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CONTRIBUTION OF DIFFERENT BIO-SOLIDS ON THE GROWTH, NPK NUTRITION AND NPK USE EFFICIENCY OF CORN UNDER DIFFERENT NPK DOSAGES

SUMMARY

This study evaluated the effects of four bio-solids, biogas digestate (BD), alkaloid industry waste (ALK), industrial sewage sludge (ISS) and urban sewage sludge (USS) on the growth, NPK use efficiency and mineral nutrition of corn grown under different NPK dosages. The experimental soil was treated with BD, ALK, ISS and USS at rates of 0, 20, and 40 t ha^{-1} at 0, 20, and 40 t ha^{-1} and three NPK levels (NPK0: 0, NPK1: 150–100–50, NPK2: 300–200–100 mg kg^{-1}) then corn was grown for 2 months under greenhouse conditions. Plant dry weight (DW) increased significantly with both mineral fertilization and bio-solid applications. The lowest DW (6.48 g pot^{-1}) was recorded in the unfertilized conditions where no bio-solid or NPK application were done, whereas the highest values (23.6 g pot^{-1}) were obtained from 40 t ha^{-1} of BD+NPK2 and 40 t ha^{-1} of ISS+ NPK1 treatments. Mean DW increased from 11.6 g pot^{-1} (NPK0) to 20.2 g pot^{-1} (NPK2). Total N uptake ranged from 74 to 639 mg pot^{-1}. Benefit rate from fertilizer (BFF) for N varied between 5.6% and 48.9%, with BD and USS. Phosphorus uptake increased from 9.1 to 49.9 mg pot^{-1}, although fertilizer BFF for P remained low (<6%). Potassium uptake reached 890 mg pot^{-1} under 40 t ha^{-1} of ISS+NPK1. Bio-solid applications generally promoted biomass accumulation. Low bio-solid dosage (20 t ha^{-1}) combined with reduced NPK improved nutrient use efficiency more effectively than high mineral inputs. Overall, ISS, BD, and USS demonstrated strong potential to partially substitute mineral fertilizers and support plant growth.

Keywords: bio-solid, NPK use efficiency, plant growth, plant nutrition

INTRODUCTION

The increase in global population, rapid urbanization, and industrialization are causing a continuous increase in the amount of solid waste generated worldwide. One of the most problematic waste products resulting from increasing

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urbanization and industrialization is sewage sludge. Generated globally as a byproduct of wastewater treatment facilities, sewage sludge, frequently referred to as bio-solids, is a biodegradable material characterized by its diverse physicochemical properties. During biogas production, a waste material called digestate is generated. It contains noteworthy amounts of mineral elements, enzymes, and amino acids, as well as significant amounts of organic matter. The agricultural industry is indispensable for the processing of agricultural products and food supply, but the waste generated during production and processing can cause serious environmental problems if not managed properly. Alkaloid waste is a chemically processed byproduct of the opium poppy industry, in Türkiye. Formerly utilized as a livestock feed supplement, this material is now subject to strict prohibitions or usage restrictions. Consequently, it is primarily diverted to energy facilities for incineration as biofuel or deposited in landfills (Mejri, 2024). Improper management and unregulated disposal of these waste streams pose significant environmental threats. While efforts are underway to find ways to dispose of these materials, there is also a focus on how to utilize them in sustainable and environmentally friendly ways. Materials such as the bio-solids mentioned above can be transformed from a problem into valuable resources.

The application of sewage sludge as a soil amendment improves the physicochemical, microbiological, and enzymatic characteristics of the soil, ultimately boosting crop yields (Bourioug *et al.,* 2015). Lemainski and da Silva (2006) highlight that sewage sludge serves as a potent organic fertilizer and conditioner. In practice, sewage sludge can partially substitute conventional chemical fertilizers (De Andrade *et al*., 2016). As a byproduct of anaerobic digestion, biogas digestate serves as a high-quality organic fertilizer due to its high nutrient concentrations (Yaylacı and Erdal, 2021; Mejri, 2024). It helps to maintain and improve soil fertility, soil structure, and humus balance (Odlare, 2005), as well as increase the bacterial fauna of plants in the rhizosphere region (Yu *et al.,* 2010).

Although the agronomic potential of bio-solids is acknowledged, there is a scarcity of comparative assessments of chemically and biologically different bio-solid types under varied mineral NPK conditions, especially concerning their interactive effects on nutrient uptake efficiency and fertilizer benefit rates. Specifically, waste from alkaloid processing has undergone very little agronomic assessment. Therefore, this study contributes new knowledge by comparatively evaluating multiple bio-solid types, including a rarely studied alkaloid waste, under different NPK regimes, and by explicitly examining their interactive effects on nutrient use efficiency and fertilizer benefit rates. Consequently, the primary research question of this study is: To what degree can biogas digestate, alkaloid industry waste and sewage sludges replace or enhance mineral NPK fertilizers in boosting biomass yield, nutrient uptake, and fertilizer efficiency for corn across different NPK conditions.

