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Improving Water Efficiency, Nutrients Utilization, and Maize Yield using Super Absorbent Polymers Combined with NPK during Water Deficit Conditions

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ABSTRACT

Background: The increasing global population poses a significant challenge, resulting in a scarcity of food resources on a global scale. Addressing this issue necessitates advancements in agricultural practices, particularly in drought-prone areas. Super absorbent polymers (SAPs) are crucial in improving crop production's water and nutrient utilization efficiency, making them highly relevant for drought-affected areas. Thus, this research aimed to assess the impact of SAPs, combined with manure and fertilizers, on the growth of maize (*Zea mays*) cv. Ts-1004.

Material and Methods: The experiment consisted of nine treatment groups, namely, T_1 (Nitrogen, N), T_2 (Potassium, K), T_3 (Phosphorus, P), T_4 (NPK), T_5 (Compost), T_6 (SAPs), T_7 (NPK + Compost), T_8 (NPK + SAPs), and T_9 (Control). These treatments were evaluated under two water level conditions: well-watered (W_1) and water-stressed (W_2) in a greenhouse environment. The plants were subjected to water stress by maintaining soil moisture content at 20 – 25% during the knee height and flowering stages for 8 days.

Results: The results revealed that significantly ($P < 0.05$) higher values in ear girth, ear length, number of seeds per ear, and ear weight were observed in the T8 treatment compared to other treatments. Additionally, the T8 treatment exhibited the highest yield under well-watered and water-stressed conditions (3,274.4 kg/ha). The application of SAPs improved soil moisture content, leading to enhanced water use efficiency (24.53 kg/ha/mm) and harvest index. Moreover, SAPs positively influenced the concentration percentage of N, P, K, Ca, and Mg in roots, stems, leaves, and seeds, with T8 showing the highest values under water stress conditions.

Conclusion: These findings highlighted the effectiveness of SAPs in enhancing crop growth and productivity, particularly under water stress conditions. This approach will help farmers reduce water stress on crops.

Key words: WUE; NUE; Harvest index; Water deficit condition; NPK; Compost; SAPs

INTRODUCTION

Maize, a prominent cereal crop and the third most cultivated crop globally after wheat and rice, belongs to the Poaceae family (Kaul et al., 2011). Maize is extensively utilized for both direct and indirect human consumption, as well as for animal husbandry, and is even used in the production of traditional beverages (Asghar et al., 2010). Worldwide production of maize is estimated to be around 60 to 70 million tons (Kidist, 2013). The global population is steadily increasing and is projected to exceed 9.1 billion by 2025 (FAO, 2009). Consequently, the growing rate of population will require 70% more food by 2050, equating to an annual demand of 43 million metric tonnes of cereals (Bruinsma, 2009). However, despite only 18% of the world's arable land being irrigated, it is responsible for producing 40% of the world's food (FAO, 2006). Efforts are being made to expand irrigated areas, with an annual increase of nearly 1%, aiming for a target of 13.6% by 2025 (Rosegrant and Cai, 2002).

Enhancing nutrient use efficiency cannot solely rely on fertilizer management; it is influenced by the soil solution, where water stress can restrict the efficiency of soil nutrient utilization (Bossio et al., 2008). Balanced application of chemical and organic fertilizers in conjunction with proper soil moisture levels can improve nutrient and water use efficiency, leading to enhanced soil fertility, productivity, and ultimately increasing grain yield (Ryan et al., 2009). Nilson and Orcutt, (1996) stated that the effect of the drought stress one week before silking (R_2) and two weeks after silking stage (R_4) decreased the grain yield by 53%, compared to non–drought threaten plants. Maize crop needs 50–70% soil moisture level to maintain their normal physiological activities. In drought-affected areas of developing countries, cereal production often remains below 1.5 t/ha, even with the application of ample fertilizers. However, when sufficient irrigation water is available, the yield potential can exceed 8 t/ha (Thompson, 2012). Therefore, there is a strong positive correlation between water use efficiency (WUE), nutrient use efficiency (NUE), and crops yield production (Lucas et al., 2007). Maize has been found to have high WUE and NUE as compared with other crops, producing high biomass in linear response to nutrient availability without excessive evapotranspiration (Ogola et al., 2002).

