

N/P/K Leaching of Sweet Corn in Growing Media Controlled with the Coal Combustion Products Fly Ash and Bottom Ash

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Abstract

Fly ash and bottom ash, or coal combustion products (CCP), are wastes from coal-fired boilers of electricity power plants. CCP were evaluated as a soil amendment and partial fertilizer substitute in a short-term pot experiment and showed potential to influence growing media properties under controlled conditions. However, these findings are limited to the early growth stage and pot-scale conditions, and further studies under field conditions through harvest are required to confirm their effects on plant growth. The study examined the leaching of N/P/K from sweet corn growing media enriched with different CCP proportions. Latosol soil was incorporated with 0%, 25%, 50%, 75%, and 100% CCP (m/m) to support sweet corn seedlings in a pot experiment. N, P, and K leaching from the growing media was evaluated. The results showed that sweet corn growth was restricted in CCP-amended media. Increasing CCP proportion markedly reduced plant growth, with decreases of up to 57.00% in seed emergence, 59.56% in plant height, 42.50% in leaf number, 70.59% in dry weight, and 38.00% in root number compared to 100% soil; however, the 25% CCP treatment increased root volume. Increasing the CCP proportion also increased N and K leaching and leachate pH; conversely, P leaching was lower than in 100% soil. Since

there were no toxicity symptoms in sweet corn, CCP could be used as a soil amendment and a potential source of NPK, with precautions to prevent nutrient leaching.

Keywords: alternative fertilizer, circular economy, leaching management, maize, percolation, *Zea mays*

Introduction

Coal combustion products (CCP), including fly ash and bottom ash, are by-products generated by coal combustion boilers in electricity power plants. In Indonesia, the State Electricity Company (PLN) produces about 1.2 million tons of CCP annually from 47 power plants (Primadya, 2025). CCP is classified as waste with alkaline characteristics; therefore, it has been intensively studied as a soil amendment and fertilizer (Faoziah et al., 2022; Pangestu et al., 2022; Utama et al., 2025). Utilization is promoted as part of circular economy applications for electric industrial waste (Saputra, 2025).

Indonesia, through Government Regulation 22 of 2021, has classified CCP as non-hazardous waste. Moreover, the Indonesian National Standard (SNI) 9387:2025 has been developed for CCP by the National Standardization Agency (BSN) as a soil conditioner and a raw material for fertilizer (Primadya, 2025).

Chemically, CCP contains macronutrients such as P, K, Ca, Mg, and Na, as well as trace elements required by plants (Faoziah et al., 2022; Jayaranjan et al., 2014; Tauanov et al., 2020). Many studies have shown their suitability to enrich growing media, such as in tomato (Faoziah et al., 2022), mustard greens (Aziz et al., 2023), capsicum (Restini & Dewi, 2023), lettuce (Yuniar, 2024), shallot (Irawan & Andriani, 2025), timber plants (Pangestu et al., 2022), and cereals (Varshney et al., 2020). At the same time, Ahmad et al. (2021) reported that fly ash application at concentrations above 40% promoted the accumulation of heavy metals such as Al, Pb, and Cd, thereby reducing pumpkin growth and yield. Despite these findings, previous studies have largely examined nutrient benefits and heavy metal risks independently, without addressing their combined effects on nutrient dynamics and plant growth during the early developmental stage. This study provides the first integrated assessment of nutrient availability versus potential toxicity of CCP amendments specifically for sweet corn seedlings, directly informing optimal CCP application rates for early-stage growth.

We used sweet corn (*Zea mays* var *saccharata*) as a model in the present experiment. Corn exhibits superior adaptation to diverse environments (Sahoo & Mohanty, 2020). However, it is sensitive to soil nutrient status, particularly N, P, and K (Barson et al., 2021; Nguyen & Huynh, 2024; Oktem et al., 2010; Sofyan & Sara, 2019; Vieira et al., 2019).

Here, the contribution of CCP to soil chemistry was evaluated based on the amounts of N/P/K leaching. Nutrient leaching, generally considered a loss in agricultural systems, was used in this study as an indicator of nutrient mobility rather than direct nutrient availability, particularly for mobile nutrients. Leaching is the loss of nutrients into the deeper soil profile as water percolates (Lehmann & Schroth, 2003). N/P/K at different degrees are considered susceptible to leaching in the soil (Fetzer et al., 2022; Lehmann & Schroth, 2003; McDowell et al., 2021). We used N/P/K leaching from the lysimeter to evaluate the effectiveness of CCP

application as a fertilizer and soil amendment. The information also helps determine the appropriate dosage and further action to improve efficiency. The study examined the leaching of N, P, and K from sweet corn growing media enriched with varying proportions of CCP.