Drawing on the physicochemical properties of the materials evaluated and previous research, we proposed that (i) applying bio-solids boosts corn biomass and nutrient uptake compared to using only mineral fertilizers, especially in low or zero NPK conditions; (ii) the extent of nutrient uptake and the rate of fertilizer benefits can vary among bio-solid types; (iii) moderate bio-solid doses combined with low NPK levels can improve fertilizer efficiency more effectively than high amounts of mineral fertilizers

The aim of the study is to evaluate the effects of biogas digestate, alkaloid processing waste, industrial and urban sewage sludges on corn growth, NPK nutrition, benefit rate from fertilizer under different NPK regimes. Additionally, the study aims to determine the effects of these bio-solids on some macro and micro element nutrition of corn.

MATERIAL AND METHODS

The experimental soil is characterized by a clay-loam texture, a slightly alkaline reaction with a pH of 7.5. Some other characteristics of the soil are listed in Table 1.

Table 1. Some physico-chemical properties of the experiment soil

Properties		Available nutrients (mg kg^{-1})	
Soil texture	Clay-loam	P	10.5
Soil pH (1/2.5 soil/water, w/v)	7.5	K	161
Electrical conductivity (EC, ds m^{-1})	0.14	Ca	5227
Total N (%)	0.044	Mg	189
Organic matter (%)	1.5	Fe	3.5
$CaCO_3$ (%)	28	Mn	15.6
Field capacity (w/w, %)	28	Zn	1.2
Pot capacity (w/w, %)	36	Cu	3.7

As test materials, 4 different bio-solids were used. The biogas digestate (BD) was collected from the biogas decanter outputs. The alkaloid industry solid waste (ALK) was supplied by an opium alkaloid facility and had been stored in bulk within the facility's storage area for approximately 6 months. The industrial sewage sludge (ISS) was sourced from Isparta Süleyman Demirel Organized Industrial Zone Wastewater Treatment Plant, where it was subjected to a thermal treatment at 70 °C for sterilization. The urban sewage sludge (USS) used was obtained from Isparta Municipal Wastewater Treatment Plant. This sludge had been stored for approximately 6 months after undergoing a passive aerobic fermentation and being solar dried. Before being incorporated into soil, all materials underwent a seven-day air-drying process, followed by grinding, homogenization and sieving (2 mm). Some specific characteristics of the bio-solids are given in Table 2.

The research was carried out in greenhouse as 3 replications according to completely randomized design. For this, 0, 20 and 40 t ha^{-1} of each bio-solid were mixed to the 4 kg soil containing pots. 3 NPK levels were applied to the soils. NPK levels were applied, categorized as; control NPK0 (0 mg kg^{-1} NPK), NPK1 (150 mg kg^{-1} N, 100 mg kg^{-1} P, and 50 mg kg^{-1} K) and NPK2 (300 mg kg^{-1} N, 200 mg kg^{-1} P, and 100 mg kg^{-1} K). The NPK fertilizations were done using urea, mono ammonium phosphate, and potassium nitrate.

Table 2. Some characteristics and elemental compositions of the bio-solids used for the experiment

Bio-solids	pH	EC (ds m^{-1})	OM	TC	N	P	K	Ca	Mg
						(%)			
BD	7.1	3.4	76	44	2.2	1.24	0.94	3.2	0.75
ALK	9.8	7.0	80	47	1.0	0.23	0.84	5.4	0.65
ISS	7.6	9.7	64	37	4.1	1.63	0.38	1.93	0.41
USS	6.8	3.9	68	42	5.5	1.14	0.17	2.50	1.0
	Fe	Cu	Mn	Zn	Pb	Ni	Cr	Co	
				(mg kg^{-1})					
BD	3247	42	278	561	6.6	6.6	11.4	0.43	
ALK	513	16	19	20	3.8	1.6	3.5	*	
ISS	4103	48	51	1037	26	112	625	1.2	
USS	5940	78	100	872	16	17	30	3.0	

**Below detection limit, EC: electrical conductivity, O.M: organic matter, T.C.: total carbon, BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge*

In each pot, 5 seeds were sown and then thinned to two after emergence. Daily irrigation was carried out based on the plant's water requirement until 70 % of field capacity. After 2 months, plants were harvested, washed with tap and deionized water, oven-dried at 70 °C and dry weights were recorded. Dried samples were ground using a steel mortal for nutrient analysis. Plant samples were dry-ashed into a muffle furnace at 500-550°C for six hours. Ash residues were dissolved in concentrated HCl, and filtered. After a proper dilution of the digests, nutrients (K, Mg, Ca, Cu, Fe, Mn, and Zn) were determined using ICP (OES ICAP 6300 Thermo Electron). Plant P concentrations were measured according to vanadomolybdophosphoric acid method. The N concentration was measured according to Khjeldahl method (Jones *et al.*, 1991).

