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RESEARCH ARTICLE

From Poultry Litter Ash to Recovered Potassium Fertilizer: Water Extraction, Characterization, and Agronomic Validation in Sugar Beet

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Abstract

Biomass power plants utilizing poultry litter as fuel generate large quantities of ash residues, including boiler ash (BA), fly ash (FA), and wet ash (WA), which represent an underutilized source of plant nutrients, particularly potassium (K). This study aimed to characterize these ash materials and their water-soluble fractions and to evaluate the agronomic effectiveness of K fertilizers recovered via simple water extraction in sugar beet cultivation. Boiler ash, FA, and WA obtained from a poultry litter-fired biomass power plant were characterized by X-ray diffraction (XRD) before and after water extraction. The water-soluble fractions were dried and formulated as ash-derived K fertilizers, designated BA-K (27.6%K_2O), FA-K (21.4%K_2O), and WA-K (25.2% K_2O). A pot experiment was conducted in which these fertilizers were compared with conventional K_2SO_4 and a non-K control. XRD results indicated distinct mineralogical transformations following water extraction, with sharper diffraction peaks in the leachates, suggesting enrichment of water-soluble K phases. All ash-derived fertilizers significantly increased aboveground biomass and tissue K concentration compared with the control, indicating enhanced K accumulation in plant tissues, while FA-K produced the highest storage root dry weight. Ash-based fertilizers also improved Ca and Mg nutrition relative to K_2SO_4. Although sugar content decreased under K fertilization, total sugar yield was highest with FA-K and WA-K. Moreover, post-harvest soil plant-available K was higher in all K-treated soils, demonstrating that a portion of the applied K remained in the soil as residual K rather than being fully taken up by plants. Ash-derived K fertilizers showed strong potential as sustainable alternatives to conventional K fertilizers within a circular nutrient management framework.

Keywords Circular economy · Waste management · Leaching process · Poultry manure ash · Sugar beet

Introduction

The rapidly increasing global population and the growing demand for intensive agricultural production necessitate the sustainable use of natural resources to meet both energy generation and plant nutrition needs, as conventional high-input farming systems increasingly strain land, water, and nutrient supplies while contributing to environmental degradation (Searchinger et al. 2019; FAO 2020; OECD and FAO 2024). In addition, an intensified use of mineral fertilizers places significant pressure on finite natural resources. Potassium (K) plays a critical role in crop productivity and quality by regulating enzyme activation, osmotic balance, photosynthesis, and carbohydrate translocation (White et al. 2021; Cao et al. 2025). Sugar beet (*Beta vulgaris* L.), a crop with high yield potential, is particularly sensitive to K supply, as K availability strongly influences storage root yield, sugar accumulation, and processing quality (Füllgrabe et al. 2022; Xie et al. 2022; Nassar et al. 2023). Consequently, ensuring a sustainable and reliable K supply has become a key challenge for modern agriculture.

The expansion of intensive poultry production has resulted in the generation of large quantities of poultry litter

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(PL), which is increasingly utilized as a fuel in biomass power plants for renewable energy production (Lynch et al. 2013; Santos Dalólio et al. 2017; Gunes et al. 2024; Sarker and Nanda 2025). Combustion of PL at high temperatures (typically 800–900 °C) generates substantial amounts of solid residues, namely BA, WA, and FA (Gunes et al. 2024; Dula and Kraszkiewicz 2025; Moslehi et al. 2025). These ashes are rich in essential plant nutrients, particularly phosphorus (P), K, calcium (Ca), magnesium (Mg), and micronutrients, reflecting the mineral composition of the original biomass (Gunes et al. 2024; Kan et al. 2024; Moslehi et al. 2025; Taskin et al. 2025). From both environmental and circular economy perspectives, the valorization of these ashes as secondary resources is of considerable importance, as their disposal without proper management may pose risks such as alkalinity, salinity, and trace element accumulation in soils (Kan et al. 2024; Cempa et al. 2025; Taskin et al. 2025). Despite their high total nutrient contents, most nutrients present in PL combustion ashes are not readily available to plants. The high combustion temperatures promote the transformation of elements into thermodynamically stable oxide, carbonate, and phosphate mineral phases, which are characterized by low solubility in water and limited short-term bioavailability (Gunes et al. 2024; Kan et al. 2024; Taskin et al. 2025). In particular, P and several micronutrients are often immobilized in sparingly soluble forms, restricting their agronomic effectiveness when ashes are directly applied to soil. In contrast to these elements, K behaves differently during combustion. Due to its chemical properties and lower tendency to form highly stable mineral structures, a significant fraction of K in poultry litter ash remains in water-soluble forms, such as chlorides, sulfates, or alkali salts (Gunes et al. 2024; Kan et al. 2024; Taskin et al. 2025). This distinctive behavior makes K a promising target for selective recovery from ash matrices.

Water extraction has emerged as a simple, low-cost, and environmentally useful approach for recovering readily soluble nutrients from various combustion ashes. Through aqueous extraction, soluble K can be efficiently separated from the insoluble mineral fraction, enabling the production of K-rich liquid or solid fertilizers. However, along with K, other soluble elements such as sodium (Na), sulfur (S), Ca, Mg, and trace nutrients may also be transferred into the extract, potentially influencing both fertilizer performance and plant response (Gunes et al. 2024; Kan et al. 2024; Taskin et al. 2025). The nutrient composition of the extracted product is strongly dependent on ash type, combustion conditions, and post-combustion handling, highlighting the need for systematic and comparative evaluation of different ash fractions in terms of both nutrient recovery and agronomic performance. Although several studies have reported the chemical characterization and nutrient recovery potential of biomass ashes, comparative agronomic assessments of water-extracted K fertilizers derived from different PL ash types remain limited. In particular, there is a lack of information on how K-rich extracts obtained from BA, WA, and FA perform under crop conditions relative to conventional K fertilizers. Moreover, the effects of such alternative fertilizers on crop growth, nutrient uptake, and quality parameters of K-demanding crops have not been sufficiently addressed.

