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Effects of Treated Wastewater Irrigation on the Growth and Yield of Three Maize (*Zea mays* L.) Varieties in the Mining Area of Arlit, Niger

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Arlit, a mining city in northern Niger, faces severe water scarcity because of its arid climate and substantial water demand. Reusing treated wastewater for irrigation may provide an alternative water source for crop production under these conditions. This study compared the growth and yield-related responses of three maize (*Zea mays* L.) varieties—Jaune de Tassaou, Rouge de Gayi and Maka—irrigated with treated wastewater or fresh water. A randomised complete block design with three replications and six treatment–variety combinations per block was used. Fourteen phenological, growth and yield-related traits were measured, and the data were analysed using analysis of variance and principal component analysis. Irrigation water type significantly affected flowering, all measured growth traits and all evaluated yield components. Treated wastewater shortened the periods to male and female flowering and increased leaf length, leaf width, stem diameter, number of nodes, ear length, ear diameter, cob weight, stem biomass, grain number, total grain weight and 100-grain weight relative to fresh water. Total stem biomass and grains per row increased by 45.31% and 20.64%, respectively. The first principal component explained 30.41% of the total variation and distinguished the two irrigation treatments. The findings indicate that treated wastewater may support maize production under the water-limited conditions of Arlit, although its use requires regular assessment of water quality, soil conditions and potential contaminant accumulation.

Keywords: Treated wastewater; Zea mays L.; irrigation water quality; arid agriculture; crop growth; grain yield; water reuse; varietal response; principal component analysis; Arlit.

1. Introduction

Sustainable water resource management has become a critical challenge in arid regions, exacerbated by unprecedented climate variability and continuous demographic pressure (Food and Agriculture Organization of the United Nations, 2025; UNESCO World Water Assessment Programme, 2023). In northern Niger, particularly in the mining city of Arlit, water scarcity has reached alarming levels. More than five decades of intensive uranium mining have not only depleted fossil aquifers but have also raised concerns regarding chemical and radiological contamination of the remaining freshwater reserves (CRIIRAD & AGHIRIN'MAN, 2025). Field evidence from semi-arid environments further indicates that the choice of irrigation method can influence crop productivity and water-use efficiency, reinforcing the importance of context-specific water-management strategies (Kifle & Asseffa, 2025).

Under these conditions of extreme water stress, the reuse of treated wastewater (TWW) is no longer merely an alternative option but rather a strategic necessity for peri-urban agriculture (Hashem & Qi, 2021). Irrigation using non-conventional water resources makes it possible to sustain the production of staple crops such as maize (*Zea mays L.*) while simultaneously recycling residual nutrients, including nitrogen (N), phosphorus (P), and potassium (K), which can act as natural fertilisers (Kandasamy et al., 2025; Pedrero et al., 2010).

Evidence from degraded semi-arid soils also suggests that treated wastewater can support the recovery of soil organic matter and phosphorus, thereby strengthening its relevance to resource-constrained agricultural systems (Martins et al., 2019). Nevertheless, the agronomic benefits of treated wastewater are closely linked to water quality, soil properties, and crop context, while salinity, heavy metal accumulation, and changes in soil hydraulic behaviour require site-specific evaluation and monitoring (Wang et al., 2024; Saleh et al., 2025). However, evidence remains limited regarding the performance of climate-resilient maize varieties irrigated with treated wastewater under the specific physicochemical conditions of the Arlit mining environment. Therefore, this study aimed to contribute to local food security by proposing a sustainable circular irrigation model adapted to the edaphoclimatic conditions of the Nigerien Sahara.

2. Materials and Methods

2.1 Study Site Description

The SOMAIR market gardening site is located in the urban municipality of Arlit in the Agadez region of northern Niger, between 7°15′ and 7°45′ East longitude and 18°25′ and 18°55′ North latitude (Fig. 1). The study area is situated within the mining city of Arlit, characterised by an arid Saharan climate and severe water scarcity.