Soil OM was determined according to Walkley and Black (1947). Khjeldahl method was used for total N determination. Soil pH and EC were measured using pH and EC meter. Calsimetric method was used to determine $CaCO_3$ amount in the soil. Available P was quantified after the extraction of soil with $NaHCO_3$ using spectrophotometer. Soil K, Ca, and Mg determined after the extracted with NH_4OAc. The available concentrations of Zn, Cu, Fe and Mn were measured by the DTPA-$CaCl_2$-TEA extraction method. The amount of the K, Ca, Mg, Zn, Cu, Fe and Mn were measured using an ICP. Soil analysis were performed using the methods described in Kacar (2012).

The pH and EC values of bio-solids were measured according to Belhaj *et al.*, (2016). N and P concentrations were measured following the procedure as in plant samples. Materials underwent wet digestion in a concentrated 4: 1 HNO_3: $HClO_4$ solution then subjected to analysis for K, Ca, Mg, Fe, Zn, Mn, Cu and heavy metals using ICP-OES (Kuboyama *et al.*, 2005).

Benefit rate from fertilizer (BFF) was calculated by comparing the total nutrient removal to applied nutrient with fertilizer using below equations (Erdal *et al.*, 2006).

N uptake (mg pot-1) = DW × N
NUFF (mg pot-1) = N uptake1 – N uptake0
BFF (%) = NUFF × 100/NF

Where DW is oven dry weight of corn (g pot^{-1}), N is N concentration of plant (%), NUFF is N uptake from fertilizer (mg pot^{-1}), N uptake1 is N uptake from fertilized pots (mg pot^{-1}), N uptake0 is N uptake from un-fertilized pots (mg pot^{-1}), BFF is benefit rate from fertilizer (%), and NF is N amount applied with fertilizer (mg pot^{-1})

Statistical analysis of the data were made by using Minitab software version 17 (Minitab TM Inc. State College, PA, USA). One-way analysis of variance (ANOVA) and multiple comparison tests (Tukey HSD) were applied. A significance level of $p<0.05$ was used throughout the study.

RESULTS AND DISCUSSION

Effects of bio-solids on dry weight of corn

The interaction effects of NPK levels, bio-solid types and application rates and means of individual factors on corn growth are presented in Fig 1. As shown in Fig. 1, both the main effects of the treatments and their interactions significantly influenced plant dry weight ($p<0.05$). The lowest plant dry weight was recorded under NPK0 conditions without bio-solid application. In contrast, the highest dry weight values were obtained from pots receiving half-dose NPK (NPK1) in combination with 40 tons of BD and ISS. When the means of NPK treatments were examined, dry weights increased markedly with increasing NPK dose. This represents an increase of approximately 63% (NPK1) and 74% (NPK2) relative to the control. Among the bio-solids, ALK showed comparatively limited effects. The other three materials were found to be more effective, and their effects were statistically similar. Increasing bio-solid application rates resulted in a consistent and significant enhancePrimarment of corn dry weight.

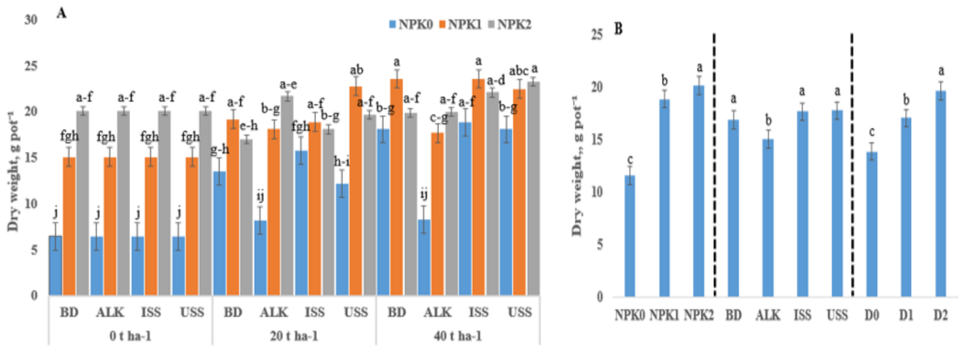

Fig.1. Effects of treatments on dry weight of corn (A: interactions, B: means)

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p<0.05$. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg^{-1} NPK, NPK1:150 mg kg^{-1} N, 100 mg kg^{-1} P, 50 mg kg^{-1} K, NPK2: 300 mg kg^{-1} N, 200 mg kg^{-1} P, 100 mg kg^{-1} K; D0, D1, D2: 0, 20 and 40 t ha^{-1} of bio-solid

Effects of bio-solids on N concentrations, N uptakes and benefit rate from fertilizer (BFF) of corn

Interactions and means of the individual factors significantly influenced N concentrations and N uptakes of corn (Fig. 2). Under NPK0 conditions without bio-solid application, corn exhibited the lowest N concentrations and total N uptake. Across all bio-solid free treatments, increasing NPK supply resulted in a substantial rise in plant N concentration under NPK2, corresponding to an increase of approximately 70% compared with NPK0. Among bio-solid treatments, the highest N concentrations were recorded in 20 and 40 tons of BD under NPK2 treatment. Notably, application of 40 tons of ISS produced a remarkably high N concentration even in the absence of mineral fertilizer. N uptake followed a similar tendency. While control treatments remained below 80 mg pot^{-1}, the highest uptake was achieved in 40 tons of ISS and NPK1 combination, representing an almost 8.6-fold increase compared with the unfertilized control. Other high-performing treatments were 40 tons of BD and NPK2 combination and 40 tons of ISS and NPK2 combination. As for means of individual treatments, NPK2, ISS and D2 were the most efficient treatments for N uptake.