Materials and Methods

The research was conducted from September to October 2023 (the end of the dry season) at the Leuwikopo Experimental Station, IPB Dramaga, Bogor, Indonesia. Sweet corn of the commercial variety 'Bonanza' was obtained from the market. Fly ash + bottom ash (CCP) of coal firing was obtained from the National Electric Company (PLN) located in Banten (PT. PLN Indonesia Power - UBP Suralaya). The soil was Latosol Darmaga; it had a pH of 5.11, C-org 1.26%, total N 0.14%, available P < 0.08 ppm, exchangeable K 0.26 cmol/kg, and exchangeable Mg, Ca, Na, and Al were 0.97, 9.26, 0.05, and 0.44 cmol/kg, respectively. Further details of the nutrient content of soil and CCP before the experiment are presented in Table 1.

The evaluation of heavy metal concentrations in soil was based on established critical or toxic threshold limits for each element. Cadmium (Cd) is critical at 0.76 mg/kg. Lead (Pb) starts to cause problems at 55 mg/kg. Zinc can be toxic when it exceeds 16 mg/kg of soil. Copper (Cu) becomes toxic at 3.5 mg/kg of soil. Chromium (Cr), especially in its hexavalent form, is toxic at around 3.8 mg/kg of soil. As and Hg become toxic at 4.5 mg/kg and 1.9 mg/kg of soil, respectively Vodyanitskii (2016). Compared to our data, Cd was recorded at <1 mg/kg, Pb at <0.3 mg/kg, Zn at 92.76 mg/kg, Cu at 49.51 mg/kg, Cr at 9.67 mg/kg, As at <0.002 mg/kg, and Hg at <0.002 mg/kg, indicating that Cd, Pb, As, and Hg were below their critical/toxic limits, whereas Zn, Cu, and Cr exceeded their respective toxic threshold limits.

The study used a randomized complete block design with a single factor, i.e., the proportion of soil and CCP in the growing media. The proportion is based on weight: weight (m/m), with each treatment replicated three times. The

combinations were: 100% soil (control); 75% soil + 25% CCP; 50% soil + 50% CCP; 25% soil + 75% CCP; and 100% CCP. The total growing media was 600 g, with a water content of about 12% at the mixing stage. Each media combination was repeated three times with a single plant.

Sweet corn seeds were planted in a plastic pot equipped with a lysimeter, following Lehmann and Schroth (2003) with modifications (Figure 1). The container had three sections: a pot, a tube as a stake, and a water container. The pot was 20 cm in diameter and filled with growing media. Cotton filters (Hitech for aquariums) were stacked under the pot and along the tube to filter the percolate. Finally, the percolate water was collected in a container to estimate N, P, and K leaching. Leachate was collected at the end of the 21-day experimental period to represent total nutrient leaching under controlled irrigation

conditions. Plants were watered to maintain field capacity without intentional leaching treatments, so the collected leachate reflected total nutrient losses over the entire experimental period. A 100 ml subsample of leachate was collected for laboratory analysis of N, P, and K concentrations.

Plant growth parameters (plant height, leaf number, fresh biomass, and dry biomass) and nutrient concentrations (N, P, and K) were expressed relative to their corresponding control values to facilitate comparisons across variables measured on different scales and units. For each parameter, the mean value obtained under the 0% coal combustion product (CCP) treatment was used as the reference and set at 100%. The relative value at each CCP proportion was calculated using the following equation:

$$RV_{ij} (\%) = (\bar{X}_{ij} / \bar{X}_{i0}) \times 100$$

Table 1

Chemical Content of Soil and CCP (Fly Ash and Bottom Ash) Before the Experiment

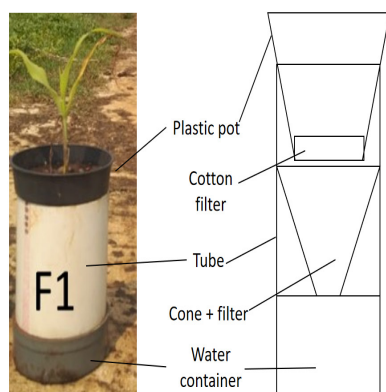
Variable	Unit	Soil	CCP
pH	-	5.11	11.45
C-org	%	1.26	0.95
N-total	%	0.14	0.01
P ₂ O ₅ total	%	0.097	0.160
K ₂ O total	%	0.024	0.220
Fe total	ppm	54663	33762
Zn total	ppm	92.76	122.19
Na total	%	0.01	0.72
Ca total	%	0.09	3.54
Mg total	%	0.04	1.51
Mn total	ppm	2986	611.60
Cu total	ppm	49.51	26.32
S	%	0.02	0.17
B total	ppm	13.18	60.63
SiO ₂	mg/kg	-	<12.5
Pb	ppm	<0.3	5.89
Cd	ppm	<1	0.10
Cr	ppm	9.67	19.51
As	ppm	<0.002	8.46
Hg	ppm	<0.002	

Note. – = not measured

where RV_{ij} is the relative value (%) of parameter i at CCP proportion j ; $\bar{X}_{ij}$ is the mean observed value of parameter i at CCP proportion j ; and $\bar{X}_{i0}$ is the mean value of the corresponding parameter under the control treatment (0% CCP). A relative value of 100% indicates that the parameter value was equal to the control value, whereas values below or above 100% indicate that the parameter value was lower or higher than the control value, respectively. The calculated relative values were used only to present response patterns across CCP proportions, while statistical analyses were performed using the original, untransformed data.

