

Article

Impact of Starter Phosphorus Fertilizer Type and Rate on Maize Growth in Calcareous Soil Irrigated with Treated Wastewater

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Abstract: Phosphorus (P) is an essential macronutrient, but its limited availability in calcareous soils remains a major constraint to crop nutrition. Treated wastewater (TWW) offers a sustainable irrigation source in arid regions, enhancing water supply and contributing nutrients such as P. This study evaluates the effects of TWW and tap water (TW) irrigation, combined with varying rates of phosphorus fertilizers, such as single superphosphate (SSP) and diammonium phosphate (DAP), on maize (*Zea mays* L.) growth, nutrient uptake, and soil properties. A greenhouse experiment was conducted using maize grown in sandy calcareous soil. TWW irrigation with SSP (40 kg/ha) and DAP (20 kg/ha) resulted in the highest shoot dry matter (2.6 g), while TW with DAP at 20 kg/ha produced 2.2 g. Root biomass was generally higher, peaking at 8.3 g under TWW-SSP (40 kg/ha) and 5.7 g under TW-SSP (40 kg/ha). Nitrogen uptake was highest under TWW, with TWW-DAP (40 kg/ha) yielding the highest N content in shoots (1.9%) and roots (1.2%). Phosphorus content peaked at TWW-DAP (30 kg/ha) in shoots (0.52%) and roots (0.26%). Potassium uptake also improved with TWW, particularly in shoots (4.5%) under TWW-SSP (40 kg/ha) and roots (2.6%) under TWW-DAP (40 kg/ha). Post-harvest soil analysis showed TWW maintained stable EC (0.3–0.5 dS/m) and neutral pH (7.6–7.8). Higher DAP rates (40 kg/ha) with TWW increased soil organic matter, nitrogen (266.2 mg/kg), phosphorus (38.0 mg/kg), and potassium (385.3 mg/kg). In contrast, TW irrigation had lower nutrient enhancement, though high DAP rates still improved soil fertility. These findings highlight the potential of integrating TWW with phosphorus fertilizers to improve crop performance and soil fertility in calcareous soils. This approach offers a sustainable alternative to conventional practices, supporting sustainable crop production in water-limited environments. Further long-term studies are recommended to assess the sustainability of TWW irrigation in arid soils.

Keywords: irrigation; nutrients; phosphorus; plant growth; soil properties; water reuse



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1. Introduction

Phosphorus (P) is a vital macronutrient for plant growth and development, participating in key physiochemical processes such as energy transfer, photosynthesis, and the synthesis of nucleic acids and cell membranes [1–3]. However, in arid and semi-arid regions, the efficiency of P utilization is often constrained by soil characteristics, notably the sandy texture, low organic matter content, elevated temperatures, and high calcium carbonate (CaCO₃) levels that result in the precipitation of P as insoluble forms, thereby reducing its bioavailability [2,4–6].

Starter P application, which involves applying a portion of the recommended P fertilizer at planting, is a widely adopted strategy to support early root development and crop establishment. Nevertheless, the effectiveness of starter P is influenced by several factors, including the fertilizer type, application rate, soil physiochemical properties, and interactions with irrigation practices [7–9].

Given the increasing water scarcity in arid regions, alternative water sources such as treated wastewater (TWW) have garnered significant attention [7–10]. When adequately treated, TWW not only provides a reliable irrigation source but also supplies essential nutrients, including P, thereby offering a dual benefit of addressing both water and nutrient limitations [5,6,11–14]. Numerous studies have reported the positive effects of TWW on soil fertility, crop nutrient uptake, and plant productivity in calcareous soils [15,16]. However, the potential risks associated with prolonged TWW use, such as soil salinization and heavy metal accumulation, necessitate careful management [15,17].

Ammeri et al. [18] demonstrated that phosphorus biofertilization substantially enhanced soil fertility, microbial activity, and plant growth in arid Tunisian soils irrigated with treated wastewater, suggesting a sustainable approach for soil remediation under water scarcity. Conversely, Muscarella et al. [19] observed that treated wastewater irrigation improved tomato growth by increasing nutrient availability without significant alterations to soil pH or salinity. However, supplemental fertilization was necessary, and bacterial populations exhibited a greater increase than fungal populations. Furthermore, this study emphasized the modulating effect of soil pH on sodium hypochlorite impacts, underscoring the importance of rigorous soil monitoring.

While the contribution of TWW to soil nutrient dynamic has been recognized [8,10,20,21], most existing studies have primarily focused on its general impact on soil properties and overall crop performance. Limited research has specifically addressed the interaction between TWW irrigation and starter P fertilization strategies, particularly regarding their combined influence on early plant growth and P availability in calcareous soils. Considering the complex interplay between soil chemistry, organic matter content, and nutrient dynamics under TWW irrigation, a deeper understanding of these interactions is essential.