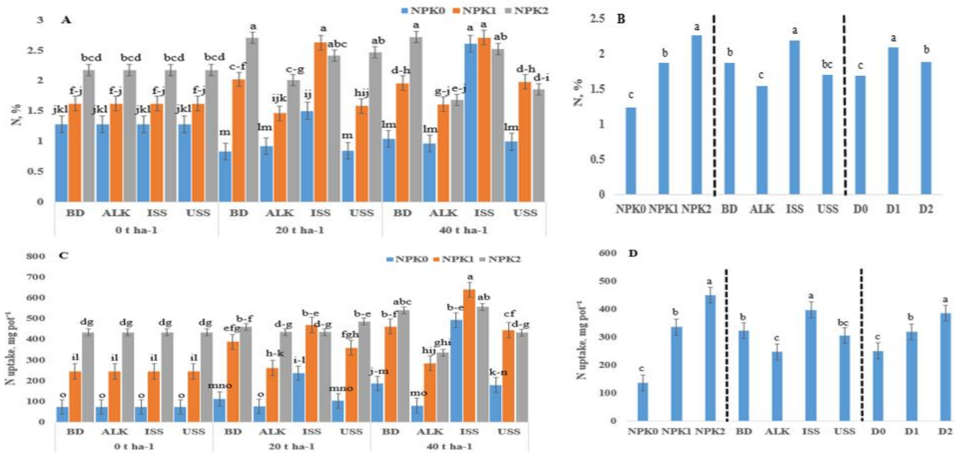

Fig. 2. Effect of treatments on N concentrations (A: interactions, B: means) and N uptake (C: interactions, D: means) of corn

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p<0.05$. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg^{-1} NPK, NPK1:150 mg kg^{-1} N, 100 mg kg^{-1} P, 50 mg kg^{-1} K, NPK2: 300 mg kg^{-1} N, 200 mg kg^{-1} P, 100 mg kg^{-1} K; D0, D1, D2: 0, 20 and 40 t ha^{-1} of bio-solid

Changes in N uptake from fertilizer (NUFF), and benefit rate from fertilizer (BFF) are given in Fig 3. In bio-solid-free treatments, NUFF rose from 171 mg pot^{-1} at NPK1 to 360 mg pot^{-1} at NPK2. Among bio-solids, USS consistently showed high NUFF values, reaching 383 mg pot^{-1} in 20 t ha^{-1} of

USS+NPK2 combination, the highest recorded fertilizer N uptake. In contrast, 40 tons of ISS treatments exhibited a sharp decline in NUFF with increased NPK dosage. BFF values varied widely across treatments, ranging from 5.6% to 48.9%. The highest BFF was observed in 20 and 40 tons of BD with NPK1 combinations, corresponding to a 38% increase in fertilizer benefit compared with the bio-solid free NPK1 treatments. Similarly, USS treatments under NPK1 exhibited consistently high BFF values. Depending on the means of treatments it was seen that NPK1, BD and D1 were superior when compared to other individual treatments.

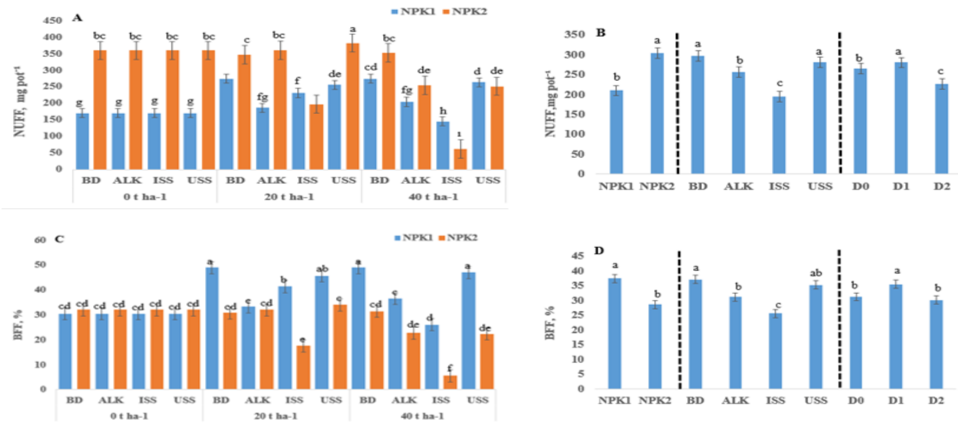

Fig.3. Effect of treatments on N uptake from fertilizer (NUFF, A: interactions, B: means) and benefit rate from fertilizer (BFF, C: interactions, D: means)