Figure 1

Lysimeter Design to Collect Leaching Water from Planting Media



Initially, two seeds were planted in each pot and grown in an open field. At 7 days after planting (DAP), one superior seedling was maintained. The plant was maintained without any additional fertilizer. During the experiment, rainfall was infrequent, and additional daily watering was applied manually at about 50 ml per pot. At 21 DAP, the plants were harvested and measured. Water samples were collected for analysis of N/P/K content. N was analyzed by the Kjeldahl method (Hicks et al., 2022), P by spectrophotometry (Habibah et al., 2018), and K by atomic absorption spectrophotometry (Tangketasik et al., 2024). The 21-day experimental duration was selected to represent the early vegetative stage of sweet corn, a plant establishment phase when growth is influenced

by the composition of the growing medium and nutrient availability.

Data were analyzed using ANOVA in SAS 9.4. For variables showing a significant effect, further testing was performed using Duncan's multiple range test (DMRT) at $\alpha = 5\%$. Pearson correlation was performed to evaluate the relationship among variables.

Results and Discussion

Plant Growth

Seed germination, plant height, leaf number, and biomass weight were affected by different CCP mixtures (Table 2). Germination was delayed in the presence of CCP, particularly in media containing 75% or more CCP, by 3-4 days. Sweet corn grown in 100% soil had the tallest canopy (29.67 cm), while that in 100% CCP had the shortest (12.00 cm). It is evident that increasing the proportion of CCP suppresses plant height.

Table 2 shows that leaf number and plant biomass, both fresh and dry weight, exhibited a similar trend to plant height, with increasing CCP proportion decreasing these values. Leaf number of sweet corn in media mixtures with CCP was lower (2.3–3.0 leaves) than in 100% soil (4.0 leaves), irrespective of CCP proportion.

Increasing the proportion of CCP tended to reduce sweet corn growth (Figure 2). Application of 25% CCP reduced plant height, leaf number, and plant dry mass by 11%, 25%, and 34%, respectively, and at 50% CCP by 26%, 25%, and 62%. Compared with other variables, both plant fresh and dry weights were markedly reduced, reaching only 35% and 38% at 50% CCP relative to 100% soil. This indicates their sensitivity to CCP application. This finding is consistent with previous research by Faoziah et al. (2022) and Aziz et al. (2023), in which increasing the CCP proportion suppressed the growth of tomato and mustard greens, respectively. On the other hand, Restini and Dewi (2023) on capsicum and Yuniar (2024) on lettuce noted that increasing the CCP proportion increased plant growth. It seems that the effect of the proportion of CCP in growing

media depends on the species.

Suppression in CCP-supplemented media could be related to sweet corn growth stage. Leaf number is commonly used as an indicator of growth stage in maize during the vegetative stage (Zhang et al., 2022). Here, the corn produced 4.0 leaves in 100% soil, while 2.2-3.0 in media with CCP (Table 2). The maize seedling in the present study referred to the growing stages of V3-V4 as described by Orteza and Licht (2024). Based on their explanation, energy for growth up to stage

V3 primarily comes from reserve nutrients in the kernel. Thus, low seedling performance is likely due to less favorable environmental conditions (such as water availability, pH, and stressors) after CCP application, although the role of existing roots should not be overlooked.

Potential stressors in CCP include high pH and metals (Table 1). Heavy metals such as As, Cr, Pb, and Hg can interfere with nutrient absorption, photosynthetic processes, and enzyme activity, thereby inhibiting plant growth.