Accordingly, this study aims to elucidate the interactive effects of TWW irrigation, starter P fertilizer type, and application rate on early maize (*Zea mays* L.) growth and P dynamics in calcareous soils. By addressing this gap, this research seeks to contribute to the development of integrated water and nutrient management strategies that optimize fertilizer use efficiency and enhance the sustainable use of TWW in arid agriculture.

2. Materials and Methods

2.1. Study Soil and Treated Wastewater (TWW) Collection and Preparation

The soil used in this experiment was collected from an uncultivated area at the Agricultural Research and Experiments Station of King Saud University, Dirab, Riyadh, Saudi Arabia. After collection, the soil was air-dried, thoroughly mixed to homogenize, sieved (<2 mm), and stored under dry conditions before potting to ensure uniformity across all treatments. Thereafter, this soil was analyzed for its basic physical and chemical properties (Table 1). Similarly, treated wastewater (TWW) was collected in a single batch to ensure consistency and analyzed prior to use (Table 2). Pots were filled with the same soil volume and bulk density to standardize conditions across replicates further.

Table 1. Basic physical and chemical properties of study soil.

Parameter	Value
pH	8
EC (dS m ⁻¹)	0.18
CEC (meq/100 g soil)	10.4
OM (%)	0.44
CaCO ₃ (%)	33
Clay (%)	16.2
Silt (%)	15.3
Sand (%)	68.5
Olsen-P (mg kg ⁻¹)	1.95
N (mg kg ⁻¹)	8.2
K (mg kg ⁻¹)	163.7

Table 2. Some physical and chemical properties of treated wastewater and tap water.

Property	(TW)	TWW
pH	7.30	7.67
EC (dS m ⁻¹)	0.64	2.20
NO ₃ ⁻ (mg L ⁻¹)	2.42	9.24
NH ₄ ⁻ (mg L ⁻¹)	0.11	3.59
K ⁺ (mg L ⁻¹)	9.0	19.35
Na ⁺ (mg L ⁻¹)	5.81	205.36
Mg ²⁺ (mg L ⁻¹)	10.86	52.52
Ca ²⁺ (mg L ⁻¹)	15.3	145.51
PO ₄ ³⁻ (mg L ⁻¹)	0.37	41.88
SO ₄ ²⁻ (mg L ⁻¹)	12.0	520.93
Cl ⁻ (mg L ⁻¹)	10.34	315.20
HCO ₃ ⁻ (mg L ⁻¹)	7.89	177.86

2.2. Experimental Design and Treatment Applications

The experiment was conducted under controlled greenhouse conditions at the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia. The ambient temperature was maintained at 26 ± 2 °C during the day and 18 ± 2 °C at night, relative humidity was kept between 55–65%. This study was conducted under a completely randomized design (CRD), where treatments were randomly assigned to experimental units (pots) with equal probability. Each treatment combination (irrigation water source $\times$ fertilizer type $\times$ fertilizer rate) was replicated three times.

One kilogram of soil was packed into a PVC column (28 cm height; 5.5 cm diameter) and preincubated for 3 days at 70% of field capacity before the start of the experiment.

The experimental treatments consisted of:

- Two phosphorus (P) fertilizer types: Single superphosphate (SSP) and diammonium phosphate (DAP).
- Four rates of starter P application: Equivalent to 0, 20, 30, and 40 kg P ha⁻¹.
- Two irrigation water sources (IWS): Tap water (TW) and treated wastewater (TWW).

One control for TW and one control for TWW were included where both controls received no P fertilizer.

Nitrogen and potassium nutrients were applied to all treatments, including the controls at 300 kg N ha⁻¹ and 65 kg K ha⁻¹ using urea and potassium sulfate, respectively.

The fertilizers were mixed with the top 3 cm of the soil column.

Five maize (*Zea mays* L.) seeds were sown in each column, and after emergence, the plants were thinned to retain the three most vigorous seedlings per column.

The soil moisture content was maintained at 80% of field capacity by weighing each soil column daily and replenishing the lost water based on weight loss. Irrigation was performed manually with tap water TW or treated wastewater TWW to restore the original weight corresponding to 80% field capacity. The plants were grown for six weeks under these conditions.

2.3. Measurements

After six weeks, the entire plant was carefully removed from the soil column and separated into shoots and roots. The following parameters were measured:

- Shoot and root length (cm) were measured using a standard ruler immediately after harvest.
- Dry biomass weight (g) was determined after oven-drying samples at 70 °C for 48 h until constant weight.
- Shoot and root phosphorus (P), nitrogen (N), and potassium (K) contents (%) were determined according to the method described by [17]. Briefly, dried plant tissues were ground, digested using a sulfuric acid–hydrogen peroxide digestion, and analyzed:
 - Total N was measured using the Kjeldahl digestion method.
 - Total P was determined colorimetrically (molybdenum blue method).
 - Total K was measured by flame photometry.