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at p<0.05. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg^{-1} NPK, NPK1:150 mg kg^{-1} N, 100 mg kg^{-1} P, 50 mg kg^{-1} K, NPK2: 300 mg kg^{-1} N, 200 mg kg^{-1} P, 100 mg kg^{-1} K; D0, D1, D2: 0, 20 and 40 t ha^{-1} of bio-solid

Effects of bio-solids on P concentrations, P uptakes and benefit rate from fertilizer of corn

Fig 4 indicates that P concentration and P uptake were significantly affected by bio-solid type, application rate, NPK levels (p<0.05) interactions and their individual effects. The lowest P concentrations and P uptake were obtained from applications where NPK and bio-solids were not applied. On the other hand, the highest P concentration and P uptake were determined in the plants exposed to the combined application of 20 tons of ALK and NPK2 treatments. Increasing mineral fertilization from NPK0 to NPK2 increased P concentration by approximately 21% and P uptake by ~276%. PUFF and BFFvalues are given in Fig 5. PUFF ranged from 3.4 mg pot^{-1} (40 tons of BD and NPK1 combination) to a maximum of 37.6 mg pot^{-1} in 20 tons of ALK and NPK2 combination.

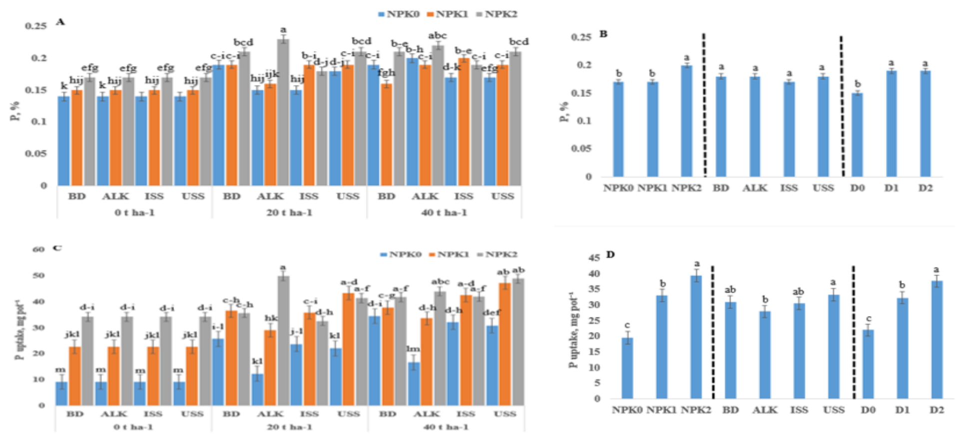

Fig.4. Effect of treatments on P concentrations (A: interactions, B: means) and P uptake (C: interactions, D: means) of corn

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at P<0.05. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg^{-1} NPK, NPK1:150 mg kg^{-1} N, 100 mg kg-1 P, 50 mg kg^{-1} K, NPK2: 300 mg kg^{-1} N, 200 mg kg^{-1} P, 100 mg kg^{-1} K; D0, D1, D2: 0, 20 and 40 t ha^{-1} of bio-solid

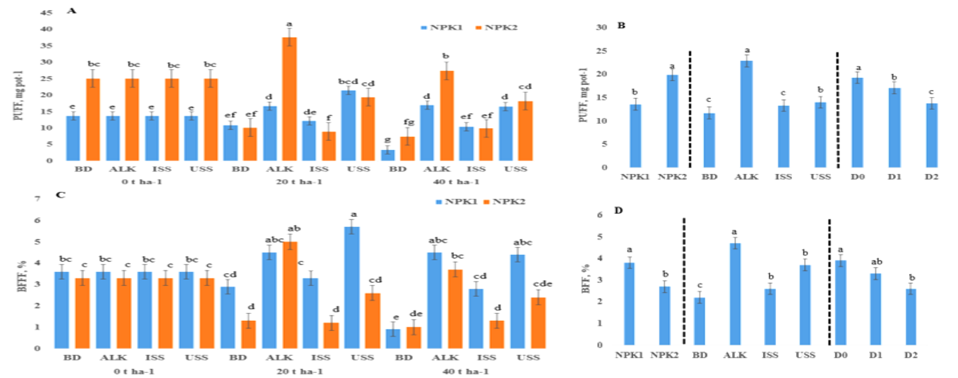

Fig.5. Effect of treatments on P uptake from fertilizer (PUFF: A: interactions, B: means) and benefit rate from fertilizer (BFF, C: interactions, D: means) of corn

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at P<0.05. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg^{-1} NPK, NPK1:150 mg kg^{-1} N, 100 mg kg^{-1} P, 50 mg kg^{-1} K, NPK2: 300 mg kg^{-1} N, 200 mg kg^{-1} P, 100 mg kg^{-1} K; D0, D1, D2: 0, 20 and 40 t ha^{-1} of bio-solid

Results showed that some treatments had no effect on BFF. However, treatments had partial contributions to BFF and these values were mostly below the 6 %. As in PUFF, the lowest BFF was determined in plants grown under 40 tons of BD and NPK1 combination. On the other hand, the highest BFF value was achived by the plants grown under 20 tons of USS and NPK1 combination. Means of the main factors indicate that P concentration significantly varied with NPK treatmens and with bio-solid dosages. However, bio-solid diversity did not effect plant P concentration. The effects of all applications on plant P uptake, PUFF, and BFF were statistically significant ($p<0.05$). While plant P uptake increased steadily with NPK and bio-solids doses, it was determined that USS was the most effective material on P uptake, while ALK had the lowest efficiency. Increasing NPK dosages increased PUFF values while causing BFF values to decrease. The effect of bio-solid dosages on PUFF and BFF were found to be negative. Among the materials, ALK was the most effective materials on PUFF and BFF.