Table 2

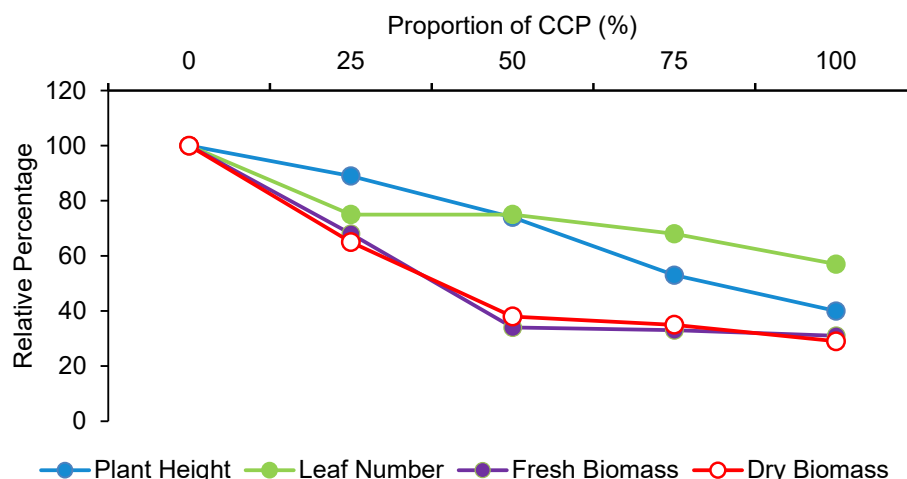
Time to Germination, Plant Height, Leaf Number, and Weight of Sweet Corn Biomass from Different Media Compositions at 21 Days After Planting

Growing media	Time to germination (days)	Plant height (cm)	Leaf number	Biomass weight (g)	
				Fresh	Dry
S100%	3.0 b	29.67 a	4.0 a	3.16 a	0.68 a
S75%+CCP25%	3.0 b	26.50 ab	3.0 b	2.21 a	0.45 b
S50%+CCP50%	4.0 b	22.00 bc	3.0 b	1.10 b	0.26 bc
S25%+CCP75%	6.0 a	15.83 cd	2.7 b	1.07 b	0.24 c
CCP100%	7.0 a	12.00 d	2.3 b	0.99 b	0.20 c
F test	**	**	*	**	**

Note. Values in the same column followed by the same letter are not significantly different according to the DMRT, $\alpha < 5\%$; * = significantly different at $\alpha < 5\%$, ** = significantly different at $\alpha < 1\%$; S = soil, CCP = coal combustion product fly ash + bottom ash.

Figure 2

The Effects of CCP Fly Ash and Bottom Ash Compositions on the Relative Percentage of Sweet Corn Plant Height, Leaf Number, Fresh and Biomass Dry Weight at 21 Days After Planting



Note. Statistical differences refer to Table 2. CCP= coal combustion product fly ash + bottom ash.

Ahmad et al. (2021) noted that fly ash application at a lower proportion of 10%-30% increases pumpkin growth, including plant height, fresh and dry biomass, leaf number, and average leaf area; however, application at higher proportions of 40% and 50% of the growing media inhibits growth, chlorophyll synthesis, and reduces yield due to metal toxicity. In maize seedlings, Zhang et al. (2024) noted that nitrogen uptake depends on soil pH; for example, in acid soils, they prefer NO_3^- , whereas in neutral or alkaline soils, they prefer NH_4^+ .

Root Growth

CCP application significantly reduced root number and root length (Table 3). Increasing the CCP proportion by over 25% reduced the length by a greater margin (9.50–13.67 cm). At higher CCP proportions, the overall inhibition of root development indicates a reduced capacity for root exploration. Root inhibition in radish has been studied by Nguyen and Nguyen (2024), in which the application of 20% fly ash reduced root length by 14.06% and root diameter by 20.07% compared with 10% fly ash. The limitation in root development likely constrains water and nutrient uptake, which, in turn, affects shoot growth, explaining the observed decline in aboveground performance at higher CCP proportions.

In contrast, sweet corn grown in media containing 25% CCP showed a root volume

comparable to that of 100% soil (3.17 vs 3.00 cm^3 ; Figure 3; Table 3), with no statistically significant difference between treatments. Although some studies have suggested that heavy metals in CCP may restrict plant growth (e.g., Purnamasari et al., 2024), the present results indicate that the inclusion of 25% CCP did not negatively affect root development under the conditions of this study. According to Atta et al. (2023), maize varieties ‘Pak-Afgoi’ and ‘Neelem’ exhibit tolerance to 50 ppm Cr and 30 ppm Pb, and Cr is accumulated in the shoot, while Pb is accumulated in the roots. Table 1 shows that the Cr and Pb contents of CCP are 19.51 ppm and 5.89 ppm, respectively, both within the range reported by Atta et al. (2023). In this study, the ‘Bonanza’ variety maintained comparable growth under the tested conditions, although further studies are required to better understand its response to Cr and Pb.

Based on visual observation, many sweet corn seedlings had seminal and nodal roots at 100% soil, whereas nodal roots were limited in CCP-enriched media. Seminal roots emerge from the maize seed at the V1 stage, and at the V3 stage, the nodal roots start to develop (Ortez & Licht, 2024). Nodal roots emerged from stem segments after stem elongation, along with leaf production (Protto et al., 2024). Thus, limited rooting of sweet corn in CCP-enriched media is likely due to reduced stem elongation and fewer leaves, as shown in Table 2.

