 c	24.7 ± 1.97 bc	81.1 ± 1.05 b	1428 ± 46.4 a
H_3PO_4-L	0.95 ± 0.30 c	12.2 ± 3.43 c	70.9 ± 5.34 b	932 ± 44.0 b
F value	7.87^{**}	4.10^{*}	12.1^{**}	24.2^{**}
LSD	2.70	30.9	14.3	136
Second Crop Maize				
Control	6.00 ± 0.41	22.8 ± 4.42 c	65.4 ± 2.15 a	244 ± 37.7 c
Water-L	4.60 ± 0.64	32.5 ± 2.61 bc	54.7 ± 3.40 bc	402 ± 50.7 bc
HCl-L	5.85 ± 0.57	50.4 ± 8.89 ab	58.3 ± 1.59 abc	498 ± 72.9 ab
H_2SO_4-L	6.00 ± 1.47	65.7 ± 11.4 a	53.9 ± 3.28 bc	608 ± 4.43 a
HNO_3-L	4.30 ± 0.76	40.1 ± 8.58 bc	63.4 ± 5.76 ab	587 ± 90.1 a
H_3PO_4-L	4.30 ± 0.39	49.6 ± 5.48 ab	52.4 ± 1.64 c	602 ± 28.7 a
F value	1.17^{ns}	4.04^{*}	2.60^{*}	6.85^{**}
LSD	-	22.3	9.81	164

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan Multiple Range Test. ns: not significant; *: $p < 0.05$; **: $p < 0.01$. (Uptake = Dry weight x Element concentration)

Table 6 Impact of boiler Ash leachates obtained using water (Water-L), HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L) on plant-available phosphorus (P), exchangeable potassium (K), calcium (Ca), and magnesium (Mg) concentrations in soil after harvesting the first and second crop maize

Treatments	After first crop	After second crop	After first crop	After second crop
	P, mg kg^{-1}	*P*, mg kg^{-1}	K, mg kg^{-1}	K, mg kg^{-1}
Control	6.60 ± 0.31 d	7.59 ± 0.81 d	235 ± 5.72 d	185 ± 4.72 b
Water-L	18.7 ± 0.96 c	14.8 ± 0.39 c	430 ± 5.06 a	244 ± 12.5 a
HCl-L	20.0 ± 0.69 c	14.1 ± 0.79 c	368 ± 1.50 b	231 ± 22.9 a
H_2SO_4-L	41.2 ± 2.21 b	24.0 ± 1.07 b	306 ± 4.71 c	166 ± 6.01 b
HNO_3-L	23.5 ± 0.80 c	15.3 ± 1.32 c	268 ± 4.64 d	168 ± 9.17 b
H_3PO_4-L	89.3 ± 6.41 a	30.5 ± 2.74 a	386 ± 12.7 b	172 ± 8.78 b
F value	110**	33.6**	127**	7.83**
LSD	8.40	4.17	19.7	36.4
	Ca, mg kg^{-1}	Ca, mg kg^{-1}	Mg, mg kg^{-1}	Mg, mg kg^{-1}
Control	5199 ± 91.9	5637 ± 77.3 a	552 ± 3.96 c	567 ± 7.03 b
Water-L	5392 ± 66.4	5636 ± 98.9 a	630 ± 10.7 ab	620 ± 16.0 a
HCl-L	5305 ± 64.4	5448 ± 81.9 a	615 ± 2.62 b	618 ± 10.4 a
H_2SO_4-L	5324 ± 55.3	5595 ± 86.3 a	633 ± 11.2 ab	631 ± 5.19 a
HNO_3-L	5281 ± 149	5574 ± 24.4 a	612 ± 12.9 b	616 ± 1.16 a
H_3PO_4-L	5225 ± 26.9	5027 ± 264 b	650 ± 3.99 a	596 ± 21.1 ab
F value	0.56ns	3.31*	15.4**	3.68*
LSD	-	384	25.6	36.1