The number of leaves, their size, and the expansion of leaf area in maize are influenced by turgor pressure and the availability of assimilates. However, under drought conditions, both turgor pressure and assimilation rates are reduced (Rucker et al., 1995). Water-limiting conditions severely impact plants' fresh and dry weight (Zhao et al., 2006). In maize, the stem girth and plant height experience significant reductions under water-limiting conditions (Khan et al., 2015). Similarly, both maize and sugarcane (*Saccharum officinarum* L.) exhibit reduced growth and net assimilation rate under heat and water stress conditions (Wahid and Close, 2007).

The grain-filling processes in cereal crops are regulated by four key enzymes: sucrose synthase, starch synthase, starch branching enzyme, and adenosine diphosphate glucose pyrophosphorylase (Taiz and Zeiger, 2006). Drought stress has been reported to decrease the activity of these enzymes, negatively impacting the yield of major cereals (Ahmadi and Baker, 2001). Maize yield is significantly reduced when exposed to drought conditions during tasseling stage (Anjum et al., 2011).

Drought conditions can cause an imbalance in assimilate distribution, leading to increased translocation of assimilates to the roots in order to enhance water uptake (Leport et al., 2006). Water stress disrupts the sink and source relationship, impairing the utilization of assimilates effectively (Kim et al., 2000). The acid invertase enzyme plays a crucial role in maintaining a balance between phloem loading and unloading pathways.

However, under water stress, the functionality of this enzyme is negatively affected, disturbing the mechanism of organ partitioning and adversely impacting dry matter distribution (Zinselmeier et al., 1999). Generally, drought and heat stress negatively impact nutrient cycling, uptake, and availability to plants, affecting various physiological functions within plants (Schimel et al., 2007). One approach to address this challenge is the utilization of superabsorbent polymers (SAPs). SAPs offer a way to increase fertilizer use efficiency while minimizing water application. These polymers can retain water and release it gradually, providing to crops available water and essential nutrients during their growth stages (Pawlowski et al., 2009).

SAPs can store water 400 times more than their dry weight and increase soil water retention capacity by 100–260%, which is recommended 2–8g kg^{-1} of soil (Rafiei and Noor mohammadi, 2013), while decreased nutrients percolation below the root zone and evaporation from the surface of the soil (Sarvas et al., 2007). The utilization of SAPs has been found to enhance soil productivity by optimizing the air-water ratio, an important aspect of soil productivity. Additionally, the presence of SAPs promotes improved soil microbe activities, which in turn strengthens crop growth (Orzeszyna et al., 2006). When SAPs are incorporated into the soil, they contribute to improved soil physical properties, leading to enhanced crop growth and increased yield. Furthermore, using SAPs reduces plants' irrigation requirements (Yazdani et al., 2007). However, it should be noted that including SAPs may also prolong the period before wilting occurs in plants (Karimi et al., 2009). Therefore, this study aimed to investigate the effectiveness of combining chemical fertilizers with SAPs to improve the soil's water-holding capacity, specifically focusing on enhancing water use efficiency (WUE), nutrient use efficiency (NUE), and crop yield.

MATERIALS AND METHODS

Experimental design and treatments

The greenhouse experiment was conducted at the Department of Agronomy, Faculty of Agriculture, Kasetsart University in Bangkok, Thailand, during the rainy season of 2017. A pot experiment with a lifespan of 105 days was conducted, following a randomized block design with a factorial treatment arrangement. The experiment consisted of nine different treatments such as T_1 (Nitrogen), T_2 (Potassium), T_3 (Phosphorus), T_4 (NPK), T_5 (Compost), T_6 (SAPs), T_7 (NPK + Compost), T_8 (NPK + SAPs), and T_9 (Control). These treatments underwent to well-water (W_1) and water-stressed (W_2) conditions. All the above treatments were applied to the pot surface area (0.42 sq m) in the experiment, including RDF of NPK fertilizer rate is 120:60:40 kg/ha, compost at a rate of 730.7 kg/ha, and SAPs at a rate of 312.5 kg/ha. These amounts were equivalent to 11 g of urea, 5.5 g of P_2O_5, 3.3 g of K2O, 43 g of compost, and 13 g of SAPs per pot. Water deficit condition imposed 25 days after sowing (DAS) (at knee height stage) and 62 DAS at flowering stage.