Table 3

Root Growth of Sweet Corn Treated with Different CCP Fly Ash and Bottom Ash Compositions at 21 DAP

Growing media	Root number	Longest roots (cm)	Root volume (cm^3)
S100%	15.0 a	24.67 a	3.00 ab
S75%+CCP25%	11.3 b	19.50 b	3.17 a
S50%+CCP50%	10.3 b	13.67 c	2.10 bc
S25%+CCP75%	10.7 b	12.50 c	2.10 bc
CCP100%	9.3 b	9.50 c	1.70 c
<i>F test</i>	*	**	*

Note. Values in the same column followed by the same letter are not significantly different according to the DMRT, $\alpha < 5\%$; * = significantly different at $\alpha < 5\%$, ** = significantly different at $\alpha < 1\%$; S= Soil, CCP= coal combustion product fly ash + bottom ash; DAP= days after planting.

Moreover, maize rooting and stem elongation are affected by water deficit (Protto et al., 2024), soil pH (Zhang et al., 2022), and heavy metals, primarily Cr and Pb (Atta et al., 2023). Thus, the decrease in root performance in CCP-treated growing media could be due to the direct negative effects of minerals and/or alkaline pH (Table 1). Due to CCP also delaying seed emergence (Table 2), decreased rooting ability might imply different resource allocation in sweet corn among treatments.

N, P, and K Leaching

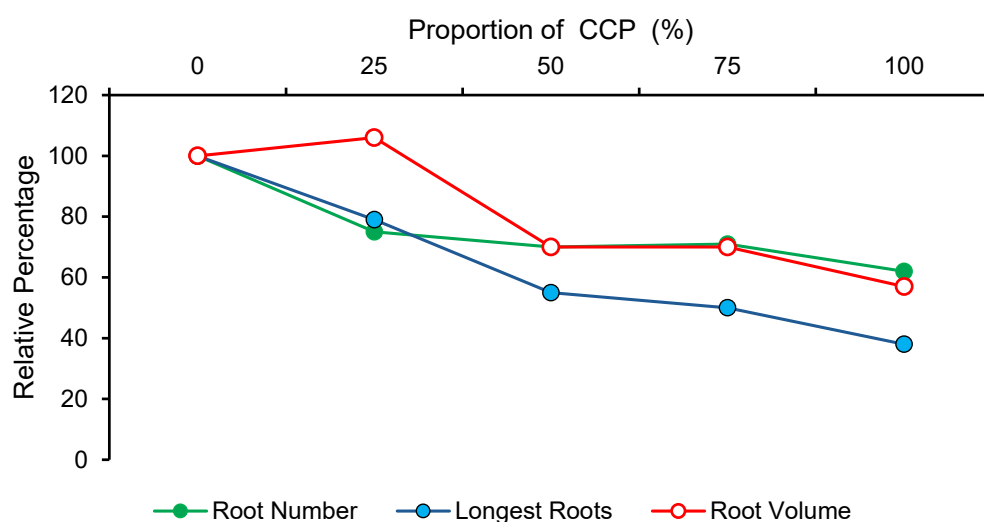
N/P/K leaching from growing media was significantly influenced by CCP proportion (Table 4). The amounts of N and K leaching from 100% soil were the lowest among treatments (6.97 ppm and 2.30 ppm), and N and K concentrations increased with increasing CCP proportion (Figure 4). Growing media with 75% CCP tended to leach more N, although its N concentration did not differ significantly from that of other CCP proportions at 1%. On the other hand, 100% CCP yielded the highest K leachate (3.84 ppm).

The differences in N, P, and K leaching among treatments were influenced by both the

mineral composition of CCP and changes in soil properties. In particular, the high CaO content in CCP increased soil pH (Komonweeraket et al., 2015; Singh et al., 2016) which, in turn, affected nutrient solubility and mobility. Nutrient leaching in this study is defined as the loss of essential elements from the soil system, thereby reducing their availability for plant uptake. At higher pH, K becomes more mobile and prone to leaching, while N losses increase due to enhanced nitrification, which converts ammonium into the more mobile nitrate. In contrast, P showed a more complex response, as its mobility is controlled by adsorption and fixation processes (Barrow & Hartemink, 2023). Under alkaline conditions, phosphorus can be adsorbed onto soil mineral surfaces and react with Ca to form insoluble calcium-phosphate compounds, thereby reducing its solubility and leaching potential (Meyer et al., 2020). In addition to these chemical effects, CCP also alters soil physical properties, such as porosity and water flow, which further influence nutrient movement (Swain et al., 2026). Therefore, the observed differences in nutrient leaching resulted from the combined effects of CCP mineral content and its impact on soil chemical and physical characteristics.

Figure 3

The Effects of CCP (Fly Ash and Bottom Ash) Compositions on the Relative Percentage of Sweet Corn Root Number, the Longest Root, and Root Volume at 21 Days After Planting



Note. Statistical differences refer to Table 2. CCP= coal combustion product fly ash + bottom ash.