Sugar beet represents an ideal model crop for evaluating the agronomic effectiveness of alternative K fertilizers. Its high K requirement, coupled with its economic importance and sensitivity of quality traits to nutrient management, provides a robust framework for comparative fertilizer studies (Füllgrabe et al. 2022; Xie et al. 2022). Potassium sulfate (K_2SO_4) is widely used in sugar beet cultivation due to its favorable effects on yield and quality, making it an appropriate benchmark for assessing novel K sources. However, it should be noted that ash-derived fertilizers obtained through water extraction may contain not only K but also varying amounts of other soluble nutrients such as Ca, Mg, Na, S, and trace elements. Therefore, comparisons with K_2SO_4, which primarily supplies K and S, may not fully isolate the specific contribution of K to plant response. Any observed agronomic effects may partly reflect synergistic or antagonistic interactions among co-extracted nutrients, representing an inherent limitation of the comparative approach adopted in this study. Nevertheless, evaluating these materials against a conventional K fertilizer remains valuable for assessing their overall agronomic performance under practical conditions. Based on the differential solubility and mineralogical characteristics of K in poultry litter ashes, we hypothesized that water extraction would effectively concentrate plant-available K into recoverable fractions. Furthermore, we anticipated that the agronomic performance of the recovered K fertilizers would vary depending on the type of ash used (BA, WA, and FA). We also proposed that these recovered K sources could achieve comparable or even improved K uptake and yield performance relative to conventional K_2SO_4, while simultaneously contributing to the buildup of residual K pools in the soil. The present study aims to recover water-soluble, K-rich fertilizers from BA, WA, and FA generated by poultry litter ash from biomass power plants through simple water extraction. The extracted products were chemically characterized and subsequently evaluated in a comparative pot experiment using sugar beet as the test crop, with potassium sulfate serving as the reference fertilizer. The effects of ash-derived K fertilizers on sugar beet growth, nutrient uptake, and key quality parameters were systematically investigated. By integrating waste valorization with agronomic performance assessment, this study seeks to contribute to the development of sustainable fertilizer alternatives, promote nutrient recycling, and

support circular economy strategies in agriculture and energy production systems.

Materials and Methods

Preparation and Characterization of Water Leach of Boiler Ash, Fly Ash, and Wet Ash

Four kg of ashes (BA, FA and WA) were weighed into 19-L containers. Then, 6 L of water was added, the mixture was shaken, and after settling, it was filtered. Another 6 L of water was added to the remaining material, and after settling again, it was filtered once more. Then, the filtrates were combined, dried at 65 °C and evaluated as K-rich fertilizers (BA-K, FA-K, and WA-K). Total element concentrations (P, K, Ca, Mg, iron (Fe), zinc (Zn), copper (Cu), manganese (Mn) and Na of raw and water-treated ash materials were determined by ICP-OES (inductively coupled plasma-optical emission spectrometry, PerkinElmer Model DV 2100) (Table 1). The characterization of the ash materials was determined by powder X-ray diffraction (XRD) using CuKα radiation (λ = 0.15406 nm) on an EQUINOX diffractometer, with diffraction patterns collected at room temperature over a 10–80° 2θ interval at a scan step of 0.02°. In addition, the recovery rates (%) of K-rich fertilizers are determined on an elemental basis (Table 1) and calculated using the formula given in Eq. (1).

Table 1 Total elemental concentrations and recovery rate of boiler ash (BA), fly ash (FA), wet ash (WA), and water-extracted potassium fertilizers derived from BA, FA, and WA (BA-K, FA-K, and WA-K)

Parameters	Unit	BA	BA-K	Recovery %
Total K	g kg^{-1}	166	230	20.7
Total P		73.3	49.8	10.2
Total Ca		125	227	27.1
Total Mg		218	141	9.70
Total Na		30.6	39.2	19.2
Total Fe	mg kg^{-1}	7599	4821	9.50
Total Zn		2768	1460	7.90
Total Cu		695	1160	25.0
Total Mn		5502	3856	10.5
Parameters	Unit	FA	FA-K	Recovery %
Total K	g kg^{-1}	191	178	14.3
Total P		14.8	32.4	33.6
Total Ca		80.4	135	25.8
Total Mg		23.5	120	78.4
Total Na		71.3	105	22.6
Total Fe	mg kg^{-1}	1810	1084	9.20
Total Zn		6041	856	2.20
Total Cu		359	940	40.2
Total Mn		1409	1009	11.0
Parameters	Unit	WA	WA-K	Recovery %
Total K	g kg^{-1}	258	210	23.7
Total P		63.0	24.4	11.3
Total Ca		123	192	45.5
Total Mg		410	110	7.80
Total Na		18.6	33.8	53.0
Total Fe	mg kg^{-1}	6801	690	3.00
Total Zn		1304	502	11.2
Total Cu		891	440	14.4
Total Mn		4260	849	5.80

Raw ash biomass: 4000 g; recovered BA-K biomass: 598 g; recovered FA-K biomass: 614 g; recovered WA-K biomass: 1167 g. Content: biomass of the material x concentrations of elements

$$\text{Recovery rate}(\%) = \frac{\text{K rich fertilizer element content}}{\text{Raw ash element content}} \times 100 \quad (1)$$

The recovery rates of K-rich fertilizers were examined in terms of their K content. The rates for BA-K, FA-K, and WA-K were determined to be 20.7%, 14.3%, and 23.7%, respectively.

Plant Growth Conditions and Treatments

The experiments were carried out in a naturally lit greenhouse in the summer season, with temperatures ranging from 25 to 30 °C during the day and 15–18 °C at night, and a relative humidity of 65–75% at the Ankara University Faculty of Agriculture, Department of Soil Science and Plant Nutrition. The soil sample used in the experiment was also taken from the plow layer (0–20 cm) from the Turkish Sugar Factories Inc. Sugar Institute Etimesgut Experimental Station Management. The experimental soil was clay-textured, highly calcareous (84.3 g kg^{-1} $CaCO_3$), and strongly alkaline (pH 8.91). Electrical conductivity was low (0.48 dS cm^{-1}). Organic matter and total N contents were 6.70 and 1.20 g kg^{-1}, respectively. Available P was 6.35 mg kg^{-1}, while NH_4OAc-extractable K, Ca, and Mg were 551, 5156, and 1078 mg kg^{-1}, respectively. DTPA-extractable Fe, Zn, Cu, and Mn concentrations were 5.53, 0.63, 4.45, and 8.89 mg kg^{-1}, respectively. Sugar beet (*Beta vulgaris* L. cv. Matador) plants were grown in plastic pots with 40 kg of air-dry soil. This experiment was conducted between May 9, 2025, and September 2, 2025. Before sowing, nitrogen (N) and P were applied as a basal fertilizer to all pots as a solution of diammonium phosphate (18–46-0), at 50 mg N kg^{-1}. Sugar beet plants were grown with K applied at a rate of 200 mg K kg^{-1} from K_2SO_4 (50% K_2O), BA-K (27.6% K_2O), FA-K (21.4% K_2O), or WA-K (25.2% K_2O). Nitrogen fertilizer, supplied as ammonium nitrate, was applied uniformly to all pots during the top-dressing period at a rate of 200 mg kg^{-1}.