Effects of bio-solids on K concentrations, K uptake and benefit rate from fertilizer of corn

Plant K concentration showed a significant variations depending on the applications, with an approximate 42% difference between the minimum and maximum values. Plant K uptake showed a pronounced response, ranging from a minimum of 249 mg plant^{-1} under control treatments to a maximum of 890 mg plant^{-1} under 40 tons of ISS+NPK1 combination representing an increase of approximately 257 % (Fig 6).

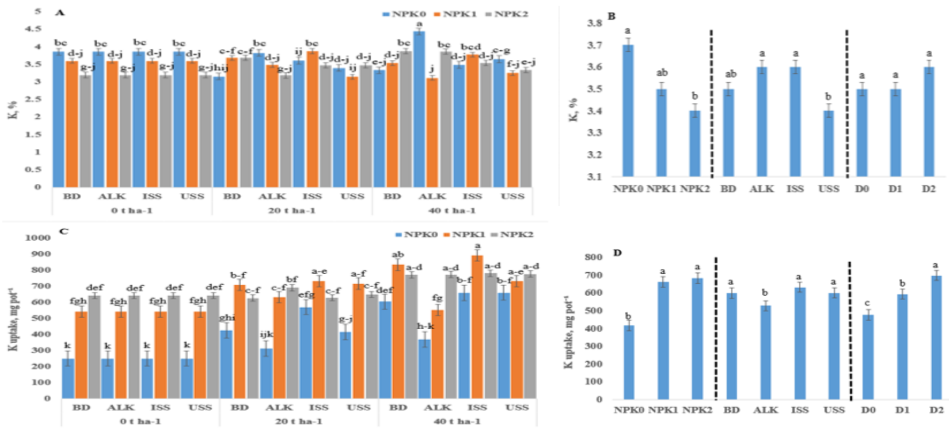

Fig.6. Effect of treatments on K concentrations (A: interactions, B: means) and K uptake (C: interactions, D: means) of corn

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at P<0.05. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg-1 NPK, NPK1:150 mg kg-1 N, 100 mg kg-1 P, 50 mg kg-1 K, NPK2: 300 mg kg-1 N, 200 mg kg-1 P, 100 mg kg-1 K; D0, D1, D2: 0, 20 and 40 t ha-1 of bio-solid

KUFF values increased from 59 mg pot^{-1} (20 tons of ISS treated with NPK2to a maximum of 404 mg pot^{-1} (40 tons of ALK treated with NPK2). BFF ranged from 15.8 % (20 tons of ISS+NPK2) to 169.7 % (20 tons of ALK+NPK1), reflecting more than a 10-fold variation across treatments (Fig 7). According to means of the factors, plant K concentrations significantly decreased with increased NPK applications. On the other hand, bio-solid differences and their application dosages did not affect plant K concentrations. In contrast to K concentration, KUP increased significantly with NPK and bio-solid dosages. ALK was found to be the least effective material on K uptake. While NPK1 and NPK2 treatments had similar effect on KUFF, NPK1 was superior on BFF. On KUFF and BFF, ALK was found to be the most effective material. Increased material dosages similarly decreased KUFF and BFF.

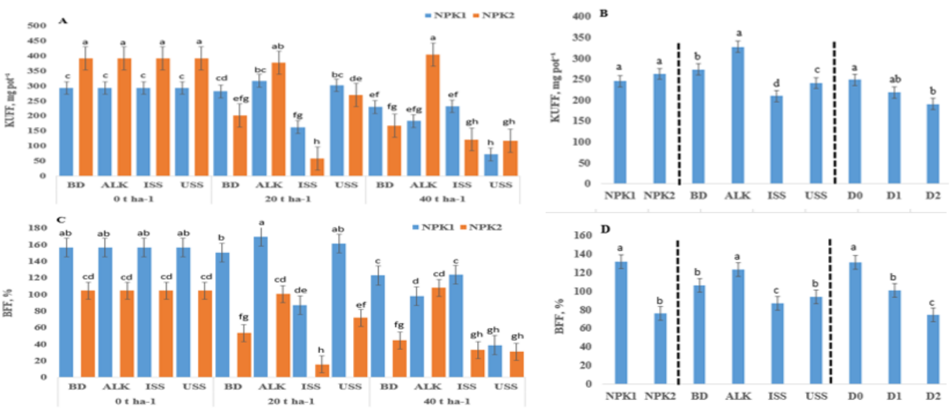

Fig. 7. Effect of treatments on K uptake from fertilizer (KUFF: A: interactions, B: means) and benefit rate from fertilizer (BFF, C: interactions, D: means) of corn