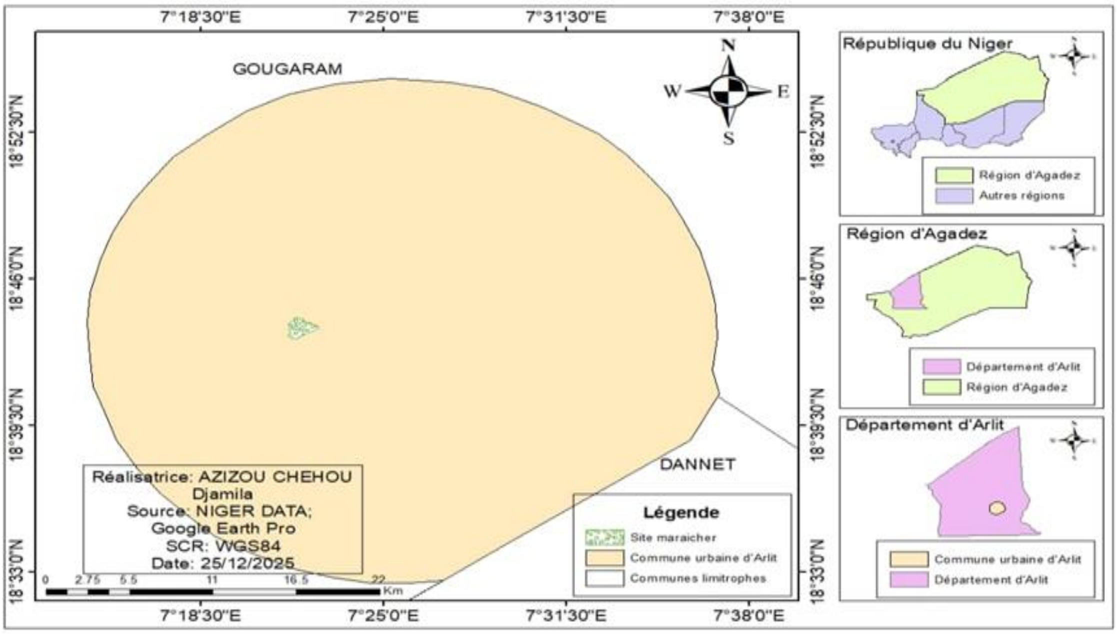

Fig. 1. Location of the SOMAIR vegetable farm

2.2 Plant Material

The plant material consisted of three maize varieties: Jaune de Tassaou, Rouge de Gayi, and Maka. These varieties were obtained from the experimental station of André Salifou University of Zinder and supplied by the seed bank of the Faculty of Science and Technology.

Table 1. Characteristics of the Maize varieties

Variety	Origin	Grain Color	Variety Type
Jaune de Tassaou	Tassaou	Yellow	Local variety
Maka	Zinder	Yellow	INRAN* variety
Rouge de Gayi	Gayi	Red	Local variety

**INRAN : National Institute of Agronomic Research of Niger.*

2.3 Experimental Design

The experiment was conducted under sole cropping conditions using a randomized complete block design (RCBD) with three replications. Two irrigation water treatments were evaluated: treated wastewater (T1) and fresh water (T2), combined with three maize varieties (V1, V2, and V3). Each experimental block contained six elementary plots corresponding to the different treatment–variety combinations. Blocks and plots were separated by distances of 2 m and 1.5 m, respectively. Each elementary plot consisted of 16 planting hills arranged in four rows with a spacing of 0.5 m between hills (Fig. 2). Sowing was carried out manually on 16 August 2024, with four seeds placed per hill. Agro-morphological assessments were performed to evaluate the physiological and agronomic responses of the three maize varieties under the two irrigation treatments. Irrigation was applied every two days.