Experimental Design and Harvest

Twelve sugar beet seeds were sown per pot and gradually thinned to four plants at the four-leaf stage. The experiment was conducted in a completely randomized design with three replications, each consisting of three pots with four plants per pot. Plants were irrigated with tap water to maintain approximately 70% field capacity. Leaf samples were collected one month before harvest at the vegetative stage. Plants were harvested by cutting 1 cm above the soil surface, and aboveground biomass and storage root yields were recorded. Aboveground biomass samples were washed, oven-dried at 65 °C, ground, and passed through a 0.20-mm sieve for analysis. Storage roots were washed and stored at 4 °C for quality analyses. After harvest, 100-g soil samples were collected for post-harvest soil available K determination.

Determination of Macro-Element Concentrations in Plant Parts

Aboveground biomass parts and storage root samples were digested with concentrated HNO_3-$HClO_4$ acid mixture (4/1: v/v). The total P concentration was determined using the vanadomolybdophosphoric acid colorimetric method (Barton 1948). The total N concentration was determined by a micro-Kjeldahl method (Moore et al. 2010). The total K, Ca, Mg concentrations were determined by ICP-OES (Perkin Elmer, Waltham, MA; Optima 2100 DV) following Temminghoff and Houba (2004). Wheat flour with the code 1567a (NIST) was used as the standard reference material.

Determination of Quality Parameters in Storage Root Samples

The storage root samples were first washed and homogenized. Storage root pulp was obtained, and the samples were clarified using a 0.3% aluminum sulfate solution following the ICUMSA (2003) method. For clarification, 26 g of sliced storage root were ground in a beaker with 178.2 mL of aluminum sulfate solution using a mixer, after which the pulp was filtered. Sugar content (SC) was determined polarimetrically using the cold-water digestion method (ICUMSA 2003). Potassium and Na concentrations in the filtrates were measured by flame-emission photometry, while α-amino N concentration was determined using the blue number method (Kubadinow and Wieninger 1972). Total sugar yield (TSY) is calculated using the following Eq. (2):

$$\text{TSY} = \frac{\text{SC}}{100} \times \text{Root yield} \quad (2)$$

A portion of the prepared storage root pulp was separated, dried at 65 °C, and ground.

Statistical Analysis

The significance of treatments was determined with one-way ANOVA using OriginPro2025b (OriginLab, Northampton, MA). Significant differences among treatment means were calculated by the Tukey HSD test ($p < 0.05$). Before analysis, all data were tested for homogeneity of variances using Levene's test. All bar and XRD graphs were generated using Microsoft Excel 365 (Microsoft Corp., Redmodi, WA, USA) and OriginPro2025b (OriginLab, Northampton, MA), respectively.

Results

XRD Characterization of Ash Materials and Their Leachates

In the XRD patterns of the BA, peaks were identified at 21.17, 21.32, 23.71, 25.72, 28.26, 29.19, 30.98, 32.85, 35.78, 40.41, 42.81, 46.53, 59.87, 62.34, 64.04, 65.63, 70.38, 73.58, and 78.57 (2θ). Among these, the peaks at 29.19, 30.98, and 32.85 (2θ) were sharper than the others (Fig. 1A). In the XRD patterns of BA-K, peaks were observed at 33.08, 35.59, 36.87, 42.63, 47.58, 52.03, 59.13, and 65.51 (2θ). Among these, the peak at 33.08 (2θ) was sharper than the others (Fig. 1B). In the XRD pattern of the FA, peaks were observed at 21.53, 28.07, 31.13, 36.38, 40.15, 43.89, 49.75, 54.96, and 65.79° (2θ). In the XRD pattern of FA-K, the peaks at 28.41, 31.87, 33.59, 38.80, 40.74, 44.70, 50.13, 50.97, 56.69, 59.23, 63.70, 65.52, 66.49, 71.06, 73.76, and 77.98° (2θ) became more pronounced (Fig. 2A and 2B). In the XRD pattern of the WA, peaks were identified at 22.72, 24.49, 26.14, 28.68, 31.08, 33.21, 37.27, 40.50, 43.27, 46.05, 54.19, 58.08, 59.97, 69.09, 76.38, and

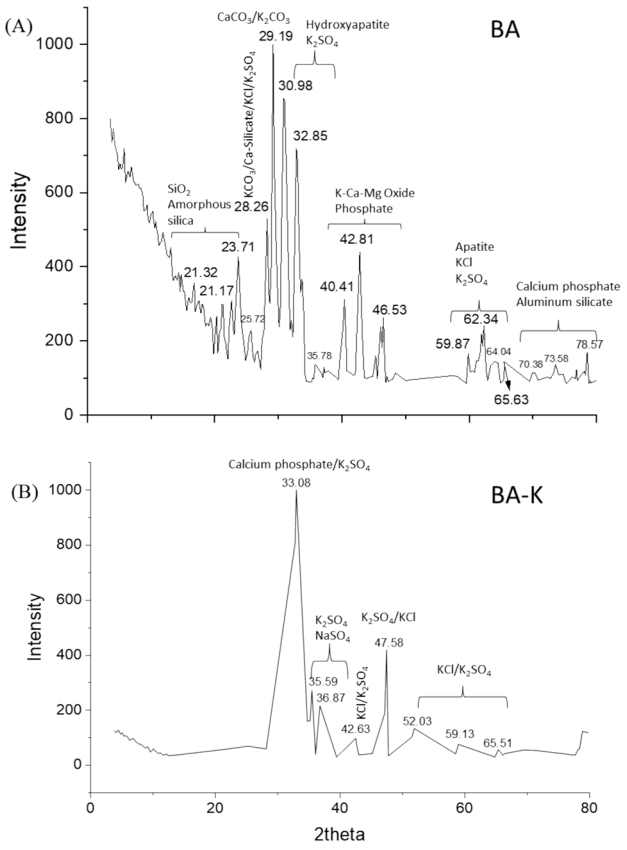


Fig. 1 X-ray diffraction (XRD) pattern of boiler ash (BA) (**A**), and water-extracted potassium fertilizer from BA (BA-K) (**B**)