Measurements and parameters

The soil moisture content (SMC), water use efficiency, nutrient use efficiency, yield and harvest index were tested according to the methods Wang et al. (2017), Singh et al. (2007), Lija (2014), Khaliq et al. (2006), and Nwachukwu and Ikeadigh, (2012), respectively, after harvesting. The daily water requirement was determined using the FAO's recommended method (Blaney-Criddle equation, 1950). A 20–25% soil moisture content was maintained for 8 days during the knee height and again during the flowering stages to ensure optimal soil moisture conditions. The nutrient uptake level and its utilization efficiency were assessed using the infrared spectrometer model (Agri Quant) with the serial number QIN1384058-001. The grinded samples were utilized and passed through the lens tube, enabling the determination of element percentages in different plant parts. The procedure followed as described by Lija. (2014). The below formula is used for the calculation of nutrient use efficiency percentage:

NUE% = TNF – TNU / RFA * 100; TNF: is the total nutrient uptake by fertilized treatment, TNU: is the total nutrient uptake by non-fertilized treatment, and RFA: is the rate of fertilizer applied.

Statistical analysis

The data was analyzed based on a one-way analysis of variance (ANOVA) using SPSS (version 16) statistical software. Differences among the treatments were separated using Tukey's test at $\alpha = 0.05$ significance level.

RESULTS

Ears girth, length, and weight

After harvesting, the ears' girth was studied in well-watered (W_1) and water-stressed (W_2) block treatments. The findings of the study indicated significant differences among the treatments, with the highest value recorded in T8 (3.32 ± 0.07 cm), while the lowest value was observed in T9 (2.12 ± 0.35 cm) across both blocks. Additionally, significant differences were observed between the water level and soil management factors among the treatments. However, the statistical analysis did not reveal any significant interactions between the water level and soil management factors in relation to the ear's girth, as shown in Table 1. A significant difference in ear length was observed in T_8 (13 ± 1.9 cm), whereas the minimum value among the treatments on both sides at T_2 (7.08 ± 1.5 cm) was observed. However, no significant differences were found among the treatments in relation to the effect of water levels: well-watered and water-stressed. Similar results were observed in the water level and soil management interaction (Table 1). The ear weights (gr) were extensively studied among the treatments after harvesting in both blocks. Significant differences were observed, with T_8 exhibiting the highest value (64.92 ± 22.1 g) in both blocks, as shown in Table 1. On the other hand, the lowest value was recorded in T_9 (13.9 ± 5.31 g) in both blocks among the treatments. However, no significant differences were found in the interaction between the two factors (water levels and soil management). However, significant results were noted in the two water levels among the treatments in both blocks, as indicated in Table 1.

Yield and its components

The average number of seed per ear was counted after the harvesting and threshing. It was found that highly significant differences among the treatments in both blocks at T_8 (255.83 ± 59.34). In contrast, the minimum number of grains per ear was recorded at T_9 (35.5 ± 72.5) in both blocks (Table 1). In the first step collected randomly three ears of grain from each treatment. After the seeds' moisture was decreased to 13–15%, the samples were randomly selected three times and weighed. The higher weight was noted in T_8 in both treatments (42.37 ± 4.2 g) (Table 1), while the lowest weight of the hundred (100) seeds within treatments was observed in both blocks at T_9 (16.9 ± 5.31g) (Table 1). A significant difference in yield production among the treatments was observed in both blocks at T_8 treatment, with a value of 3,390.1 ± 51.7 kg/ha, as shown in Table 1. Conversely, the lowest expected yield was obtained in T_9 in both blocks, with a value of 694.4 ± 90.7 kg/ha. Significant differences were also observed among the treatments in the two water levels (W_1 and W_2). However, no significant differences were found in the interaction between the two factors (water level and soil management) among the treatments, as presented in Table 2.

Soil moisture contents

The study investigated the soil moisture content (SMC), and it was observed that T_8 in W_1 block exhibited significantly higher SMC ($P \leq 0.05$), while T_9 had the lowest SMC, as shown in Figure 1. A similar trend was observed for T_8 and T_9 in W_2 blocks (Figure 1).