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan Multiple Range Test. ns: not significant; *: $p < 0.05$; **: $p < 0.01$

3.7 Plant Available Phosphorus, Potassium, Calcium and Magnesium Concentrations of the Soils after Harvest

After harvesting the first maize crop, the available P concentration in the soil was significantly higher with fertilizer applications compared to the control. A similar effect was observed after the second maize crop. The available P concentrations measured after the first maize crop decreased across all treatments following the harvest of the second maize crop. When comparing the leached fertilizers, it was found that the H_3PO_4- and H_2SO_4-leached fertilizer applications resulted in higher soil P concentrations after the harvest of both crops compared to other treatments (Table 6).

After the first maize plant was harvested, the plant-available K concentration in the control soil was measured at 235 mg kg^{-1}, while it increased to 430 mg kg^{-1} with the water-leach treatment. In other leach treatments, the soil K concentrations were also higher than the control. In the second maize plant, the soil K concentrations showed a noticeable decrease compared to the first maize plant. However, in the water and HCl-leach treatments, the soil K concentrations were significantly higher compared to the control and other treatments (Table 6).

After the harvest of the first maize plants, no differences were observed in the soil Ca concentrations among the treatments. In the second maize crop, however, the H_3PO_4-leach treatment caused a decrease in the plant-available Ca concentration in the soil, while the other treatments, as with the first maize crop, did not cause any changes in the soil Ca concentration (Table 6).

In the first maize crop, the plant-available Mg concentration in the soil was higher in all treatments compared to the control. After the second maize crop, the plant-available Mg concentration in the soil remained significantly higher than the control in all treatments except for the H_3PO_4-leach treatment (Table 6).

3.8 Plant Available Iron, Zinc, Copper and Manganese Concentrations of the Soils After Harvest

After the harvest of the plants, no differences were observed in the plant-available concentrations of Fe, Zn and Cu in the soil. However, following the harvest of the first maize crop, the highest Mn concentration, at 68.9 mg kg^{-1}, was recorded with the HNO_3-leach treatment compared to other treatments. After the second maize crop, higher plant-available Mn concentrations were observed with the H_3PO_4 and H_2SO_4-leach treatments compared to the control (Table 7).

Table 7 Impact of boiler Ash leachates obtained using water (Water-L), HCl (HCl-L), H_2SO_4 (H_2SO_4-L), HNO_3 (HNO_3-L), and H_3PO_4 (H_3PO_4-L) on plant-available iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) concentrations in soil after harvesting the first and second crop maize

Treatments	After first crop	After second crop	After first crop	After second crop
	Fe, mg kg^{-1}	Fe, mg kg^{-1}	Zn, mg kg^{-1}	Zn, mg kg^{-1}
Control	38.5 ± 1.41	32.6 ± 1.19	3.39 ± 0.20	3.32 ± 0.09
Water-L	34.5 ± 0.40	32.3 ± 0.87	3.19 ± 0.13	3.09 ± 0.15
HCl-L	33.9 ± 0.69	30.8 ± 1.84	3.61 ± 0.13	3.37 ± 0.06
H_2SO_4-L	38.1 ± 1.38	34.8 ± 1.14	3.43 ± 0.06	3.27 ± 0.05
HNO_3-L	35.8 ± 0.31	33.9 ± 0.63	3.35 ± 0.19	3.24 ± 0.07
H_3PO_4-L	35.9 ± 2.44	35.8 ± 1.03	3.72 ± 0.11	3.53 ± 0.23
F value	1.89^{ns}	2.40^{ns}	1.70^{ns}	1.32^{ns}
LSD	-	-	-	-
	Cu, mg kg^{-1}	Cu, mg kg^{-1}	Mn, mg kg^{-1}	Mn, mg kg^{-1}
Control	8.48 ± 0.25	7.86 ± 0.27	59.2 ± 3.48 b	30.6 ± 1.26 c
Water-L	7.69 ± 0.11	7.51 ± 0.20	54.2 ± 1.30 b	32.8 ± 4.40 c
HCl-L	7.80 ± 0.09	7.37 ± 0.19	54.5 ± 1.28 b	34.9 ± 4.64 bc
H_2SO_4-L	8.23 ± 0.19	8.07 ± 0.21	58.4 ± 2.94 b	51.2 ± 6.67 ab
HNO_3-L	7.85 ± 0.05	7.73 ± 0.16	68.9 ± 3.26 a	47.3 ± 9.29 abc
H_3PO_4-L	8.27 ± 0.38	8.23 ± 0.25	59.1 ± 3.15 b	54.9 ± 4.45 a
F value	2.96^{ns}	2.24^{ns}	3.87^{*}	3.38^{*}
LSD	-	-	8.10	16.9