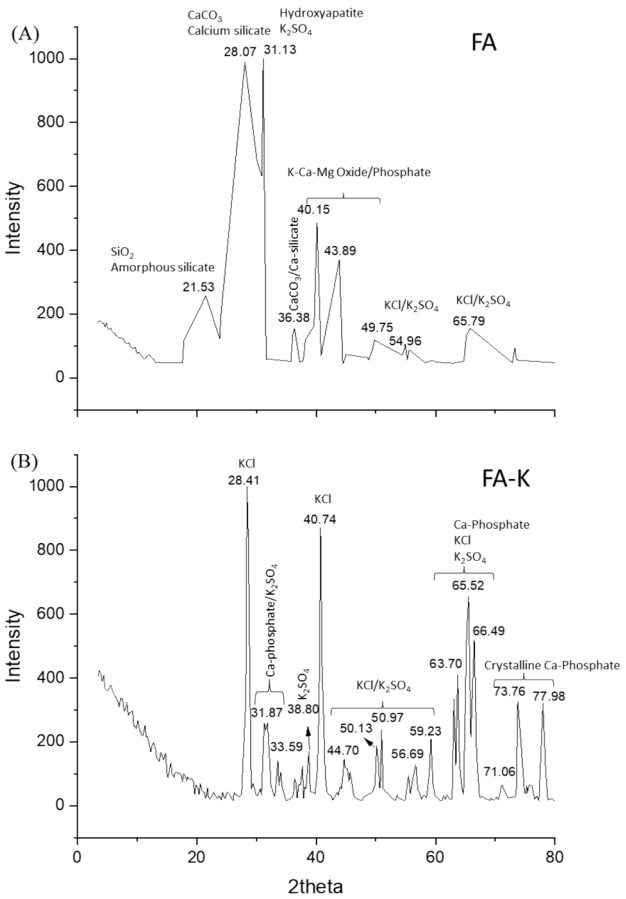


Fig. 2 X-ray diffraction (XRD) pattern of fly ash (FA) (**A**), and water-extracted potassium fertilizer from FA (FA-K) (**B**)

78.46 (2θ). Among these, the peaks at 31.08 and 33.21 (2θ) were sharper than the others (Fig. 3A). In the XRD pattern of WA-K, peaks were observed at 18.31, 22.80, 24.26, 28.29, 30.91, 33.76, 35.82, 36.97, 39.02, 40.51, 43.22, 44.00, 48.87, 50.50, 51.70, 55.75, 62.75, 66.30, 68.68, 73.70, and 77.83 (2θ). Among these, the peaks at 28.29, 30.91, and 36.97 (2θ) were considerably sharper than the others (Fig. 3B).

Aboveground Biomass and Storage Root Dry Weights of Sugar Beet

Ash-based K fertilizer applications significantly increased the above ground biomass of sugar beet compared with the control. The aboveground biomass weight, which was 447 g pot^{-1} in the control, increased to 1410, 1495, and 1204 g $plant^{-1}$ with BA-K, FA-K, and WA-K, respectively (Fig. 4A). Storage root weight was 884 g pot^{-1} in the control, while it was determined as 1006, 801, 1260, and 1179 g pot^{-1} with K_2SO_4, BA-K, FA-K, and WA-K applications, respectively. Among these increases relative to the control, only the FA-K application resulted in

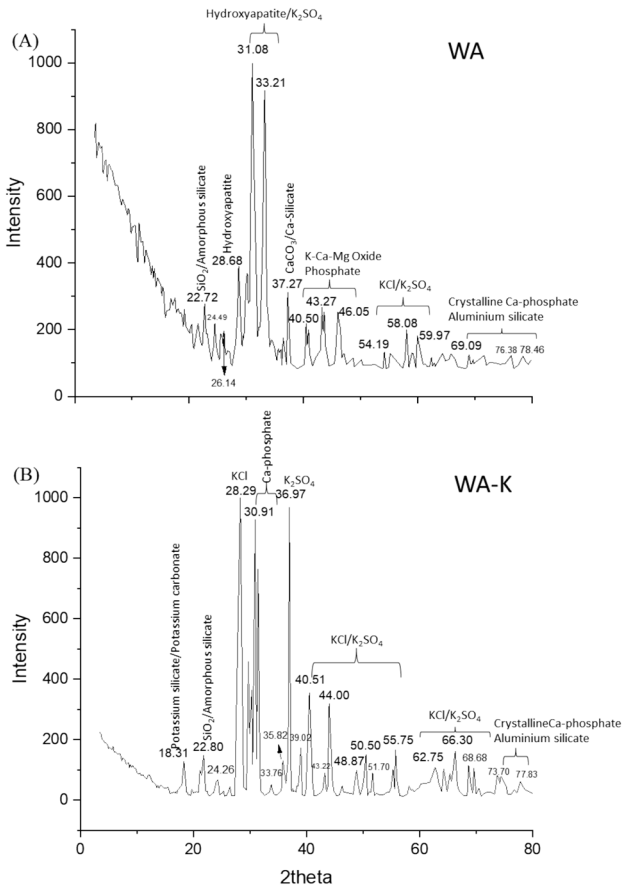


Fig. 3 X-ray diffraction (XRD) pattern of wet ash (WA) (**A**), and water-extracted potassium fertilizer from WA (WA-K) (**B**)

a statistically significant increase (Fig. 4B) in sugar beet storage root weight.

Nitrogen, Phosphorus, and Potassium Concentrations of Aboveground Parts and Storage Roots

Although K fertilizer applications appeared to increase plant N concentration in leaf samples collected at the vegetative stage compared with the control, this increase was found statistically insignificant. Storage root N concentration, however, increased significantly under FA-K and WA-K applications compared with the control (Table 2). Phosphorus concentration of the aboveground biomass increased significantly compared with the control only under the BA-K application. The treatments had no significant effect on storage root P concentration (Table 2). Potassium fertilizer applications significantly increased K concentration in both the aboveground biomass and the storage roots compared with the control (Table 2).