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at P<0.05. BD: Biogas digestate, ALK: Alkaloid industry waste, ISS: Industrial sewage sludge, USS: Urban sewage sludge; NPK0:0 mg kg^{-1} NPK, NPK1:150 mg kg^{-1} N, 100 mg kg^{-1} P, 50 mg kg^{-1} K, NPK2: 300 mg kg^{-1} N, 200 mg kg^{-1} P, 100 mg kg^{-1} K; D0, D1, D2: 0, 20 and 40 t ha^{-1} of bio-solid

DISCUSSION

The positive effects of bio-solids on corn growth can be attributed to their contribution of essential macro- and micronutrients, improved soil organic matter content, and enhanced nutrient availability through mineralization processes (Singh *et al.*, 2020). The primary reason for the distinct effects of bio-solids on dry weight can be attributed to differences in their chemical compositions (Zapałowska and Jarecki, 2024). Indeed, ALK, which has notably low nutrient content, particularly of N and P compared to others, has the lowest impact on dry weight. Beyond their nutrient supply, the observed increase in biomass can also be explained by improvements in soil physical and biological properties. Bio-solid additions likely enhanced soil structure, porosity, and water-holding capacity, which in turn improved root growth and nutrient acquisition. In addition, the stimulation of microbial activity by organic substrates may have accelerated nutrient mineralization and increased the availability of growth-limiting elements. Previous studies have reported similar growth-promoting effects of sewage sludge and composted organic wastes, highlighting their role in improving soil fertility and crop productivity (Eid *et al.,* 2021). The application of organic matter in combination with NPK has been found to be more effective than the application of organic matter or NPK alone. These findings align with the results of previous studies (Shisanya *et al.,* 2009). According to Huang *et al.,* (2010), the combination of organic and chemical nutrient sources boost a synergy that synchronizes nutrient release with plant uptake, ultimately driving superior plant growth. The contribution of the materials to dry weight increase, decreased with increasing NPK doses. This interaction effect indicates a shift from nutrient-limited to nutrient-saturated conditions. Under low mineral fertilization, plant growth is primarily constrained by nutrient availability, allowing bio-solid-derived nutrients to significantly enhance growth. However, under high NPK conditions, plant growth becomes increasingly limited by non-nutritional factors. This suggests that the contribution of bio-solids becomes less pronounced when mineral nutrients are already supplied in sufficient amounts (Zaragüeta *et al.,* 2023; Edmeades, 2003). ISS and USS, which have been described as problematic materials in some studies, contributed positively to plant growth even at high doses and showed no toxic effects. This may be related to low heavy metal content, well below the permitted limit values (Sandy, 2018)

The results clearly indicate that bio-solid type, application rate, and NPK level, as well as their interactions, strongly regulate plant N concentration, NUP, NUFF, and BFF. The increase in plant N concentration and NUP with increasing NPK levels under bio-solid-free conditions agrees with established evidence that mineral N directly enhances plant N availability and uptake (Marschner, 2012). However, the observed reduction in BFF at the highest NPK level suggests diminishing fertilizer efficiency under excessive mineral N supply (Dobermann, 2007). This decline in fertilizer use efficiency can be explained with over available N supply exceeding plant demand. Among bio-solid types, ISS exhibited the strongest effect on plant N concentration and total N uptake, confirming its high intrinsic N-supplying capacity. This can be mechanistically attributed to the relatively low C:N ratio of ISS, which favors rapid mineralization and release of plant-available nitrogen forms. Similar findings have been reported by Antolín *et al.,* (2005) who attributed enhanced N availability from sewage sludge to its relatively low C:N ratio and the presence of readily mineralizable organic N fractions. ALK treatments showed comparatively limited effects on both plant N concentration and fertilizer efficiency indicators due to its lower N concentration and higher C/N ratio. Higher pH of ALK can reduce the short-term N mineralization, thereby limiting immediate plant N uptake (Lu *et al.,* 2012). Nevertheless, the marked decline in NUFF and negative contribution values observed under ISS at higher NPK levels indicate that excessive N supply from combined organic and mineral sources reduces fertilizer-derived N recovery. The exceptionally high N uptake observed in 40 t ha^{-1} of SS + NPK1 further suggests a synergistic interaction between moderate mineral N supply and bio-solid-derived N (Diacono and Montemurro, 2010). In contrast, BD and USS treatments were more effective in improving NUFF and BFF rather than maximizing absolute N uptake, suggesting a more synchronized N release with crop demand. Stabilized bio-solids have been shown to enhance fertilizer efficiency by improving soil N retention and reducing losses (He *et al.*, 2013). Application rate was also critical; while higher bio-solid doses increased total N uptake, they negatively affected NUFF and BFF. Overall, moderate bio-solid application combined with balanced mineral N supply appears essential for optimizing N use efficiency while avoiding excessive N availability.