Phosphorus leaching was lower than N and K, and increasing the CCP proportion tended to reduce the P concentration (Table 4). Such low P leachate might be related to its form. Soil analysis before the experiment showed that total P was 0.097% (970 ppm; Table 1), but available P was <0.08 ppm. On the other hand, the CCP contained a total of P 0.160% or 1600 ppm. It is likely that most P in CCP is in inorganic forms. According to Lehmann and Schroth (2003), phosphate leaching is negligible because it is

immobile in most soils, but organic phosphorus forms are more mobile.

Although 100% CCP contained N, its concentration was still lower than that of 100% soil (Table 1). As a result, the total N in growing media strictly depended on the soil: CCP proportion tended to decrease total N in the growing media (Table 5). On the other hand, increasing CCP increased the N leaching rate, e.g., 0.50% in 100% soil versus 10.46% in 100% CCP. Thus, CCP application for N enrichment

Table 4

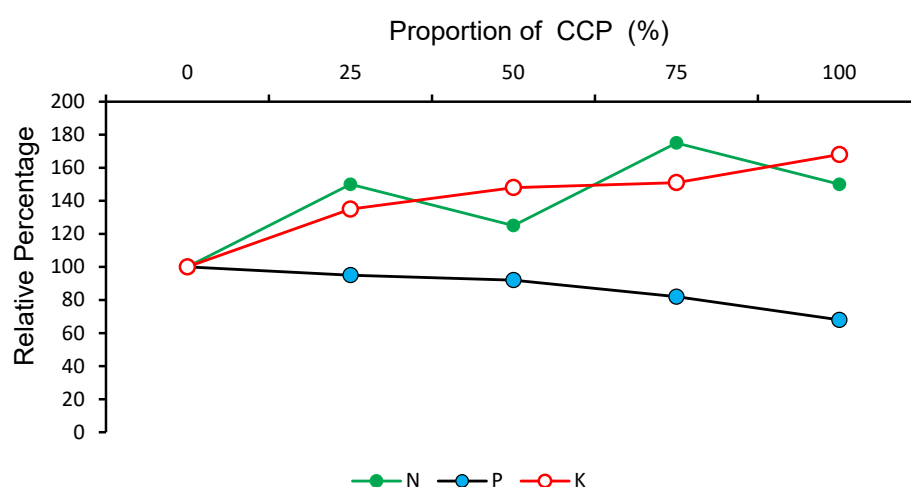
pH, N, P, and K Concentrations from Aqueous Solution of the Sweet Corn Growing Media Treated with Different CCP (Fly Ash and Bottom Ash) Compositions at 21 DAP

Growing media	N (ppm)	P (ppm)	K (ppm)	pH
S100%	6.97c	0.34 a	2.30 d	4.33 c
S75%+CCP25%	10.46 ab	0.32 a	3.10 c	5.59 b
S50%+CCP50%	8.70 bc	0.31 a	3.39 b	5.88 b
S25%+CCP75%	12.20 a	0.28 ab	3.46 b	6.84 a
CCP100%	10.46 ab	0.23 b	3.84 a	6.69 a
F test	**	*	**	**

Note. Values in the same column followed by the same letter are not significantly different according to the DMRT, $\alpha < 5\%$; * = significantly different at $\alpha = 5\%$, ** = significantly different at $\alpha = 1\%$; S= Soil, CCP= coal combustion product fly ash + bottom ash; DAP= days after planting.

Figure 4

Relative Percentage of N, P, and K Leached from Sweet Corn Growing Media after Treatment with Different CCP (Fly Ash and Bottom Ash) Compositions at 21 Days After Planting



Note. Statistical notation refers to Table 4. CCP= coal combustion product fly ash + bottom ash.

purposes should be followed by proper N leaching management.

Considering the leaching rate, CCP appears to be a potential source of P and K, as the increasing CCP proportion increased total P and K in the growing media but reduced the leaching rate of both nutrients (Table 5). P and K leaching rates at 25% CCP were 0.03% and 0.42%, while at 100% CCP they were 0.01% and 0.17%, respectively. Since the reduction of the leaching rate indicates low solubility of both nutrients in soil solution (Lehmann & Schroth, 2003), understanding the potential cause is important. Phosphorus dynamics in the growing media are governed by adsorption and fixation processes. Phosphorus can be adsorbed onto Fe and Al oxides present in CCP or precipitated with Ca to form less soluble compounds, thereby reducing its mobility and leaching potential. These processes increase total P retention in the media while simultaneously decreasing P losses through leaching (Shen et al., 2011). As a result, increasing the CCP proportion leads to higher total P content but lower P leaching rates.