Calcium and Magnesium Concentrations of Aboveground Parts and Storage Roots

BA-K and FA-K applications significantly increased Ca concentration in the aboveground parts at the vegetative stage compared with the control. At harvest, the treatments had no significant effect on Ca concentration in either the aboveground biomass or the storage roots (Table 3). Potassium sulfate application caused a decrease in Mg concentration of leaves at the vegetative stage, whereas FA-K and WA-K applications significantly increased Mg concentration compared with the K_2SO_4 treatment. At harvest, the treatments had no significant effect on aboveground part Mg concentration. Storage root Mg concentration increased significantly with ash-derived K fertilizers compared with the control, with the WA-K fertilizer resulting in the highest storage root Mg concentration (Table 3).

Quality Parameters of Sugar Beet

Potassium fertilizer applications led to a reduction in sugar content (%) (Fig. 5A). Total sugar yield was higher under FA-K and WA-K applications compared to BA-K (Fig. 5B). While BA-K and FA-K applications increased Na concentrations in sugar beet storage roots (Fig. 6A), FA-K and WA-K applications enhanced α-amino-N (Fig. 6C) compared to control. Similarly, all K fertilizers increased K concentration related to control (Fig. 6B).

Plant-Available Potassium Concentration of Post-Harvest Soil

In soil samples collected after harvest, plant-available K concentration was higher under K fertilizer treatments compared with the control (Fig. 7).

Discussion

In this study, the potential to obtain water-soluble K-rich fertilizer fractions through water extraction of BA, FA, and WA generated from a biomass power plant using PL as fuel was evaluated. In this context, XRD characterization of both the original ash materials and the water-soluble fractions obtained after washing served as a key tool to elucidate the binding forms of K within the ash matrix and its extractability by water. The broad features observed in the XRD pattern of BA within the 21–35° (2θ) range suggest the presence of predominantly amorphous Ca, K, P-rich SiO_2 phases, together with contributions from calcium phosphate derivatives (such hydroxyapatite-like structures), as inferred from comparison with reference patterns (Fiameni et al. 2021; Gunes et al. 2024). The reflections around 28.26–29.19°

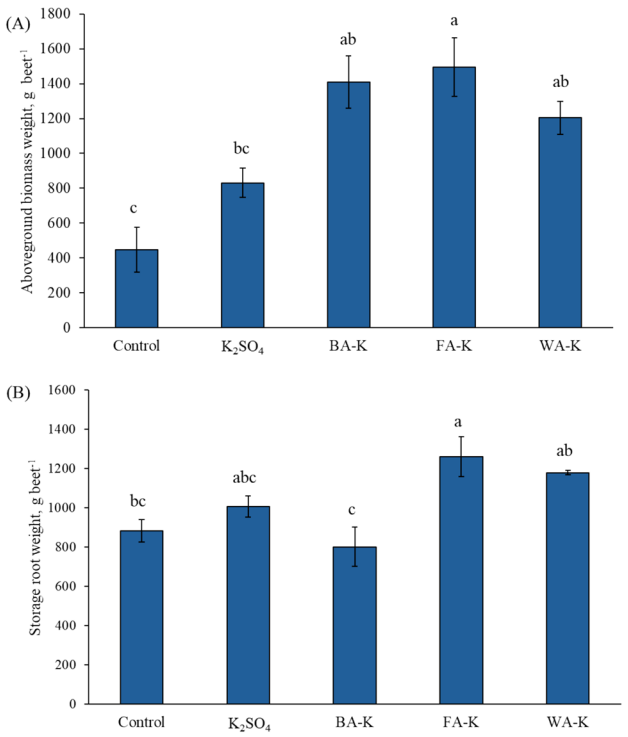


Fig. 4 Effect of K_2SO_4 and water-extracted potassium fertilizers from boiler ash (BA-K), fly ash (FA-K) and wet ash (WA-K) on aboveground biomass part (**A**) and storage root (**B**) weight of sugar beet plant. The values are means of three replicates ± standard error. Different letters in each column indicate significant differences at $p < 0.05$ level based on Tukey HSD test

(2θ) can be qualitatively associated with phases such as K_2CO_3, K_2SO_4, and $CaCO_3$; however, it should be noted that these assignments are tentative and multiple crystalline phases may overlap within this region. The relatively sharp peak at around 29.19° (2θ) may indicate the presence of well-crystallized carbonate phases, although their exact composition cannot be resolved without quantitative phase analysis. Similarly, reflections at 30.98 and 32.85° (2θ) are consistent with K-Ca phosphates and K_2SO_4, while weak signals at higher angles (40–46° and > 60° 2θ) suggest contributions from CaO, MgO, and silicate derivatives (Acharya et al. 2014; Fiameni et al. 2021; Gunes et al. 2024). In the BA-K pattern, reflections attributed to relatively less soluble Ca-bearing phases appear reduced, while the peak near 33.08° (2θ) becomes more pronounced. This feature can be qualitatively linked to soluble K salts such as K_2SO_4 (Acharya et al. 2014; Li et al. 2021), although overlap with other phases cannot be excluded. Additional peaks at 35.59 and 36.87° (2θ), together with reflections between 42.63 and 65.51° (2θ), are consistent with K_2SO_4 and KCl-type phases. These observations suggest that water washing may promote the redistribution of K into more soluble crystalline forms; however, in the absence of quantitative phase analysis, this should be interpreted as indicative rather than conclusive evidence of K transfer to the aqueous phase. In the FA pattern, low-intensity reflections at approximately 21.53, 28.07, and 31.13° (2θ) indicate the presence of limited crystalline phases embedded within a predominantly amorphous aluminosilicate matrix (Gunes et al. 2024). Peaks near 28–29° (2θ) may partially correspond to calcite, while features in the 36–44° (2θ) range are compatible with CaO, Ca-silicates, and feldspathic structures (Ţopa et al. 2025). Reflections between 54.96 and 65.79° (2θ) can be associated with KCl and K_2SO_4 (Fahimi et al. 2020; Li et al. 2021), although phase overlap remains likely. This mineralogical pattern suggests that a substantial portion of K may be incorporated within the glassy matrix, limiting its direct solubility during washing. In the FA-K pattern, the relative sharpening of peaks at 28.41, 31.87, and 33.59–38.80° (2θ) can be interpreted as indicative of the presence of soluble K-bearing salts such as K_2SO_4 and KCl (Acharya et al. 2014; Fahimi et al. 2020; Li et al. 2021). Additional reflections in the 50–60° (2θ) region may correspond to recrystallized K salts and Ca-phosphate phases formed during drying. Nevertheless, the overall low peak intensity suggests that FA is a comparatively less efficient source for K recovery via simple water extraction. In the WA pattern, distinct peaks at 31.08 and 33.21° (2θ) are consistent with K_2SO_4, KCl, and K-Ca phosphate phases (Fiameni et al. 2021; Gunes et al. 2024), although, as noted above, these assignments are qualitative. Features within the 22–26° (2θ) range likely reflect amorphous hydroxyapatite and poorly crystalline silicates. This distribution suggests that K may occur in relatively more labile forms compared to BA and FA. In the WA-K pattern, the sharpening of reflections at 28.29, 30.91, and 36.97° (2θ) can be interpreted as indicative of well-crystallized K_2SO_4 and KCl phases (Fahimi et al. 2020; Li et al. 2021), while additional peaks at lower angles (around 18.31° 2θ) may reflect secondary potassium silicate or carbonate phases formed during the washing–drying process. Weak reflections in the 39–68° (2θ) region further support the presence of KCl and K_2SO_4. These observations suggest that WA may be a more suitable precursor for producing water-soluble K-rich fractions; however, this interpretation should be considered in light of the qualitative nature of the XRD analysis. The XRD-based phase identification indicates that K in BA, FA, and WA is likely present in sulfate, chloride, and carbonate forms. However, it must be emphasized that all phase assignments are qualitative and based on comparison with reference diffraction patterns, and that overlapping reflections may obscure definitive identification. Therefore, interpretations regarding K speciation and transfer during washing should be regarded as indicative trends rather than quantitative conclusions. The apparent predominance of