Post-harvest soil samples were analyzed for the following properties:

- Available phosphorus (P) was determined using the Olsen method [18]
- Available nitrogen (N) was measured following extraction with 2 M KCl and analysis via Kjeldahl methods as described by [22,23].
- Available potassium (K) was extracted using ammonium acetate (1 M, pH 7.0) and measured by flame photometry, according to Pratt [24].
- Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-water suspension using a pH meter and a conductivity meter, respectively.
- Organic matter (OM) content was determined using the Walkley–Black dichromate oxidation method.

2.4. Statistical Analysis

These data were subjected to analysis of variance (ANOVA) following a factorial design using the Statistix 8.1 (Tallahassee, FL, USA) software to assess significant differences among treatments. Prior to ANOVA, these data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene’s test. These assumptions were met, validating the use of ANOVA for statistical analysis.

The effects of phosphorus fertilizer rate, irrigation water source, and their interaction on plant and soil parameters were tested using three-way ANOVA. The mean differences were compared using the least significant difference (LSD) test at a 5% significance level ($p \leq 0.05$ to conduct all pairwise comparisons among treatment means). Graphs were plotted using Origin Pro 2025 (Origin Lab, Northampton, Massachusetts, MA, USA).

Each treatment combination was replicated three times, and the experimental units (pots) were arranged in a randomized complete block design to account for variability.

ity. Graphs were plotted using Origin Pro 2015 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Effects on Maize Growth Parameters

Irrigation with TWW, either alone or in combination with P fertilizers, significantly enhanced maize growth parameters compared with TW, both with and without fertilizers ($p < 0.001$). For plant height, the largest recorded value was 86.3 cm under TWW combined with DAP at 30 kg/ha, whereas TW with the same treatment resulted in a significantly lower height of 72 cm (Figure 1a). Even in the absence of fertilizers, TWW alone supported a plant height of 77.3 cm, significantly outperforming TW, which only reached 63 cm “ $p < 0.001$ ”, Figure 1a). A similar trend was observed for root length, where TWW combined with DAP at 40 kg/ha produced a maximum root length of 61.7 cm, while TW under the same conditions yielded a reduced length of 51 cm “ $p < 0.001$ ”. Notably, even without fertilizers, TWW alone resulted in a root length of 59.7 cm, far exceeding the 36.7 cm observed under TW “ $p < 0.001$ ” (Figure 1b).