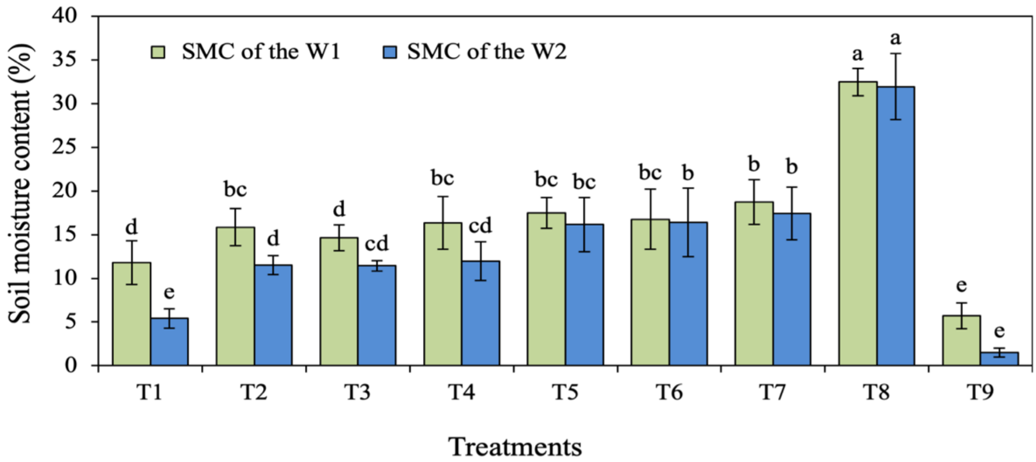

Figure 1. Effects of well-water and water-stressed condition on soil moisture content integrated with soil nutrients.

Harvest index

The economic yield of the harvested plant production over the biological yield of the plants considered the harvest index (HI) in the percentage of the reference plant. The harvest index was studied among the treatments of both blocks after the harvesting; no significant differences were observed when the plants were dried and weighed in both blocks. However, the highest value (HI %) was noted at T_8 (0.68 ± 0.3 %) in both blocks among the treatments (Table 3), whereas the minimum harvest index was observed in both blocks among the treatments in T_9 (0.33 ± 0.01%). Similar significant results were noted in both blocks among the treatments in the interaction between the two water levels at well-watered and water-stressed blocks (Table 3).

Water use efficiency

The water use efficiency (WUE kg/ha/mm) is a measure of maximizing production while utilizing a minimal amount of water per unit area. WUE was measured in both blocks and observed the significant differences among the treatments in two water levels, the well-watered and water-stressed, and also about the soil management in T_8 (24.53 ± 5.5 kg/ha/mm) in both blocks. In contrast, the minimum water use efficiency was recorded in both blocks among the treatments again in T9 (4.98 ± 2.5 kg/ha/mm) (Table 4). However, no significant differences were found between the interactions among the treatments for soil management in both blocks among the treatments (Table 4).

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Table 1. Yield parameters within blocks among the treatments at different growth stages.

Water management	Ear girth (cm)	Ear length (cm)	No. of seeds/ear	Ear weight (g)	100 seeds weight (g)	Yield kg/ha
W_1	3.266^{a}	9.593^{a}	166.85^{a}	38.801^{a}	31.141^{a}	2024.2^{a}
W_2	2.712^{b}	9.648^{a}	78.48^{b}	29.187^{b}	25.715^{b}	1524.1^{b}
Mean	2.989	9.62	122.67	33.994	28.43	1774.2
CV (%)	13.69	24.74	43.03	41.15	12.4	41.29
LSD (0.05)	*	ns	*	*	*	*
Soil management	**Ear girth (cm)**	**Ear length (cm)**	**No. of seeds/ear**	**Ear weight(g)**	**100 seeds weight (g)**	**Yield kg/ha**
T1	2.9 ± 0.4^{bc}	8.33 ± 2.8^{cde}	65.7 ± 48.42^{ef}	26.2 ± 5.21^{cde}	28.8 ± 4.62^{cd}	1,149.7 ± 71.5^{de}
T2	3.01 ± 0.1^{bc}	7.08 ± 1.5^{e}	98.5 ± 66.7^{def}	31.14 ± 8.6^{bcd}	22.99 ± 3.23^{e}	1,627.5 ± 48.8^{bcd}
T3	2.98 ± 0.2^{bc}	11.3 ± 2.3^{ab}	13.7 ± 95.6^{cd}	37.16 ± 16.12^{bc}	29.1 ± 4.8^{bcd}	1,848.6 ± 41.9^{bcd}
T4	3.23 ± 0.14^{ab}	11.1 ± 3.5^{abc}	160.3 ± 95.7^{bc}	42.81 ± 8.7^{b}	30.2 ± 1.96^{bc}	2,074.8 ± 80.8^{bc}
T5	2.74 ± 0.5^{c}	7.67 ± 1de	72.7 ± 27.2^{ef}	19.36 ± 13.7^{de}	27.76 ± 1.72^{cd}	1,562.56 ± 71.7^{bcd}
T6	3.06 ± 0.4^{c}	9.42 ± 1.1^{bcde}	91.5 ± 20.21^{def}	33.44 ± 5.8^{bcd}	25.14 ± 0.9^{de}	1,222.7 ± 30.3^{cde}
T7	3.06 ± 0.2^{ab}	10.1 ± 2.7^{bcd}	194.33 ± 48.8^{b}	37.16 ± 15.4^{bc}	32.63 ± 5.1^{b}	2,397.2 ± 45.3^{b}
T8	3.32 ± 0.07^{a}	13 ± 1.9^{a}	255.1 ± 59.4^{a}	64.92 ± 22.1^{a}	42.37 ± 4.2^{a}	3,390.1 ± 51.7^{a}
T9	2.12 ± 0.35^{d}	8.58 ± 1.9^{bcde}	35.5 ± 72.5^{f}	13.3 ± 7.5^{e}	16.9 ± 5.31^{f}	694.4 ± 90.7^{e}
Mean	2.989	9.62	122.67	33.994	28.43	1774.2
C.V (%)	13.69	24.74	43.03	41.15	12.4	41.29
LSD (0.05)	*	ns	*	*	*	*