Table 2 Effect of ash-based fertilizers (BA-K, FA-K, and WA-K) on aboveground biomass parts at the vegetative stage and harvest stage and storage root nitrogen (N), phosphorus (P), and potassium (K) concentration of sugar beet plants

Treatments	Aboveground biomass part at the vegetative stage	Aboveground biomass part at the harvest stage	Storage root part
	Nitrogen, g kg^{-1}		
Control	34.2 ± 1.77 b	18.6 ± 0.59	4.91 ± 0.18 c
K_2SO_4	35.1 ± 2.42 b	19.3 ± 1.34	6.63 ± 0.42 BC
BA-K	39.2 ± 2.36 ab	19.9 ± 1.56	6.95 ± 0.28 abc
FA-K	40.9 ± 0.54 ab	20.9 ± 0.09	8.33 ± 0.74 ab
WA-K	43.5 ± 0.45 a	18.7 ± 0.58	9.39 ± 0.80 a
F value	5.05**	0.50 ns	9.74*
Phosphorus, g kg^{-1}			
Control	1.93 ± 0.04 b	1.76 ± 0.01 b	0.94 ± 0.02
K_2SO_4	1.94 ± 0.10 ab	1.92 ± 0.03 b	0.85 ± 0.03
BA-K	2.28 ± 0.11 a	2.26 ± 0.04 a	0.96 ± 0.02
FA-K	2.02 ± 0.02 ab	1.98 ± 0.06 b	0.94 ± 0.03
WA-K	2.02 ± 0.05 ab	1.85 ± 0.07 b	0.99 ± 0.07
F value	3.66*	14.4**	1.95 ns
Potassium, g kg^{-1}			
Control	29.6 ± 0.81 c	46.4 ± 0.88 b	19.0 ± 0.86 b
K_2SO_4	40.0 ± 0.06 b	57.7 ± 1.06 a	25.7 ± 1.48 a
BA-K	40.4 ± 0.77 b	66.8 ± 2.26 a	30.4 ± 0.94 a
FA-K	44.2 ± 0.66 a	62.5 ± 4.28 a	31.2 ± 1.25 a
WA-K	42.5 ± 0.78 ab	59.5 ± 0.06 a	27.9 ± 1.34 a
F value	71.2**	11.5**	16.6**

The values are means of three replicates ± standard error. Different letters in each column indicate significant differences at the $p < 0.05$ level based on the Tukey HSD test. ns: nonsignificant; $p < 0.05$: *; $p < 0.01$: **

Table 3 Effect of ash-based fertilizers (BA-K, FA-K, and WA-K) on aboveground biomass parts at the vegetative stage and harvest stage and storage root calcium (Ca) and magnesium (Mg) concentrations of sugar beet plants

Treatments	Aboveground biomass at the vegetative stage	Aboveground biomass part at the harvest stage	Storage root part
	Calcium, g kg^{-1}		
Control	11.0 ± 0.74 b	14.9 ± 0.76	1.06 ± 0.06
K_2SO_4	6.61 ± 0.42 c	13.7 ± 0.49	1.06 ± 0.05
BA-K	13.9 ± 0.40 a	16.5 ± 1.42	1.20 ± 0.07
FA-K	14.1 ± 0.78 a	13.9 ± 1.51	1.17 ± 0.02
WA-K	12.2 ± 0.47 ab	12.2 ± 1.10	1.21 ± 0.06
F value	27.2**	1.96 ns	1.82 ns
Magnesium, g kg^{-1}			
Control	18.2 ± 0.05 ab	13.7 ± 0.71	1.72 ± 0.11 d
K_2SO_4	16.8 ± 0.31 b	13.5 ± 0.34	1.93 ± 0.06 cd
BA-K	18.2 ± 0.84 ab	15.9 ± 0.91	2.24 ± 0.06 BC
FA-K	19.8 ± 0.52 a	14.1 ± 1.45	2.36 ± 0.10 b
WA-K	19.5 ± 0.08 a	13.6 ± 0.38	2.80 ± 0.01 a
F value	6.51**	1.29 ns	27.6**

The values are means of three replicates ± standard error. Different letters in each column indicate significant differences at the $p < 0.05$ level based on the Tukey HSD test. ns: nonsignificant; $p < 0.01$: **

K_2SO_4 and KCl-type phases in the dried leachates suggests their potential as rapidly soluble K sources, although accompanying Na and chlorine (Cl) contents should be considered, particularly for salt-sensitive crops.