2.4 Crop Management

The soil was manually tilled using a hoe to improve water infiltration, enhance soil aeration, and control weeds. Organic manure was uniformly applied by manual broadcasting immediately after the first ploughing operation to facilitate nutrient incorporation into the upper soil layer. The applied rate corresponded to one donkey cartload per plot. This amendment aimed to improve soil structure and stimulate initial biological activity before maize sowing. Crop protection against insect pests and fungal diseases was ensured through a targeted chemical treatment applied 30 days after sowing, corresponding to the vegetative stage during which maize plants are particularly vulnerable to defoliators. Irrigation was performed manually using 10-L metal watering cans, in accordance with the most common irrigation practices used at the Arlit market gardening site.

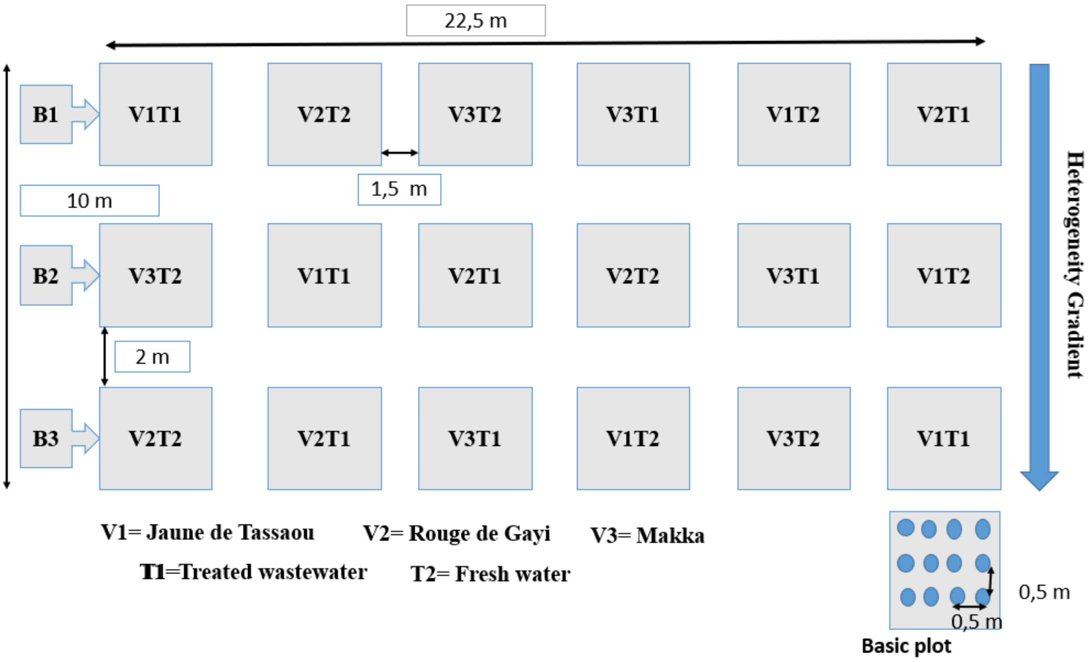

Fig. 2. Experimental Design

2.5 Data Collection

Crop monitoring was conducted continuously from sowing to harvest. Data were collected from 180 planting hills based on fourteen phenological, growth, and yield-related traits. The measured variables included germination time, leaf length, leaf width, stem diameter, plant height, number of nodes, ear length, ear diameter, number of rows per ear, number of grains per row, cob weight, total grain weight, 100-grain weight, and total stem biomass.

Table 2. Measured agro-morphological and yield-related traits during the experiment

Parameter	Growth Stage	Measurement Method
Ear length (EL)	Harvest stage	Measured using a graduated ruler
Ear diameter (ED)	Harvest stage	Measured using a digital caliper
Number of rows per ear (NRE)	Harvest stage	Counted manually
Number of grains per row (NGR)	Harvest stage	Counted manually
Cob weight (CW)	Harvest stage	Total cob weight measured after manual shelling
Total grain weight (TGW)	Harvest stage	Total grain weight measured after shelling
100-grain weight (100GW)	Harvest stage	Weight of 100 grains after shelling
Total stem biomass (TSB)	Harvest stage	Total stem weight measured at maturity
Germination time (GERM)	Germination stage	Average number of days after sowing
Leaf length (LL)	5-week stage	Measured using a measuring tape
Leaf width (LW)	5-week stage	Measured using a measuring tape
Stem diameter (SD)	5-week stage	Measured using a digital caliper
Plant height (PH)	5-week stage	Measured from soil surface to plant apex
Number of nodes (NN)	Maturity stage	Counted manually