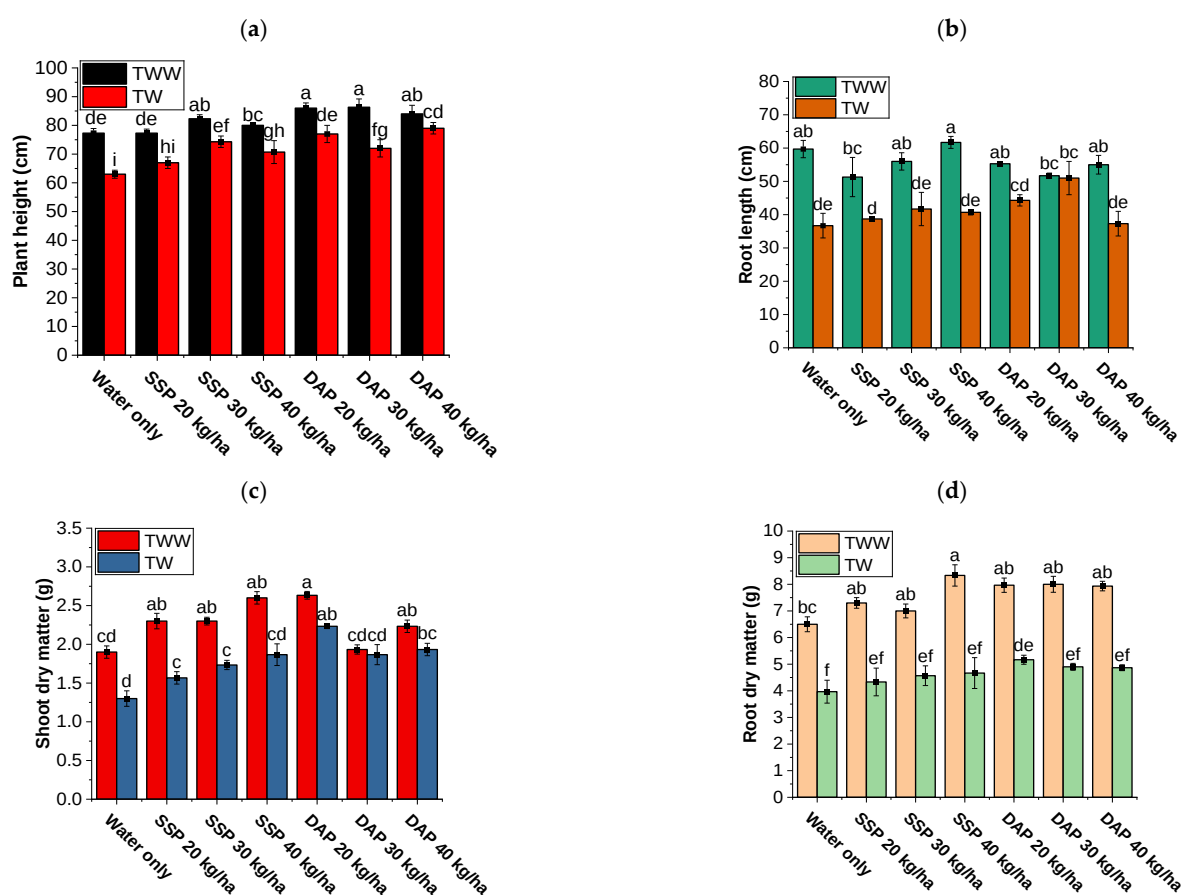


Figure 1. Effect of irrigation water source (IWS) and fertilizer type and rate on maize parameters (Plant height (a), Root length (b), Shoot dry matter (c), and Root dry matter (d)). Bars sharing the same letter among the different fertilizers rates are not significantly different ($p \leq 0.05$).

Shoot dry matter (DM) also responded positively to TWW irrigation ($p < 0.001$). Under DAP at 20 kg/ha, shoot DM reached 2.63 g with TWW, compared with 2.2 g with TW (Figure 1c). In the absence of fertilizers, TWW-supported shoot DM was 1.9 g, which was significantly higher than the 1.3 g observed with TW. ($p < 0.001$, Figure 1c). Similarly, root DM was maximized under TWW combined with DAP at 40 kg/ha, reaching 8.3 g, while TW under the same conditions produced only 4.9 g ($p < 0.001$). Even without fertilizers,

root DM under TWW was 6.5 g, substantially greater than the 4.0 g recorded under TW (Figure 1d).

3.2. Effects on Plant Nutrient Content

The nutrient contents in both shoots and roots were consistently higher under TWW irrigation compared with TW, highlighting its role in improving maize nutrient uptake ($p < 0.001$, Figure 2). For phosphorus (P), the shoot content reached a maximum of 0.51% under TWW combined with DAP at 30 kg/ha, whereas the same fertilization under TW resulted in only 0.19% ($p < 0.001$, Figure 2b). Even without fertilizers, TWW alone supported a shoot P content of 0.27%, significantly exceeding the 0.13% recorded under TW ($p < 0.001$, Figure 2b). A similar pattern was observed in the roots, where TWW combined with DAP at 30 kg/ha yielded 0.26% P content, compared with 0.15% under TW (Figure 3b). Without fertilizers, TWW resulted in 0.15% P content, more than the 0.064% observed under TW ($p < 0.001$).