The marked increase in plant P concentration and total PUP with increasing NPK supply confirms that mineral P is the primary driver of short-term P availability (Johnston *et al.*, 2014). However, the magnitude of P uptake observed under combined bio-solid–mineral fertilizer treatments indicates that organic amendments substantially modified P availability. Organic amendments are known to increase P availability through multiple mechanisms (Hinsinger, 2011). Organic amendments can enhance P availability through several complementary mechanisms, including the release of organic acids that compete with phosphate for adsorption sites, thereby reducing P fixation, and the stimulation of phosphatase enzyme activity, which promotes the mineralization of organic P forms. These processes likely explain the higher PUFF observed in treatments combining bio-solids with mineral fertilizer, particularly at moderate application rates. Despite increased PUFF values with higher mineral fertilization, the decline in BFF at elevated NPK and bio-solid doses indicates reduced recovery efficiency of applied P. Generally low BFF values (<6%) observed in this study align with the well-documented low efficiency of P fertilizers in soils. The low recovery efficiency of P fertilizer is primarily related to its strong fixation in soil through precipitation and adsorption reactions, which rapidly convert soluble P into less available forms. In calcareous soils, Ca-bound phosphates dominate, further limiting plant availability. Field trials have shown that only 10-15% of the applied P is utilized by the plants, and this rarely reaches 25% (Johnston *et al.*, 2014). Similarly, Baligar *et al.*, (2001), reported that efficiency of applied P is less than 10 % depending on the crop species. On the other hand, the sufficient level of available P in the soil and the enhancement of existing P availability through bio-solid applications may have caused the BFF ratios to be low. Increasing bio-solid dose generally enhanced PUP but reduced BFF, suggesting that higher organic P inputs can lower the proportional contribution of mineral fertilizer P (Mabagala, 2022). Increasing NPK application significantly reduced mean K concentrations. This dilution effect is attributed to enhanced plant growth under mineral fertilization, which lowers nutrient concentration despite increased total uptake (Jarrell and Beverly, 1981). On the other hand, the fact that the types and doses of bio-solids had no effect on the plant K concentration indicates that corn K nutrition was maintained regardless of the organic fertilizer source. This situation may be related to the sufficient K content of the trial soil. In contrast to K concentration, KUP responded strongly to both NPK fertilization and bio-solid application. This marked response highlights that K uptake was primarily driven by enhanced growth rather than changes in tissue K concentration (Diacono and Montemurro, 2010; Agegnehu *et al.,* 2016). ALK treatments exhibited the highest mean KUFF, indicating superior capacity to promote fertilizer-derived K uptake, whereas ISS showed the lowest KUFF. This suggests that the chemical composition and mineralization dynamics of alkaloid solid waste may enhance K availability (Sparks and Huang, 1985). Increasing bio-solid dosage led to a consistent decrease in KUFF and BFF, despite higher total K uptake. This suggests that excessive organic input may reduce the relative contribution of fertilizer-derived K. In most cases BFF values were over than 100 %. This apparent over-recovery suggests that fertilizer application stimulated root activity and soil K mobilization, leading to increased uptake of native soil K in addition to applied fertilizer K. This situation can also be explained by the increased K uptake from the soil due to plant growth, in addition to the applied K (Erdal *et al.,* 2006).

Overall, the results highlight that the effectiveness of bio-solids is governed not only by their nutrient content but also by their decomposition dynamics, interaction with soil properties, and synchronization with plant nutrient demand. The observed variability among bio-solid types reflects differences in nutrient release patterns, organic matter stability, and chemical composition. Importantly, the interaction with mineral fertilization determines whether bio-solids act primarily as nutrient sources or as efficiency-enhancing amendments. These findings emphasize the importance of optimizing both organic and mineral inputs to achieve sustainable nutrient management.

CONCLUSIONS

This study demonstrated that the agricultural application of BD, ALK, ISS and USS improved corn growth, nutrient uptake, and fertilizer use efficiency under reduced mineral NPK fertilization. The positive effects were particularly pronounced under low or zero NPK conditions confirming the substantial nutrient-supplying capacity of these materials. Statistically significant increases ($P<0.05$) in plant dry weight and nutrient uptake were observed with both bio-solid applications and NPK treatments, as well as their interactions. In particular, ISS, BD, and USS resulted in significant improvements in dry matter production and total N uptake compared to the control, while BD and USS showed significantly higher fertilizer N use efficiency and benefit rates under specific treatment combinations. In contrast, although ALK generally resulted in lower biomass production, some improvements in P and K fertilizer use efficiency were observed; however, these effects were not consistently statistically significant across all treatments. Increasing bio-solid application rates generally promoted biomass accumulation and nutrient uptake; however, higher mineral NPK levels tended to reduce the relative contribution of bio-solids to fertilizer efficiency.

These findings indicate that properly managed bio-solids can partially substitute mineral fertilizers while sustaining or even improving nutrient use efficiency in corn growth.

On the other hand, the experiment was conducted under controlled conditions. Therefore, while the results demonstrate the agronomic potential of the evaluated bio-solids, further long-term field studies are required to validate their effectiveness, under practical agricultural conditions.

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DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

CONFLICTS OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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