2.6 Data Analysis

The collected data were organised using Microsoft Excel 2016. Analysis of variance (ANOVA) was performed using Minitab 16 software. Whenever significant differences were detected, means were separated using

Tukey’s test at the 5% probability level. Principal component analysis (PCA) was performed using R software to evaluate interactions between treatments and varieties and to identify the most productive treatment combinations.

3. Results And Discussion

3.1 Effects of Irrigation Water Type on Phenological Traits

The effects of irrigation water type on maize phenological traits revealed variable responses depending on the factors studied. The varieties Maka (3.00 DAS ± 0.00) and Jaune de Tassaou (3.01 DAS ± 0.18) emerged earlier, whereas Rouge de Gayi showed delayed emergence (3.26 DAS ± 0.54). Analysis of variance (ANOVA) indicated significant differences among maize varieties for emergence time. In contrast, neither irrigation treatment nor the interaction between variety and treatment significantly affected this parameter. The male flowering date was significantly influenced by both maize variety and irrigation water type, whereas the interaction between the two factors was not significant. Plants irrigated with treated wastewater flowered earlier (37.48 DAS ± 3.10) than those irrigated with fresh water (47.47 DAS ± 5.67). Similarly, the female flowering date was significantly affected by variety, irrigation treatment, and their interaction. Rouge de Gayi exhibited earlier flowering compared with Jaune de Tassaou and Maka. The application of treated wastewater reduced the time to female flowering (42.11 DAS ± 4.44) relative to fresh water irrigation (53.03 DAS ± 5.76).

Table 3. Effects of irrigation water Type on Maize phenological traits

Factor	Emergence (DAS)	Male Flowering (DAS)	Female Flowering (DAS)
Varieties			
Jaune de Tassaou	3.01 ± 0.18b	40.79 ± 7.18b	46.75 ± 7.03b
Rouge de Gayi	3.26 ± 0.54a	45.55 ± 5.33a	50.10 ± 4.78a
Maka	3.00 ± 0.00b	41.09 ± 6.67b	45.85 ± 9.43b
Treatments			
Treated wastewater	3.08 ± 0.28	37.48 ± 3.10b	42.11 ± 4.44b
Fresh water	3.09 ± 0.36	47.47 ± 5.67a	53.03 ± 5.76a
Significance			
Variety	***	***	***
Treatment	Ns	***	***
Variety × Treatment	Ns	Ns	**

*Values followed by the same letter within a column are not significantly different according to Tukey’s test at p < 0.05. DAS: Days after sowing; ns: not significant; **: highly significant; ***: very highly significant*

3.2 Effects of Treated Wastewater Irrigation on Growth Traits

Analysis of variance of maize growth traits showed significant varietal differences for all measured variables except stem diameter and number of nodes. Treated wastewater irrigation significantly affected all measured growth variables, whereas the interaction between varieties and irrigation treatments significantly influenced only leaf length and leaf width. Jaune de Tassaou exhibited the longest leaves (46.92 cm ± 8.66) and the greatest leaf width (6.20 cm ± 1.16). The highest plant heights were recorded for Jaune de Tassaou (62.98 cm ± 36.95) and Maka (61.35 cm ± 35.85). Overall, treated wastewater significantly improved most growth traits compared with irrigation using fresh water. The longest leaves (51.38 cm ± 5.59) and widest leaves (6.46 cm ± 1.28) were observed under treated wastewater irrigation. Similar trends were recorded for stem diameter and number of nodes, with higher values consistently obtained with treated wastewater irrigation.