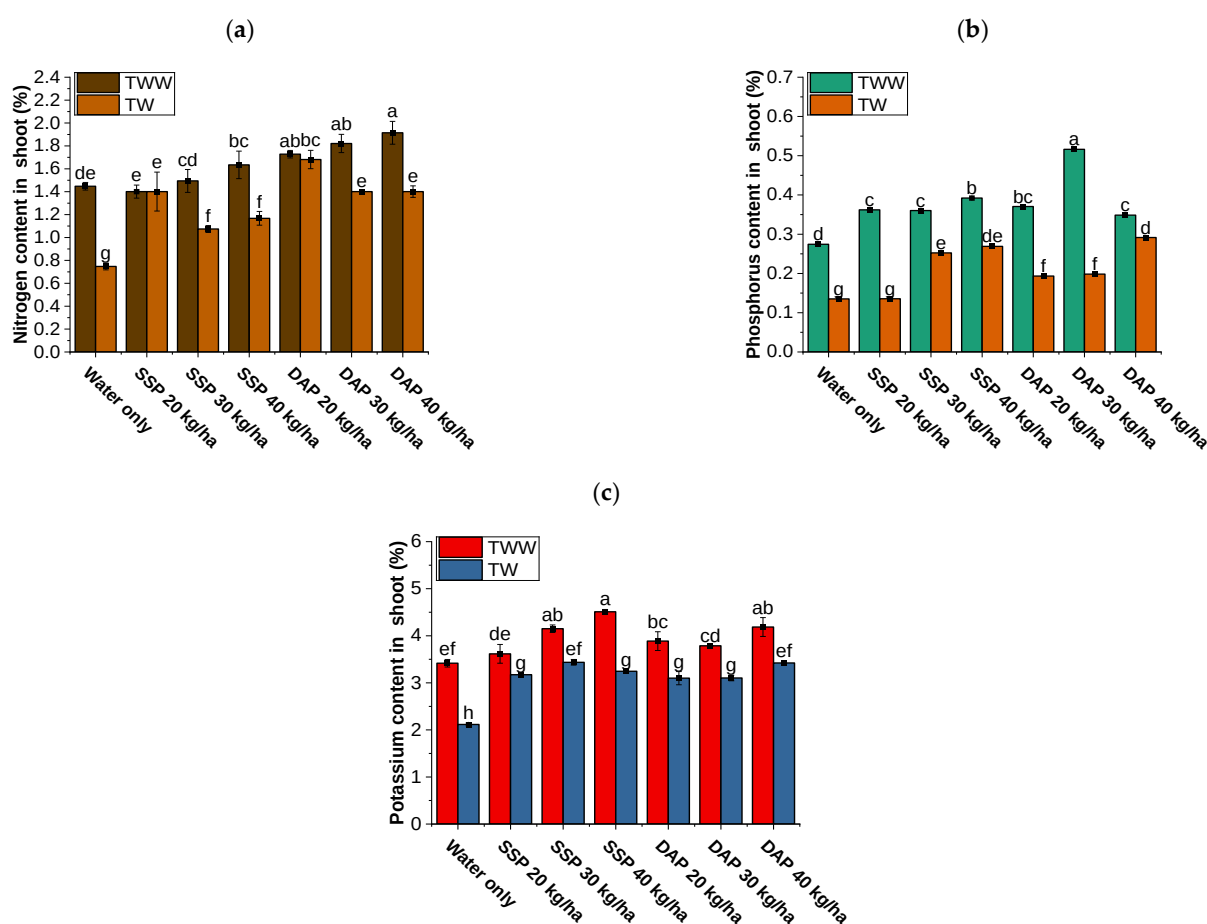


Figure 2. Effect of irrigation water source (IWS) and fertilizer types and rates on plant nutrient contents (NPK) in shoot. N content (a), P content (b), and K content (c). Bars sharing the same letter among the different fertilizers rates are not significantly different ($p \leq 0.05$).