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan Multiple Range Test. ns: not significant; *: $p < 0.05$

3.9 Principal Component Analysis

In the first maize experiment, principal component analysis (PCA) showed a total variability of 59.94% (PC1 = 41.86%; PC2 = 18.08%) (Fig. 6A). According to PCA analysis, H_2SO_4- and H_3PO_4-leached treatments were effective on dry weight, plant and soil P concentration, soil Mg and soil Ca while DW and HCl-leached treatments were effective on soil K and soil Zn concentration. HNO_3-leached treatment was also effective on soil Mn, Cu, and Fe and plant Zn and Fe concentrations. A positive correlation was found between plant dry weight and plant and soil P concentration, soil K, Ca, Mg, Zn, Mn concentrations, while a negative correlation was found with plant K, Ca, Mg, Fe, Zn, Cu, Mn and soil Fe and Cu concentrations.

In the second maize experiment, PCA showed a total variability of 53.16% (PC1 = 34.29%; PC2 = 18.87%) (Fig. 6B). According to PCA analysis, H_2SO_4- and HCl-leached treatments were effective on dry weight, plant and soil P concentration, while HNO_3- and H_3PO_4-leached treatments were effective on soil Fe, Zn, Cu and Mn concentration. DW-leached treatment also effectively affected plant Fe, soil K and C concentration. A positive correlation was found between plant dry weight and plant and soil P concentration, soil Mg, Fe, Zn, Cu and Mn concentrations. In contrast, a negative correlation was found with plant K, Ca, Mg, Fe, Zn, Cu, Mn and soil K and Ca concentrations.

4 Discussion

Producing fertilizer from BA holds significant importance from a circular economy perspective. The circular economy model emphasizes resource efficiency by reusing and recycling materials to minimize waste and reduce environmental impact (Geissdoerfer et al. 2017). Converting BA into fertilizer aligns well with these principles, as it transforms waste into a valuable resource for agriculture, supporting sustainable practices and reducing dependency on non-renewable resources like mined P (Walsh et al. 2023; Gunes et al. 2024; Kan et al. 2024). Poultry litter is rich in essential plant nutrients (Gunes et al. 2015; Sahin et al. 2017). Through incineration, these nutrients are concentrated in the ash (Gunes et al. 2024; Kan et al. 2024). By processing this ash into fertilizer, valuable nutrients are returned to the soil, promoting crop growth and maintaining soil fertility (Fahimi et al. 2020; Cempa et al. 2022; Gunes et al. 2024; Mohanty et al. 2025). Incineration of poultry litter also helps manage waste efficiently, preventing the direct land application of raw manure, which can lead to nutrient runoff, water pollution, and greenhouse gas emissions (Manogaran et al. 2022; Thakur et al. 2025).