3.3 Effects of Treated Wastewater Irrigation on Yield-related Components

The effects of treated wastewater irrigation on maize yield and yield-related traits revealed significant differences for most measured variables. Treated wastewater positively influenced all yield components evaluated in this study. The most pronounced effects were observed for total stem biomass, number of grains per row, total grain weight, and ear length, which increased by 45.31%, 20.64%, 18.86%, and 17.99%, respectively, compared with irrigation using fresh water. ANOVA results showed significant varietal effects only for ear length and 100-grain weight. In contrast, the interaction between variety and irrigation treatment significantly affected ear length only.

Table 4. Effects of treated wastewater irrigation on Maize growth traits

Factor	Leaf Length (cm)	Leaf Width (cm)	Stem Diameter (cm)	Plant Height (cm)	Number of Nodes
Varieties					
Jaune de Tassaou	46.92 ± 8.66a	6.20 ± 1.16a	2.77 ± 0.55	62.98 ± 36.95a	1.95 ± 0.28
Rouge de Gayi	40.96 ± 14.51b	5.75 ± 1.70ab	2.70 ± 0.51	43.40 ± 37.69b	1.90 ± 0.30
Maka	40.52 ± 10.97b	5.03 ± 1.37b	2.80 ± 0.48	61.35 ± 35.85a	1.93 ± 0.31
Treatments					
Treated wastewater	51.38 ± 5.59a	6.46 ± 1.28a	2.94 ± 0.54a	44.04 ± 43.96b	1.98 ± 0.23a
Fresh water	42.61 ± 8.98b	4.87 ± 1.26b	2.57 ± 0.40b	67.80 ± 25.32a	1.86 ± 0.34b
Significance					
Variety	***	***	ns	**	ns
Treatment	***	***	***	***	**
Variety × Treatment	***	*	ns	Ns	Ns

*Values followed by the same letter within a column are not significantly different according to Tukey's test at p < 0.05. ns: not significant; *: significant; **: highly significant; ***: very highly significant*

Table 5. Effects of treated wastewater irrigation on Maize yield and yield-related traits

Factor	Ear Length (cm)	Ear Diameter (cm)	Cob weight (g)	Stem Biomass (g)	Rows per Ear	Grains per Row	Total Grain Weight (g)	100-Grain Weight (g)
Varieties								
Jaune de Tassaou	19.86 ± 1.91a	3.89 ± 0.44	111.87 ± 19.97	62.98 ± 36.95	16.27 ± 2.19	30.62 ± 5.66	79.13 ± 17.44	20.23 ± 4.13b
Rouge de Gayi	18.45 ± 2.42b	3.74 ± 0.61	112.17 ± 21.50	43.40 ± 37.69	16.46 ± 2.11	29.98 ± 5.12	83.62 ± 23.21	20.25 ± 4.81b
Maka	19.96 ± 1.62a	3.80 ± 0.54	116.47 ± 20.42	61.35 ± 35.85	16.50 ± 2.70	30.72 ± 4.98	92.32 ± 20.44	22.52 ± 6.16a
Treatments								
Treated wastewater	19.82 ± 1.50a	4.08 ± 0.45a	122.84 ± 16.85a	84.18 ± 20.62a	16.95 ± 2.74a	33.31 ± 4.68a	92.27 ± 18.94a	23.70 ± 5.35a
Fresh water	19.03 ± 2.51b	3.54 ± 0.48b	104.11 ± 19.86b	57.93 ± 17.75b	15.87 ± 1.70b	27.61 ± 4.13b	77.63 ± 20.69b	18.27 ± 3.24b
Significance								
Variety	***	Ns	ns	ns	ns	ns	ns	**
Treatment	**	***	***	***	**	***	***	***
Variety × Treatment	**	Ns	ns	ns	ns	ns	ns	ns