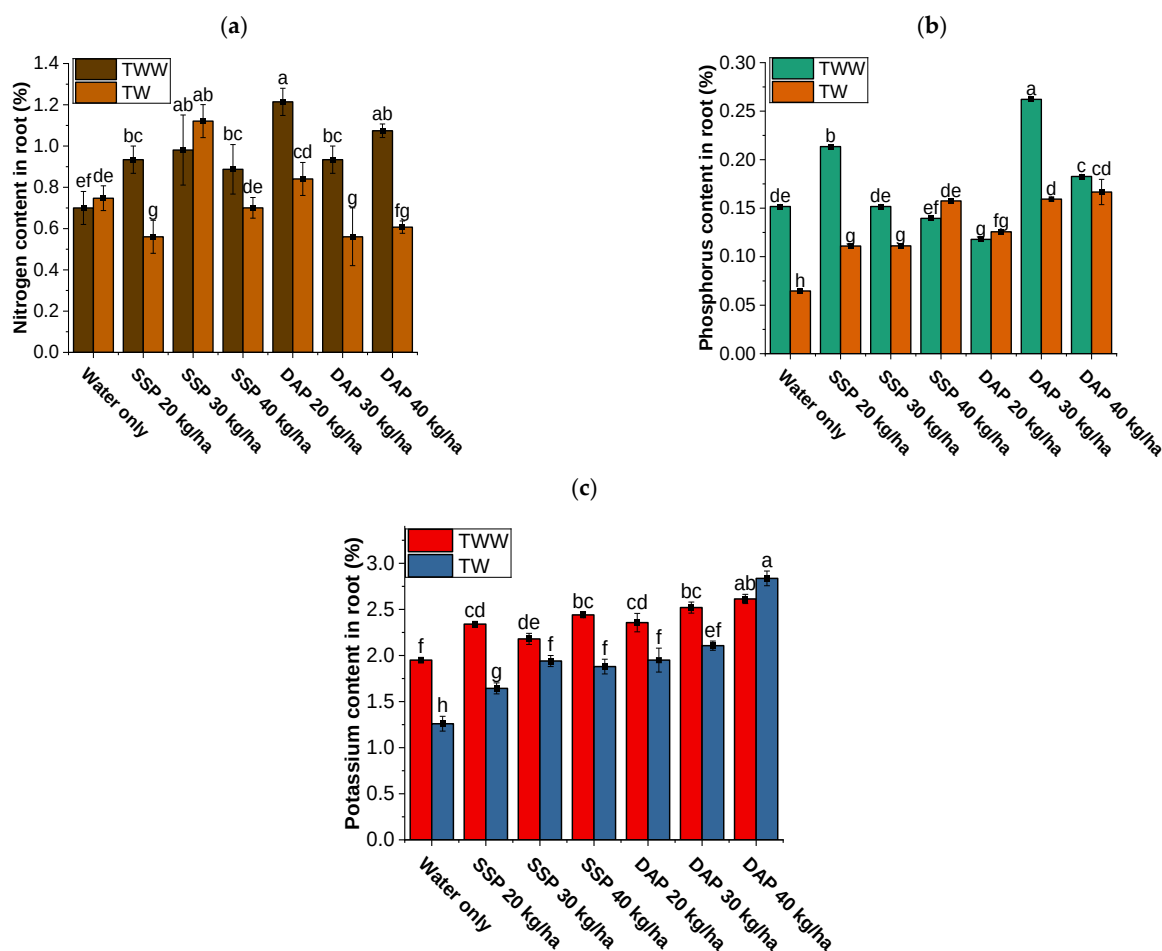


Figure 3. Effect of irrigation water source (IWS) and fertilizer types and rates on plant nutrient contents (NPK) in root. N content (a), P content (b), and K content (c). Bars sharing the same letter among the different fertilizers rates are not significantly different ($p \leq 0.05$).

The nitrogen (N) content in shoots and roots also benefited from TWW. The shoot N content peaked at 1.91% under TWW with DAP at 40 kg/ha, compared with 1.4% under TW ($p < 0.001$, Figure 2a). Even in the absence of fertilizers, TWW-supported shoot N content was 1.44%, significantly higher than the 0.74% under TW ($p < 0.001$). Similarly, in roots, the N content was 1.07% under TWW with DAP at 40 kg/ha, whereas TW under the same conditions resulted in only 0.6% ($p < 0.001$, Figure 3a). Without fertilizers, the root N content under TWW was 0.65%, still outperforming the 0.51% observed under TW ($p < 0.001$). The potassium (K) content followed a similar trend. In shoots, the highest recorded K content was 4.18% under TWW with DAP at 40 kg/ha, compared with 3.42% under TW ($p < 0.001$, Figure 2c). Even without fertilizers, the shoot K content under TWW was 3.41%, significantly higher than the 2.11% observed under the TW ($p < 0.001$). The root K content also peaked at 2.61% under TWW with DAP at 40 kg/ha, compared with 1.94% under TW ($p < 0.001$, Figure 3c). Without fertilizers, the root K content under TWW was 1.95%, surpassing the 1.26% observed under TW ($p < 0.001$).

3.3. Effects on Post-Harvest Soil Properties

Post-harvest soil analysis revealed that TWW irrigation significantly enhanced soil nutrient availability and organic matter content compared with TW ($p < 0.001$, Table 3). For available nitrogen (N), TWW combined with DAP at 40 kg/ha resulted in a peak concentration of 266.2 mg kg^{-1} , a substantial increase compared with the 84 mg kg^{-1} recorded under TW with the same treatment ($p < 0.001$). Even without fertilizers, TWW-

supported soils retained 182.1 mg kg⁻¹ of available N, far exceeding the 56 mg kg⁻¹ recorded under TW ($p < 0.001$). A similar trend was observed for available phosphorus (P), where TWW combined with DAP at 40 kg/ha resulted in 37.98 mg kg⁻¹, nearly double the 19.9 mg kg⁻¹ observed under TW ($p < 0.001$). Without fertilizers, TWW still provided a significantly higher value of 33.3 mg kg⁻¹ of available P, compared with just 4 mg kg⁻¹ under TW ($p < 0.001$). Potassium (K) also benefited from the TWW irrigation, reaching 378.3 mg kg⁻¹ with DAP at 40 kg/ha, whereas TW under the same treatment achieved 294 mg kg⁻¹ ($p < 0.001$). Without fertilizers, TWW resulted in 315.3 mg kg⁻¹ of available K, in contrast to 181.3 mg kg⁻¹ under TW, reinforcing its role in sustaining soil nutrient reserves ($p < 0.001$, Table 3).

Table 3. Interaction between IWS, MFT, and MFR on soil properties and soil nutrient contents after harvesting.