The FTIR spectra derived from the leachates afforded profound elucidations regarding the dissolution phenomena of mineral constituents, encompassing phosphates, carbonates, silicates, and sulfates. Noteworthy spectral bands, particularly those manifesting around 1100 cm^{-1},

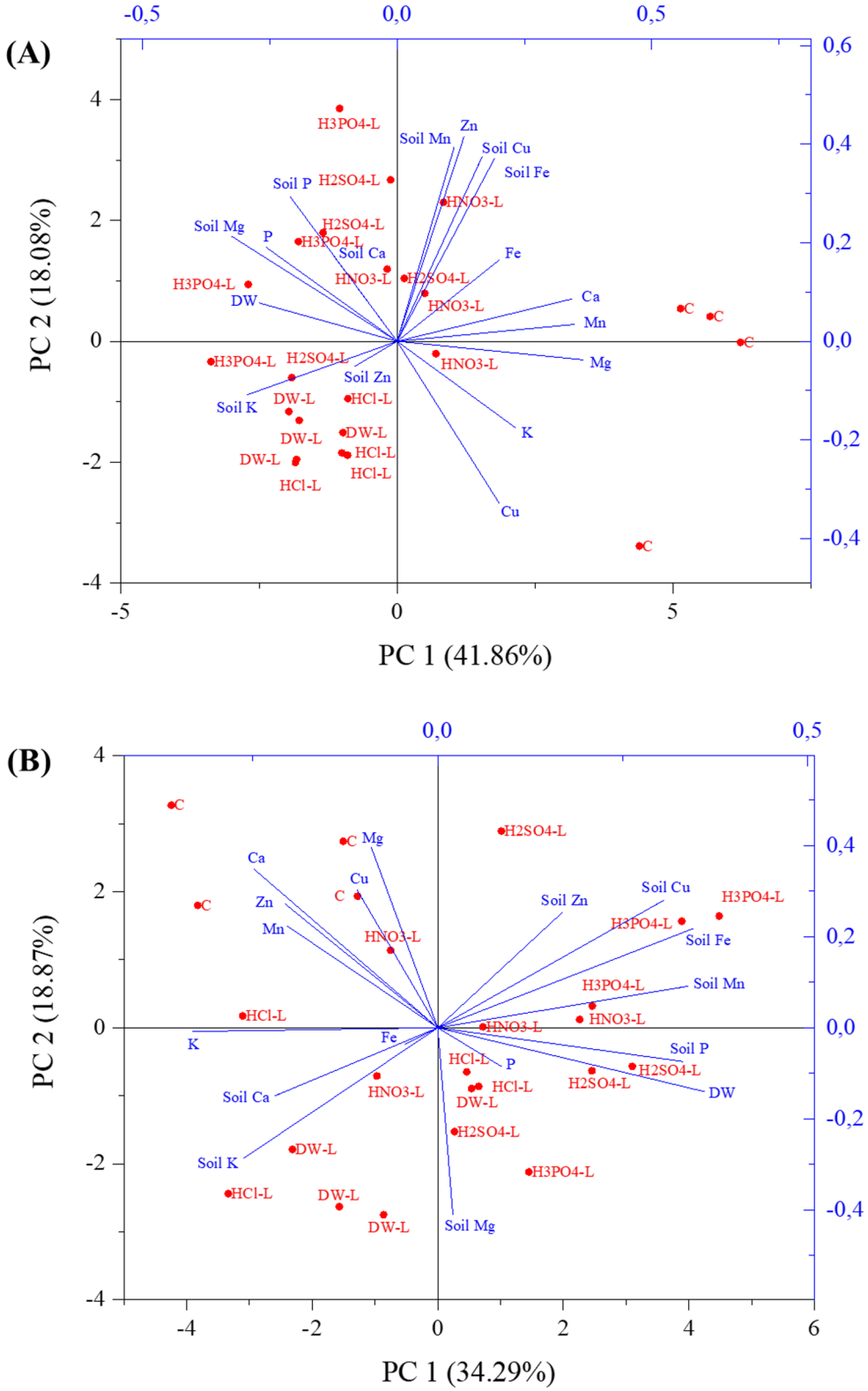


Fig. 6 The biplots from the principal component analysis (PCA) illustrate the leaching behavior of boiler ash leachates treated with water and various acids for the first maize experiment (**A**) and the second maize experiment (**B**)