*Values followed by the same letter within a column are not significantly different according to Tukey's test at p < 0.05. ns: not significant; **: highly significant; ***: very highly significant*

3.4 Relationship among Agro-Morphological Traits

Principal component analysis (PCA) highlighted the differential effects of treated wastewater and irrigation with fresh water on the three maize varieties. The first principal axis, accounting for 30.41% of the total variability, clearly discriminated plants irrigated with fresh water from those irrigated with treated wastewater, indicating a marked physiological and agronomic response to irrigation treatment. PC2 explained 9.90% of the total variation and mainly reflected intra-treatment variability without clear separation among groups. The distinct positioning of treatment centroids confirmed that treated wastewater consistently modified the overall expression of growth and yield-related traits, likely due to its specific physicochemical composition under the mining conditions of Arlit.

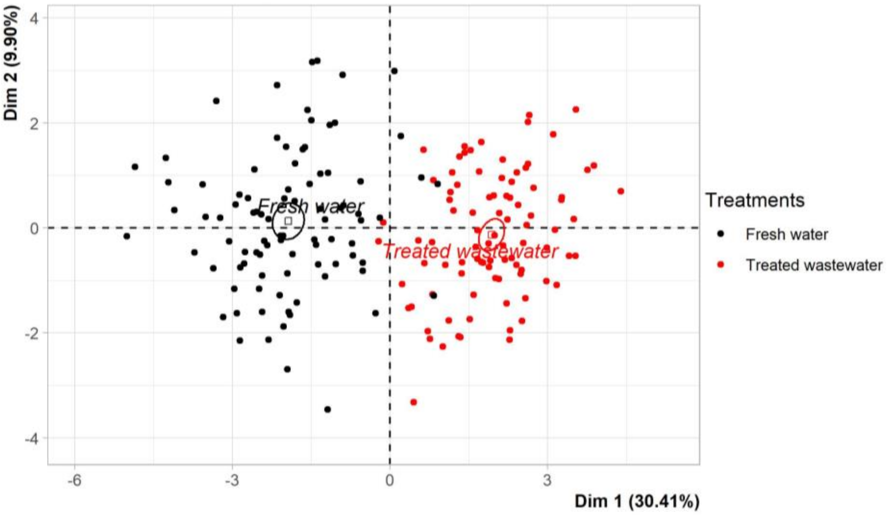

Fig. 3. PCA factor map of maize traits

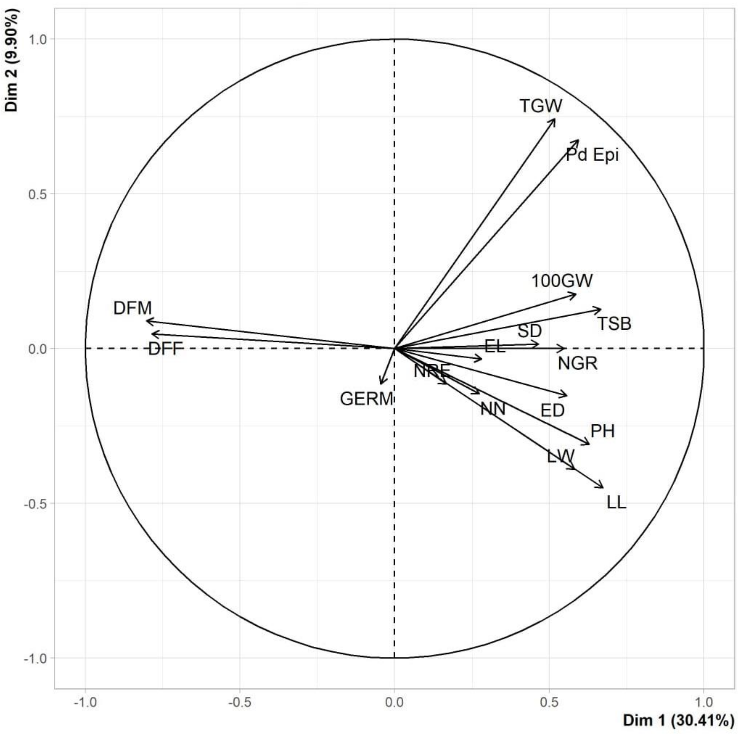

Fig. 4. PCA factorial design for genetic variability in maize

3.5 Contribution of Agro-Morphological Variables

The PCA factor map showed that the first axis, which explained 30.41% of the total variance, was mainly structured by yield-related variables and grain characteristics. Variables such as total grain weight, 100-grain weight, stem biomass, leaf length, leaf width, plant height, stem diameter, and ear length exhibited strong positive contributions to this axis. Conversely, flowering dates (male and female flowering) contributed negatively to PC1, indicating an antagonistic relationship between earliness and productivity. Late-maturing genotypes tended to exhibit lower biomass and grain production, whereas early-maturing genotypes were more closely associated with higher productivity. The second axis, accounting for 9.90% of the total variation, provided secondary information mainly associated with total grain weight and cob weight, which showed positive projections. Germination traits, branching traits, and other secondary variables were located near the origin, indicating weak contributions. Overall, the PCA variable structure suggested high coherence among yield-related traits, reflecting strong biological interdependence among productive characteristics. In contrast, germination traits appeared relatively homogeneous across treatments and varieties. These findings indicate that genetic improvement programmes could effectively target integrated productivity-related traits, while earliness may constitute a more independently regulated characteristic.

4. Discussion

The results demonstrated that treated wastewater irrigation significantly enhanced maize vegetative growth, resulting in longer and wider leaves, improved stem development, and increased plant height ($p < 0.05$). These findings are consistent with evidence that treated wastewater can supply water and plant nutrients and thereby improve soil fertility, crop nutrition, and vegetative growth, particularly in arid and semi-arid environments (Hashem & Qi, 2021; Khaskhoussy et al., 2022). Several maize studies have likewise reported improvements in leaf area, chlorophyll status, biomass, yield, and water productivity under appropriately managed recycled or treated wastewater irrigation (Kama et al., 2023; Yerli et al., 2023). The accelerated crop development observed under treated wastewater irrigation, particularly earlier flowering, may reflect improved water and nutrient availability; however, responses can vary with irrigation regime and crop developmental stage (Hirich et al., 2014; Liu et al., 2022). The increase in node number further suggests a positive effect on vegetative development. Overall, these results indicate that treated wastewater may function as both an irrigation source and an agronomic input. Nevertheless, long-term use requires monitoring of salinity, trace elements, pathogens, and other contaminants to protect soil quality, crop safety, and human health (Hashem & Qi, 2021; Kama et al., 2023). Although ear length increased only slightly, substantial improvements were recorded for cob weight, stem biomass, and overall plant vigour. These responses agree with studies in which nutrient-containing wastewater enhanced maize