CCCP contained 3.54% Ca and had a pH of 11.45 (Table 1). Such an alkaline condition might fix P in soluble complexes that reduce phosphorus availability to plants, according to

Johan et al. (2021). In CCP, potassium-bearing minerals were sylvite and feldspar, which slowly release K⁺ ions in the growing medium (Çöteli et al., 2025). Therefore, using CCP as a source of P and K should be accompanied by increased mineralization management.

Table 4 shows that the pH of the leachate was significantly influenced by the CCP proportion. CCP at a composition of 75% or 100% significantly had a higher pH (pH 6.69-6.84) than 100% soil (pH 4.33). This finding is consistent with previous studies by Putri et al. (2023) and Varshney et al. (2022), in which the application of CCP increases soil pH. The original CCP had a pH of 11.45 (Table 1), whereas media with 100% CCP had a pH of 6.69. This means that increasing the CCP proportion did not increase the media pH linearly. Although the decrease in pH in 100% CCP could be due to irrigation of water or organic compounds from sweet corn, the stability of pH as an indicator of effective soil amendment with CCP remains unclear. This non-linear pH response is attributed to the buffering capacity of the growing media, which is governed by interactions among mineral components (such as Fe and Al oxides and Ca-bearing minerals from CCP), soil solution chemistry, and exchange reactions at soil surfaces. These

Table 5

The Effects of Different Proportions of CCP (Fly Ash and Bottom Ash) on Total N, P, and K in the Sweet Corn Growing Media and Their Leaching Rates

Growing media	Total N (%)	Total P (%)	Total K (%)
S100%	0.14	0.10	0.02
S75%+CCP25%	0.11	0.11	0.07
S50%+CCP50%	0.08	0.13	0.12
S25%+CCP75%	0.04	0.14	0.17
CCP100%	0.01	0.16	0.22
Leaching rates (%)			
S100%	0.50	0.04	0.96
S75%+CCP25%	0.97	0.03	0.42
S50%+CCP50%	1.16	0.02	0.28
S25%+CCP75%	2.87	0.02	0.20
CCP100%	10.46	0.01	0.17

Note. Data were based on a stoichiometry calculation. CCP= coal combustion product fly ash + bottom ash.

components regulate proton (H^+) consumption and release, thereby moderating pH changes rather than allowing a proportional response to alkaline inputs. In addition, root activity contributes to rhizosphere buffering by selective ion uptake and the release of organic acids and other exudates, further stabilizing pH in the root zone (Neina, 2019; Tavakkoli et al., 2015). This combined chemical and biological buffering explains the observed non-linear pH behavior.

Pearson Correlation

Pearson correlation showed a positive correlation between plant height and the number of leaves ($P < 0.001$), plant fresh weight ($P < 0.001$), root volume ($P < 0.05$), the length of the longest root ($P < 0.01$), plant dry weight ($P < 0.01$), and P leaching ($P < 0.05$) (Figure 5). However, plant height was negatively correlated with N ($P < 0.05$) and K ($P < 0.001$) leaching. Similarly, the number of leaves showed a negative association with N and K leaching.

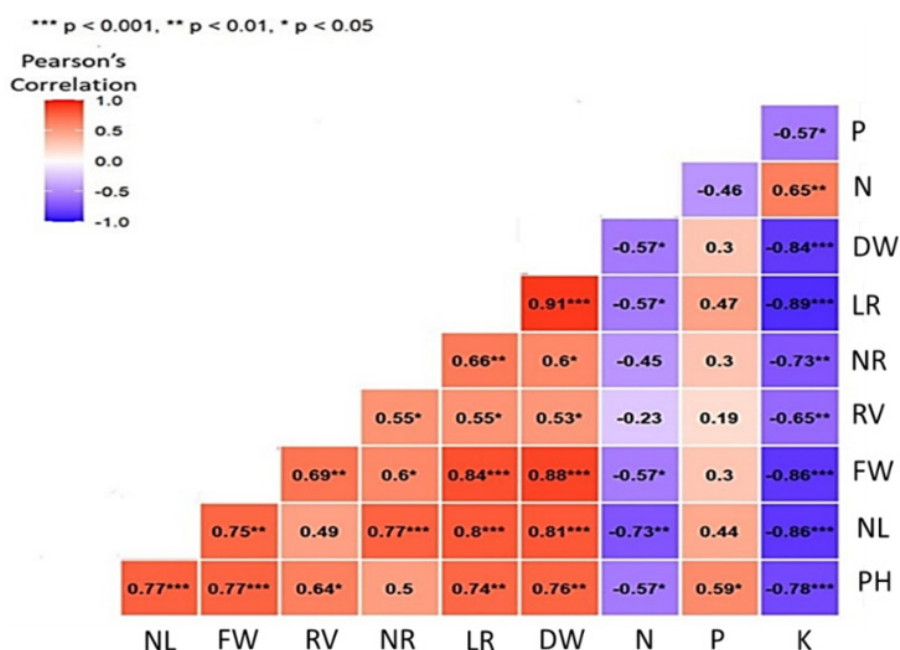
Figure 5 shows the increasing growth parameters of sweet corn seedlings, followed by higher N and K leaching. This finding implies that leaching management is important in sweet corn growth when supplemented with CCP.