600 cm^{-1}, 1300 cm^{-1}, 1625 cm^{-1}, and 800 cm^{-1}, serve as compelling indicators for the transference of these species into the leachate matrices during the process of acid extraction. The acquired data imply that acid treatments involving HNO_3 and H_3PO_4 substantially facilitate the dissolution of disparate components from the BA, thereby augmenting the leachate with critical ionic entities, including phosphates, nitrates, carbonates, and silicates. Such observations

significantly advance our comprehension of the intricate chemical dynamics of BA during acid-mediated leaching processes and emphasize its prospective utility within the domain of fertilizer production.

The XRD analysis of the mineral content in BA leachates treated with different acids shows how the solubility and reactivity of ash components differ when exposed to various acids. Water extraction mainly removes soluble salts and minerals, leading to the presence of Ca-based and silicate minerals. In contrast, the use of acids such as HCl, H_2SO_4, HNO_3, and H_3PO_4 induces specific chemical processes that result in the formation of different mineral phases. For instance, HCl primarily dissolves and recrystallizes phosphate minerals (Kaikake et al. 2009; Azeez et al. 2024), whereas H_2SO_4 leaching leads to the creation of sulfate minerals like gypsum and struvite, which suggests a strong interaction with Ca and the formation of new compounds (Gunes et al. 2024; Kan et al. 2024). Nitric acid extraction dissolves both Ca and phosphate minerals, producing a range of phosphate minerals and hydrated phases. Phosphoric acid, on the other hand, mostly generates stable phosphate minerals, particularly hydroxyapatite, indicating its preference for calcium phosphates. There is no study investigating the leaching characteristics of BA with various acids. However, our XRD results are in line with the findings obtained from the studies we have conducted to enhance the solubility of BA, particularly with respect to P (Gunes et al. 2024; Kan et al. 2024). In conclusion, the XRD results highlight the significant role that the choice of acid plays in mineral extraction and recovery, with the chemical interactions between acids and ash components resulting in varied mineral profiles that have potential uses in the fertilizer industry.

With limited phosphate rock reserves and the growing demand for food production, the need for alternative P sources has become essential (El Attar et al. 2022; Illalkwahhi et al. 2024). Fertilizer derived from BA provides a sustainable substitute, reducing reliance on non-renewable mineral fertilizers and supporting long-term food security (Scholz et al. 2013; Fahimi et al. 2020; Kan et al. 2024). Utilizing BA as a resource can also be economically beneficial, creating new revenue streams for industries involved in poultry production and waste management (Gunes et al. 2024). This value addition aligns with sustainable agricultural practices that focus on waste reduction. Circular economy practices prioritize efficient resource use. By recovering nutrients from waste, this process exemplifies resource efficiency, keeping valuable materials in use and enhancing productivity in the agricultural sector without depleting natural resources.

The study highlights the potential of BA leachates as effective fertilizers, showcasing their ability to enhance nutrient availability and plant uptake. The effectiveness of the leaching process varied depending on the acid used, influencing the nutrient composition of the leachates and their subsequent impact on maize growth and soil nutrient dynamics. The leaching treatments varied in their effectiveness for extracting different elements. Water leaching was particularly effective for K, with concentrations in the leachates being higher than those obtained from acid treatments. This suggests that K is readily soluble in water, making it a suitable and cost-effective option for K extraction. Additionally, the relative dilution of elements in the leachates, caused by the mass increase in the obtained materials due to the action of leach acids, has also played a role in this. In contrast, P extraction was significantly more efficient with acid treatments, especially HCl, H_3PO_4, and H_2SO_4, which facilitated the dissolution of P from complex compounds such as hydroxyapatite in the ash (He et al. 2010; Gunes et al. 2024; Kan et al. 2024). Magnesium recovery was also enhanced by HCl, although it remained relatively low with other treatments. Acid leachates also exhibited higher recovery rates for trace elements like Fe, Zn, Cu, and Mn, indicating the strong affinity of these metals for acidic environments.