biomass and productivity (Alves et al., 2023; Kandasamy et al., 2025; Yerli et al., 2023). The observed improvements may therefore be attributed to increased nutrient availability and enhanced uptake of essential mineral elements (Khaskhoussy et al., 2022). The organic manure applied to all plots may also have contributed to crop performance, because organic amendments can improve maize growth, yield, and water–fertiliser productivity under arid conditions (Zhang et al., 2022). Analysis of the interactions between maize varieties and irrigation treatments showed that seed germination was not significantly affected by water quality. This finding should be interpreted cautiously because maize establishment and early growth responses depend on effluent treatment level and composition; inadequately treated wastewater can reduce root hydraulic conductivity, root elongation, leaf growth, and biomass (Asli et al., 2022). In contrast, the highly significant differences observed for leaf length and width confirm that foliar responses depend on genotype and water availability, as also shown by maize experiments under contrasting irrigation strategies (Gheysari et al., 2021). The particularly vigorous foliar development observed in variety V2 supports the hypothesis that maize genotypes differ in their capacity to use water and nutrients. The absence of significant varietal differences for plant height and stem diameter, despite a slight tendency towards reduction in V3, is consistent with findings that wastewater irrigation may improve leaf area and biomass without significantly altering plant height or stem girth (Kandasamy et al., 2025). The shorter growth cycle observed in V3 reflects its early-maturing behaviour, whereas differences among maize materials and irrigation conditions can produce contrasting growth and yield responses (Mok et al., 2014). Although the number of ears per plant did not differ significantly among treatments, the superior average performance of V2 suggests a higher yield potential. Improved leaf area, chlorophyll status, and water relations have been positively associated with maize biomass and yield under recycled wastewater irrigation (Yerli et al., 2023). The results also showed that ear length was significantly influenced by the interaction between variety and irrigation treatment ($p = 0.001$). The best performances were recorded for V1 under treated wastewater irrigation and V3 under irrigation with fresh water. Such genotype-and management-dependent variability is consistent with comparative maize studies using treated wastewater and freshwater (Mok et al., 2014). Although the number of grains per row and the number of rows per ear were not significantly affected, V2 irrigated with treated wastewater exhibited a favourable trend consistent with findings showing that wastewater-derived nutrients can improve maize grain components and grain yield (Alves et al., 2023). Likewise, ear diameter, cob weight, stem biomass, and overall yield did not always exhibit statistically significant differences despite noticeable average increases. This agrees with evidence that the effects of treated wastewater on maize yield depend on irrigation level, wastewater quality, tillage, salinity, soil conditions, and plant material (Hirich et al., 2014; Mok et al., 2014; Yerli et al., 2023). Principal component analysis (PCA) further confirmed that treated wastewater irrigation induced substantial physiological and agronomic responses in maize (*Zea mays L.*), as evidenced by clear treatment discrimination along the first principal axis. Experimental studies have shown that treated or recycled wastewater can modify maize growth, biomass accumulation, leaf area, chlorophyll content, nutrient uptake, and yield through changes in water and nutrient supply (Kama et al., 2023; Kandasamy et al., 2025; Khaskhoussy et al., 2022). The weaker variability captured by PC2 mainly reflected intra-treatment variation, which is consistent with multivariate analyses in which secondary components represent less structured within-group differences. The distinct separation of the fresh water and treated wastewater centroids confirmed that irrigation water quality influenced the combined expression of growth and yield-related traits, probably through the physicochemical characteristics of treated wastewater and their effects on soil nutrient availability (Kandasamy et al., 2025).