IWS	MF Type	MF Rate	Ec	pH	Available N	Available P	Available K	Organic Matter
			dS m ⁻¹	(mg kg ⁻¹)				%
TWW	SSP	0	0.43 _b	7.67 _{gh}	182.1 _b	33.3 _c	315.3 _c	1.12 _{ab}
		20	0.5 _{ab}	7.7 _{fg}	140.1 _e	34.2 _{bc}	368.3 _{ab}	0.73 _{cd}
		30	0.42 _b	7.77 _{cd}	266.2 _a	35.91 _b	301 _{cd}	0.98 _{ab}
		40	0.54 _a	7.6 _h	147.1 _{de}	37.91 _a	378.3 _a	1.05 _{ab}
	DAP	0	0.43 _b	7.67 _{gh}	182.1 _b	33.3 _c	315.3 _c	1.12 _{ab}
		20	0.44 _b	7.75 _{de}	168.1 _c	34.2 _{bc}	283.7 _{ef}	1.05 _{ab}
		30	0.28 _c	7.8 _{bc}	147.1 _{de}	34 _{bc}	385.3 _a	1.67 _{ab}
		40	0.48 _{ab}	7.72 _{ef}	140.1 _e	37.98 _a	344.7 _b	1.7 _a
TW	SSP	0	0.2 _{cd}	7.8 _b	56 _i	4 _i	181.3 _i	0.34 _d
		20	0.19 _d	7.8 _b	63 _i	15.7 _h	211.7 _h	0.62 _{cd}
		30	0.22 _{cd}	7.8 _b	84 _h	18.3 _{ef}	270.7 _{fg}	0.87 _{cd}
		40	0.24 _{cd}	7.8 _b	98.07 _g	17.4 _{fg}	244 _g	0.57 _{cd}
	DAP	0	0.2 _{cd}	7.8 _b	56 _i	4 _i	181.3 _i	0.34 _d
		20	0.18 _d	7.9 _a	112.08 _f	16.6 _{gh}	314.7 _{cd}	0.73 _{cd}
		30	0.22 _{cd}	7.8 _b	154.1 _d	18.9 _{de}	288 _{de}	0.59 _{cd}
		40	0.21 _{cd}	7.8 _b	84 _h	19.9 _d	294 _{cd}	0.96 _{bc}
IWS * MFT * MFR			n.s	n.s	***	n.s	***	n.s
LSD			0.08	0.06	12.8	1.16	27.5	0.71

IWS donates (irrigation water sources), MFT donates (mineral fertilizer type), and MFR is (mineral fertilizer rate). Treatments sharing the same letter are not significantly different.

The soil organic matter content was notably enriched under TWW irrigation ($p < 0.001$). With DAP at 40 kg/ha, TWW increased organic matter to 1.7%, compared with only 0.96% under TW. Even in the absence of fertilizers, TWW maintained 1.12% SOM, while TW-supported soils had only 0.34%, highlighting the long-term benefits of TWW in enhancing soil structure and fertility ($p < 0.001$). However, an increase in soil electrical conductivity (EC) to 0.54 ds/m under TWW with SSP at 40 kg/ha suggests a potential risk of salinity build-up, which was less pronounced under TW (Table 3). This indicates that the prolonged use of TWW may lead to soil salinization issues.

4. Discussion

4.1. Interaction Between Irrigation Source, Fertilizer Type, and Application Rate

4.1.1. Effect on Maize Growth

The interaction between IWS, MF type, and MF rate had a significant effect on maize growth parameters. TWW irrigation consistently enhanced plant height, root length, and biomass accumulation compared with TW. This improvement is largely due to the additional nutrient contents (N, P, and K) and organic matter in TWW. For example, the maize plant height under TWW with DAP at 30 kg/ha reached 86.3 cm compared with 72 cm under TW with the same treatment. The root length under TWW with DAP at 40 kg/ha peaked at 61.7 cm, much greater than 51 cm under TW.

These results align with findings by Mussarat et al. [25], who demonstrated that phosphorus from pre-treated organic sources significantly improved maize growth in calcareous soils, primarily by enhancing nutrient solubilization and availability. Their study emphasized that alternative P sources when effectively solubilized, perform comparably or even better than soluble fertilizers under alkaline soil conditions.

Moreover, even without fertilizers, TWW irrigation alone supported superior growth (77.3 cm vs. 63 cm plant height under TW), emphasizing TWW's intrinsic fertility benefits. However, long-term use of TWW needs monitoring because of the potential risks of salinity and trace elements accumulation.

These results are consistent with previous studies [10,26,27], which highlight the beneficial effects of wastewater irrigation on plant growth because of its nutrient-rich composition. Specifically, TWW provides readily available nutrients, which improve the overall crop performance. However, excessive reliance on TWW for irrigation may introduce unintended risks such as increased salinity and potential heavy metal accumulation, which could have long-term consequences for soil health and plant performance.