The impact of these leachates on maize growth was observed in two cropping cycles. Fertilizer applications significantly increased P concentrations in maize plants, with the highest P concentrations recorded for the H_2SO_4-leached fertilizer in the first crop. In the second maize crop, P concentrations remained elevated in plants treated with H_3PO_4 and H_2SO_4, suggesting residual effects of these fertilizers in the soil. Despite a decrease in K concentrations in plant tissues, K uptake increased significantly, likely due to improved root absorption and nutrient availability from the leachates. Calcium and Mg concentrations in the plants were generally lower with most leach treatments, although uptake increased, particularly for Mg under HNO_3 treatment. The variation in Ca and Mg responses indicates that the interaction between these nutrients and the leaching agents is complex and may require further investigation to optimize fertilizer formulations. The reduction in the concentrations of elements such as K, Ca, and Mg in plants following fertilizer application can be attributed to the dilution effect, resulting from the substantial impact of fertilizers on plant growth. Indeed, the total uptake of these elements has increased significantly. The decrease in the concentration of plant nutrients in the plant, despite an increase in their uptake, was previously described in detail as the "dilution effect" by Jarrell and Beverly (1981) and Marschner (2012).

The impact of leachates on micronutrient uptake was also significant. Manganese uptake increased notably, particularly with HNO_3 treatment, suggesting that leachates enhance the mobility and absorption of micronutrients

(Alloway 2008). Although the concentrations of Fe, Zn, and Cu in plant tissues remained relatively stable, their uptake increased with specific treatments. This emphasizes the role of leachates in improving micronutrient availability and aligns with the dilution effect described for K, Ca, and Mg by Jarrell and Beverly (1981) and Marschner (2012).

Soil nutrient dynamics were similarly influenced by the leachate applications. The available P in the soil increased after both maize crops, with H_3PO_4 and H_2SO_4 treatments maintaining higher P levels even after the second crop, suggesting that these treatments may offer long-term nutrient availability. Potassium concentrations in the soil also increased with all leach treatments, particularly with water and HCl leachates. Magnesium levels were sustained at higher levels in the soil with most treatments, except for H_3PO4, which caused a decrease, possibly due to interactions between Ca and P (White 2003). Microelement concentrations in the soil showed minimal variation, except for Mn, which increased significantly, particularly with HNO_3, H_3PO_4, and H_2SO_4 treatments. This suggests that these treatments may have long lasting effects on Mn availability, benefiting subsequent crops.

5 Conclusion

Fertilizers derived from boiler ash leachates present a sustainable and effective alternative to conventional chemical fertilizers by enhancing nutrient availability and utilization. The type of leaching agent plays a significant role in determining nutrient composition, release dynamics, and subsequent effects on plant growth and nutrition. Among the treatments, acid-based leachates particularly those prepared with H_3PO_4 and H_2SO_4 demonstrated the potential to provide a more consistent nutrient supply across successive cropping cycles, whereas water-leached ash proved particularly effective for recovering potassium. These findings suggest that nutrient recovery from industrial ash wastes through targeted leaching can be tailored to produce fertilizers suited to specific crop or soil nutrient requirements. This approach aligns strongly with the principles of the circular economy, promoting the recycling of industrial by-products into valuable agricultural inputs and reducing dependence on non-renewable fertilizer resources. Future studies should aim to evaluate the long-term agronomic performance, nutrient cycling efficiency, and environmental impacts of boiler ash derived fertilizers under field conditions. Additionally, exploring the integration of these recovered fertilizers within broader nutrient management systems could further enhance their role in sustainable and circular agricultural production.

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Code availability Not applicable.

Declarations

Consent to participate Not applicable.

Consent for publication Not applicable.

Ethics approval Not applicable.

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