5. Conclusion

Under the arid conditions of Arlit, irrigation with treated wastewater altered the phenological, vegetative and yield-related performance of the three maize varieties compared with fresh water. Treated wastewater advanced male and female flowering and produced higher mean values for leaf length, leaf width, stem diameter, number of nodes, ear length, ear diameter, cob weight, stem biomass, rows per ear, grains per row, total grain weight and 100-grain weight. The greatest proportional increases were recorded for stem biomass and grains per row. The varietal responses indicated that irrigation-water effects were not uniform across all maize materials, while the principal component analysis clearly separated the irrigation treatments. These results support the potential use of treated wastewater as an alternative irrigation resource for maize production in Arlit. Nevertheless, the findings apply only to the conditions and duration of this experiment. Agricultural use should therefore be accompanied by systematic monitoring of treated wastewater quality, soil salinity, nutrients, heavy metals, microbiological safety, radiological risks and grain quality before broader or long-term adoption.

6. Limitation

The experiment was conducted at one site during a single cropping season and included only three maize varieties. The physicochemical, microbiological, heavy-metal and radiological characteristics of the treated wastewater were not reported, and baseline or post-irrigation soil-quality data were unavailable. Organic manure and crop-protection chemicals may also have influenced plant responses. Consequently, the study does not establish long-term effects on soil salinity, nutrient accumulation, contaminant transfer or grain quality. Multi-season trials with comprehensive water, soil and harvested-grain analyses are required to confirm the findings.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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