The use of DAP further amplified maize growth relative to SSP. Bio-organically acidified products, as studied by Khan et al. [28], showed enhanced phosphorus availability and, thus, superior maize performance in calcareous soils—emphasizing the need for fertilizer types that overcome P fixation.

The high solubility of DAP facilitated greater P uptake, as evidenced by the 2.63 g shoot dry matter observed under TWW with DAP at 20 kg/ha, compared with 2.2 g under TW. This underscores the critical role of balanced fertilization in maximizing nutrient use efficiency [29]. Consequently, higher DAP rates (30–40 kg/ha) consistently boasted biomass production, demonstrating the importance of matching irrigation sources with the most efficient fertilizer types and rates. These findings highlight the significance of an optimized nutrient management strategy in promoting crop growth and productivity [30–32].

4.1.2. Effect on Nutrient Content Enhancement

TWW irrigation, in combination with DAP application, notably enhanced nutrient uptake, particularly for N, P, and K. The shoot phosphorus content reached 0.51% under TWW with DAP at 30 kg/ha, compared with 0.19% under TW. Root potassium levels similarly peaked at 2.83% with TWW and DAP at 40 kg/ha, emphasizing the synergistic role of TWW and DAP in maximizing nutrient absorption [33–35].

These results are consistent with Noreen et al. [36], who showed that acidified organic extracts significantly improved phosphorus solubilization and uptake in maize. Their study reported enhanced P availability not only improving yield but also promoting greater N and K uptake by strengthening root development.

This improved nutrient uptake can be attributed to multiple mechanisms. First, the capacity of the organic compounds in wastewater can chelate calcium, reducing phosphorus fixation and improving its bioavailability [37].

Even without fertilizer, TWW irrigation improved phosphorus absorption, reaching 0.27% shoot P under TWW vs. 0.13% under TW.

The use of bio-organically treated P sources, as highlighted by Mussarat et al. [25], promoted better early-stage nutrient uptake, which is critical for maize development in high-pH soils.

Additionally, the steady nitrogen supply from TWW and its interaction with phosphorus from DAP supported better nutrient translocation, enabling efficient utilization of macronutrients and improving overall plant health [38–40].

4.1.3. Effect on Post-Harvest Soil Properties

Post-harvest soil analysis revealed significant improvements in nutrient availability and soil health with TWW irrigation. Available phosphorus increased to 37.98 mg kg⁻¹ under TWW with DAP at 40 kg/ha, compared with 19.9 mg kg⁻¹ under TW. Similarly, available nitrogen was 266.2 mg kg⁻¹ under TWW with DAP, more than three times the 84 mg kg⁻¹ observed under TW.

The soil organic matter (OM) content increased to 1.7% under TWW with DAP at 40 kg/ha compared with 0.96% under TW. This aligns with the findings of Khan et al. [28], who reported that bio-organically acidified products not only improved P fertilizer use efficiency but also contributed to enhanced microbial biomass and soil organic matter build-up.

Even without fertilizers, TWW alone raised OM to 1.12%, suggesting its potential as a soil amendment. However, a rise in soil EC (0.54) ds/m under TWW + SSP at 40 kg/ha suggests the need for monitoring salinity build-up during prolonged TWW use. While this level is still within acceptable limits for maize production, prolonged use of TWW could exacerbate salinity issues, particularly in poorly drained soils [41]. Future studies should assess the long-term impact of TWW irrigation on soil salinity and develop appropriate management strategies.

5. Conclusions

This research demonstrates the critical role of treated wastewater (TWW) irrigation, particularly when combined with soluble phosphorus fertilizers such as diammonium phosphate (DAP), in overcoming phosphorus fixation challenges in calcareous soils. By enhancing phosphorus availability, uptake, and soil retention, TWW significantly improves maize growth, nutrient use efficiency, and post-harvest soil fertility. These findings offer a sustainable solution to phosphorus management in water-limited agricultural systems, reducing dependence on freshwater and synthetic fertilizers.

The implications of this work are substantial: adopting TWW irrigation strategies can help close the phosphorus cycle in agriculture, lower fertilizer input costs, and promote the sustainable reuse of water resources—critical steps toward resilient farming systems under climate change. Additionally, optimizing TWW use supports global efforts to combat soil degradation and food insecurity, particularly in arid and semi-arid regions where phosphorus limitation severely restricts crop yields.

Future research should focus on field-scale validation, detailed microbiological assessments, and long-term monitoring of soil and ecosystem health. Integrating TWW use into nutrient management programs while addressing potential risks will be essential for sustainable application.

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