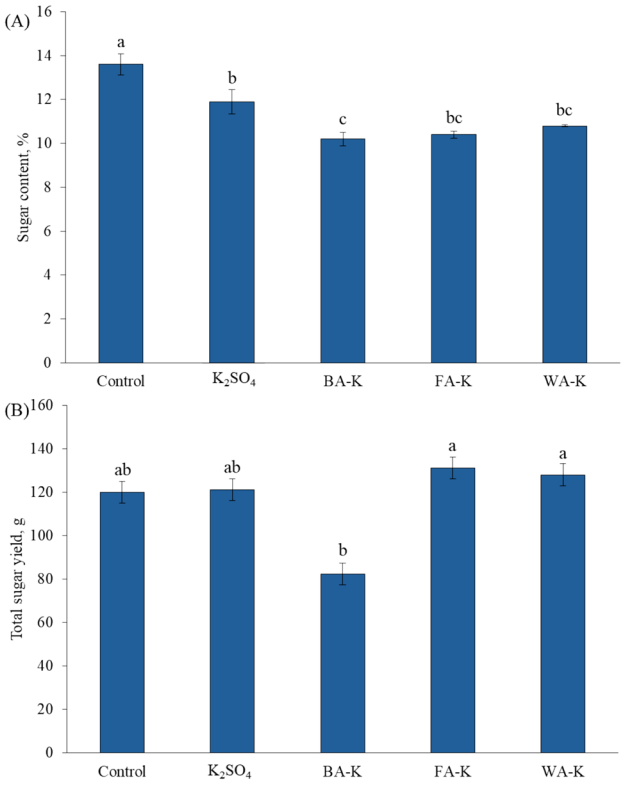


Fig. 5 Effect of K_2SO_4 and water-extracted potassium fertilizers from boiler ash (BA-K), fly ash (FA-K) and wet ash (WA-K) on sugar content (**A**) and total sugar yield (**B**) of sugar beet storage roots. The values are means of three replicates ± standard error. Different letters in each column indicate significant differences at $p < 0.05$ level based on Tukey HSD test

The present study demonstrates that K fertilizers recovered via simple water extraction from PL-derived biomass ashes can function as effective K sources for sugar beet cultivation. When compared with the conventional K_2SO_4 fertilizer, the ash-based fertilizers (BA-K, FA-K, and WA-K) generally enhanced aboveground biomass and storage root growth, nutrient uptake, and soil K availability, highlighting their potential as sustainable alternatives within a circular nutrient management framework. Potassium is a key macronutrient involved in carbohydrate metabolism, photosynthesis, and assimilate translocation, all of which support aboveground biomass accumulation and yield formation in sugar beet (Xie et al. 2022; Lamlom et al. 2025). Potassium fertilization has previously been shown to enhance beet and sugar yields compared with unfertilized controls (Füllgrabe et al. 2022). In our study, ash-derived K fertilizers substantially increased aboveground biomass dry matter compared with the control, indicating that water-extracted ash products supplied soluble K in sufficient quantities to support aboveground growth. The particularly high aboveground biomass under FA-K suggests that ash from specific thermal fractions may differ in soluble K forms or associated nutrients, impacting plant response. Although many studies report positive effects of K on storage root yield and sugar content (Füllgrabe et al. 2022; Xie et al. 2022), differential responses among K sources can occur depending on extractability and interaction with other nutrients (such as Mg, Na, K) (Xie et al. 2021; Barłóg and Grzebisz 2025). Only FA-K produced a statistically significant increase in storage root dry weight compared with the control, suggesting that not all ash-derived fertilizers are identical in agronomic effectiveness, likely due to differences in chemical composition or cation balance.

Potassium plays a central role in N uptake and utilization, partly by enhancing nitrate transport and assimilation, which can improve N use efficiency (Raddatz et al. 2020; Cao et al. 2025). In this experiment, K treatments appeared to elevate leaf N concentration at the vegetative stage, but this difference between treatments was found insignificant. Enhanced storage root N under FA-K and WA-K indicates increased translocation of N to storage tissues under improved K nutrition. This pattern is consistent with prior research showing K fertilization can influence N metabolism and assimilation in sugar beet storage roots and leaves (Füllgrabe et al. 2022; Xie et al. 2022).

Phosphorus concentrations exhibited a significant increase only under BA-K in aboveground biomass tissues. This result suggests that certain ash fractions may provide additional P, beyond that normally supplied by soil pools. However, storage root P remained unaffected, indicating complex partitioning of P between aboveground biomass and storage organs. Potassium has antagonistic interactions with other cations, particularly Mg and Ca. Excessive K can suppress Mg uptake due to competition for uptake sites, a phenomenon widely documented in the nutrient management literature (Dölger et al. 2024; Barłóg and Grzebisz 2025). Potassium sulfate treatment reduced leaf Mg concentration at the vegetative stage, whereas BA-K and FA-K did not, suggesting that ash-derived fertilizers may provide supplementary Mg or supply K more gradually, reducing competitive inhibition. The significant increase in storage root Mg, especially with WA-K, supports this interpretation and highlights an advantage of multi-element ash-based fertilizers over pure K salts. BA-K and FA-K also increased Ca concentrations in aboveground biomass tissues at the vegetative stage. Although Ca effects on yield are generally smaller than those of K, Ca supports cellular integrity and can interact with K to modulate stress responses and membrane stability. Potassium fertilization often influences quality traits differently than yield traits. While K can improve sucrose