Future Perspective

Overall, the results indicated that the application of CCP influenced plant growth and nutrient dynamics by altering the growing medium. Increasing the CCP proportion modifies the chemical environment, particularly soil pH, which in turn affects nutrient behavior, such as P retention via adsorption and fixation, as well as N and K mobility, as reflected in leaching patterns. These changes appear to be associated with plant performance, with comparable or reduced nutrient losses suggesting more efficient nutrient use within the system. At moderate levels, CCP may support a better balance between nutrient availability and retention, whereas higher proportions can alter root development and

Figure 5

Pearson Correlation of Growth Parameters with the Leaching of N, P, and K Nutrients in Sweet Corn Growing Media



Note. PH (plant height), NL (number of leaves), FW (plant fresh weight), RV (root volume), NR (number of roots), LR (longest root), DW (plant dry weight), N (nitrogen), P (phosphorus), K (potassium).

nutrient dynamics, potentially constraining plant growth. However, these findings are limited to the early vegetative stage, and further studies extending to the harvest stage are required to confirm their implications for final yield and agronomic performance.

Based on the present experiment, a CCP proportion of 25% (m/m) is recommended for sweet corn cultivation. This rate is in line with previous studies, such as those on mustard greens (Aziz et al., 2023) and guava seedlings (Swain & Padhi, 2012). On the other side, Restini and Dewi (2023) recommended 75% CCP for *Capsicum* seedlings. This indicates that different species respond differently to CCP compositions. Yuniar (2024) stated that the availability of P in growing media increases with increasing CCP proportion in lettuce. Since CCP content depends on coal resources and power plant technologies (Putra et al., 2024), it is interesting to evaluate the availability of N, P, and K in growing media for different CCP sources in the future.

The present study examines the potential of CCP as a source of N, P, and K nutrients and as a soil amendment. However, three points should be noted about fertilizers. First, CCP alone does not meet the requirements as a fertilizer due to its low content of K (0.15%–0.3%), CaO (2%–7.1%), and MgO (0.7%–1.8%), although it has very high SiO₂ (37.7–46.8%), while the requirements are 4%, 15%, 9%, and 6%, respectively (Restini & Dewi, 2023).

Second, CCP has an imbalanced nutrient composition that may adversely affect plant growth. According to Faoziah et al. (2022), CCP can release K and Na in soil, increasing pH and base saturation, but it tends to reduce the availability of P and Ca and the cation exchange capacity in soil solutions. In maize, Wang et al. (2024) stated that soil organic carbon (SOC) is a determinant of growth once NPK sufficiency is reached. It is likely that the SOC content in CCP (i.e., 0.95%; Table 1) is insufficient to support plant growth, although the NPK level in the growing media is sufficient. Mixing CCP with compost might stimulate mineralization of CCP to enhance nutrient availability. Faoziah et al. (2022) applied compost with CCP to sandy soil,

which resulted in increases in C-organic, N-total, available P, and base saturation compared to the control. In the future, supplementing CCP with organic matter to increase SOC is an interesting approach to accelerate nutrient mineralization, as the high firing temperatures during the coal-burning process form minerals such as sylvite and feldspar (Çöteli et al., 2025).

Finally, nutrient leaching after CCP application should be emphasized. In the field, nutrient leaching is an environmental loss (Yan et al., 2023). In the present experiment, the increase in actual N and K leaching (Table 4) was probably due to the increased total amount of added N and K from CCP. According to Tafteh and Sepaskhah (2012), N leaching in maize fields increases with higher N application rates, but it does not correlate linearly with the application rate. In the future, it is important to evaluate long-term nutrient stoichiometry since CCP also contains other substantial minerals and metals.

Conclusions

The proportion of coal combustion products (CCP) affected sweet corn growth and nutrient solubility dynamics. CCP could be used as a soil amendment and a partial fertilizer substitute for sweet corn, with the optimal proportions under this study's conditions being 25% and 50%. However, precautions should be taken to prevent potential nutrient leaching. A higher proportion of CCP adversely affects sweet corn growth. Increasing the CCP proportion markedly reduced plant growth, with decreases of up to 57% in seed emergence, 59.56% in plant height, 42.50% in leaf number, 70.59% in dry weight, and 38.00% in root number compared to 100% soil. CCP application increased N leaching, with rates rising from 0.97% to 10.46%, while K leaching decreased from 0.42% to 0.17% as CCP proportions increased from 25% to 100%, indicating the need to manage leaching when CCP is incorporated into soil. Further studies on stoichiometry in CCP-enriched soil should be conducted to examine its applicability in the field.

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