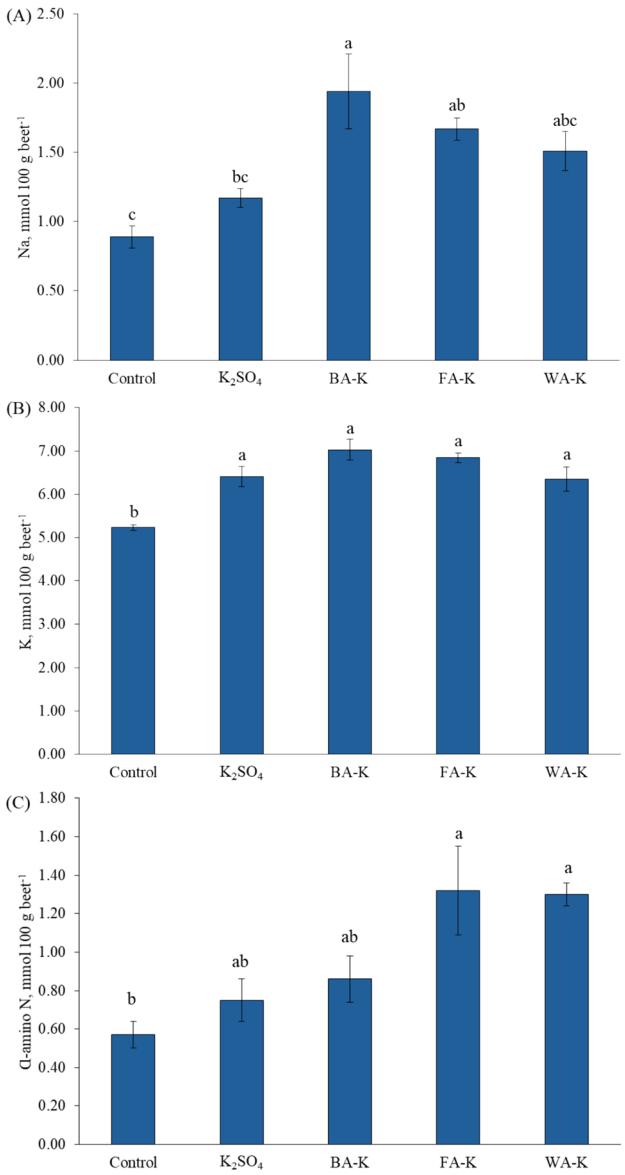


Fig. 6 Effect of K_2SO_4 and water-extracted potassium fertilizers from boiler ash (BA-K), fly ash (FA-K) and wet ash (WA-K) on sodium (Na) (**A**), potassium (K) (**B**) and α-amino nitrogen (**C**) of sugar beet storage roots. The values are means of three replicates ± standard error. Different letters in each column indicate significant differences at $p < 0.05$ level based on Tukey HSD test

formation under balanced nutrition, high rates sometimes dilute sucrose concentration due to increased vegetative growth and can increase non-sucrose components such as α-amino-N and Na, which negatively affect processing quality (Abdel-Motagally and Attia 2009; Barłóg and Grzebisz 2025). In our study, all K treatments reduced sugar content (%), most likely due to a combination of biomass dilution effects and shifts in carbohydrate partitioning toward aboveground biomass tissues. Increases in Na and α-amino-N in tubers under K fertilization align with prior observations that K fertilization can elevate these solutes, potentially complicating sugar extraction and processing quality (Brazienė 2009). However, total sugar yield remained highest under FA-K and WA-K, indicating that the negative effect on concentration was offset by greater storage root biomass, a common trade-off in sugar beet fertilization studies.

Post-harvest increases in plant-available soil K confirm that ash-derived fertilizers not only supported current crop uptake but also contributed to residual fertility. Persistence of available K in soil after harvest is advantageous for subsequent crops and suggests that some of the K from ash products may be released more slowly than that from highly soluble conventional fertilizers. While the observed trends consistently indicate positive effects of ash-derived K fertilizers on plant growth, nutrient uptake, and soil K status, the limited replication necessitates cautious interpretation

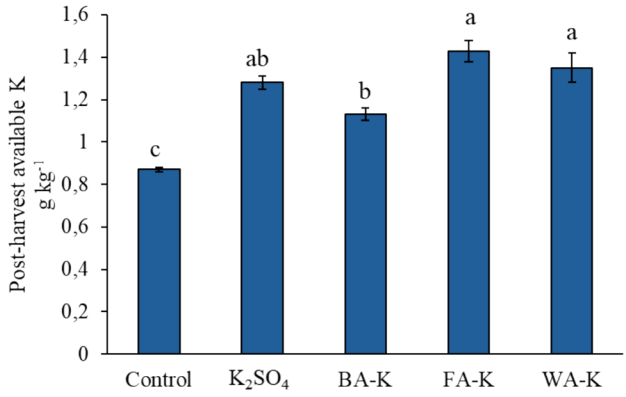


Fig. 7 Effect of K_2SO_4 and water-extracted potassium fertilizers from boiler ash (BA-K), fly ash (FA-K) and wet ash (WA-K) on post-harvest soil available potassium (K) concentration of sugar beet plant. The values are means of three replicates ± standard error. Different letters in each column indicate significant differences at $p < 0.05$ level based on Tukey HSD test

of nonsignificant differences, which should not be taken as evidence of equivalence among treatments.

Conclusion

Ash-based potassium fertilizers derived from poultry litter combustion demonstrate considerable potential as alternative K sources for sugar beet production. Among the tested fractions, FA-K and WA-K were particularly effective in enhancing aboveground biomass and storage root biomass, improving nutrient uptake including K, Mg, and Ca and maintaining or increasing soil K availability after harvest. These findings suggest that water-extracted ash fertilizers can supply readily available K while contributing to residual soil fertility, supporting both current and subsequent crops. Despite these positive outcomes, the use of ash-based fertilizers may influence sugar quality parameters, including reductions in sugar concentration and increases in α-amino-N and Na content, likely due to shifts in carbohydrate partitioning and solute accumulation. Future research should focus on long-term field trials to assess agronomic performance under variable soil and climatic conditions, as well as comprehensive chemical and mineralogical characterization including quantitative phase analysis to better understand nutrient speciation, solubility, and potential interactions with other essential elements. Such studies will be critical to fully integrate ash-derived K fertilizers into sustainable nutrient management strategies, contributing to circular economy principles by valorizing biomass power plant residues while reducing reliance on conventional mineral fertilizers.

Author Contributions **Hanife Akca did** investigation, methodology, formal analysis, validation, writing—original draft, and review and editing. **Mehmet Burak Taskin involved in** investigation, formal analysis, review and editing; **Murat Tugrul developed** formal analysis; **Yusuf Kagan Kadioglu did** review and editing; **Kiymet Deniz Yagcioglu, Ridvan Batuhan Kizilkaya, and Nevin Kocak did** formal analysis; **Aydin Gunes did** conceptualization, investigation, methodology, formal analysis, validation, supervision, writing—original draft, and review and editing. **From Poultry Litter Ash to Recovered Potassium Fertilizer: Water Extraction, Characterization, and Agronomic Validation in Sugar Beet.**

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code Availability Not applicable.

Declarations

Conflicts of interest The authors declare that they have no conflicts of interest.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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