W1: well-watered, W2: water-stressed, CV: coefficient of variation, LSD: least significant difference. The * indicates a significance level at $P < 0.05$ and ns: not significant. Different letters indicated significant difference among treatments.

Table 2. The interaction between the two water levels and soil management for yield and its components.

Water levels	Treatment	Ear girth (cm)	Ear length (cm)	No. of seeds/ear	Ears weight(g)	100 seeds weight(g)	Yield kg/ha
Well - watered	T1	3.1 ± 0.37[abcdef]	8.83 ± 2.75[bcdef]	98.3 ± 48.4[efgh]	31.93 ± 5.2[defg]	31.74 ± 4.62[b]	1,230.83 ± 71.5[efg]
	T2	3.4 ± 0.07[defg]	7 ± 1.5[cedef]	142.7 ± 66.7[cde]	34.2 ± 8.6[cdefg]	25.6 ± 3.23[def]	1,785.8 ± 48.8[efg]
	T3	3.5 ± 0.2[abc]	11.7 ± 2.31[abc]	188.7 ± 95.6[bcd]	41.81 ± 16.1[bcde]	32.92 ± 4.8[b]	2,183.14 ± 41.9[bcde]
	T4	3.6 ± 0.18[ab]	10.83 ± 3.51[abcde]	226.7 ± 95.7[abc]	56.62 ± 8.7[abc]	34.6 ± 1.96[b]	2,972.62 ± 80.8[abcd]
	T5	2.9 ± 0.52[bcdefg]	6.5 ± 1[bcde]	117.7 ± 27.3[cdef]	23.57 ± 13.7[efg]	30.5 ± 1.72[bcd]	1,667.56 ± 71.7[defg]
	T6	3.3± 0.4[abcde]	8.83 ± 1.1[bcdef]	92.7 ± 20.2[efgh]	31.69 ± 5.8[befg]	26.4 ± 0.93[cde]	1,654.4 ± 30.3[defg]
	T7	3.7 ± 0.19[ab]	11 ± 2.65[abcd]	264 ± 47.8[ab]	47.4 ± 15.4[abcd]	35.32 ± 5.1[b]	2,986.7 ± 45.3[abc]
	T8	3.67 ± 0.07[a]	13.2 ± 1.9[a]	312.7 ± 59.4[a]	67.14 ± 22.1[a]	43.6 ± 4.2[a]	3,505.9 ± 51.7[a]
	T9	2.3 ± 0.35[gh]	8.2 ± 1.9[cdef]	58.3 ± 72.5[efgh]	14.97 ± 7.5[fg]	19.94 ± 5.31[gh]	7,81.6 ± 90.7[fg]
Water stressed	T1	2.76 ± 0.4[defg]	7.83 ± 1.5[ef]	33 ± 11.5[gh]	20.5 ± 4.55[efg]	25.8 ± 4.2[defg]	1,068.6 ± 37.5[cdefg]
	T2	2.64 ± 0.99[efg]	7.2 ± 0.8[def]	54.3 ± 85.7[fgh]	28.14 ± 8.9[defg]	20.4 ± 5.9[def]	1,469.3 ± 67.3[defg]
	T3	2.46 ± 0.97[fgh]	11 ± 4.4[abcd]	70.7 ± 77.3[efgh]	32.5 ± 37.96[defg]	25.3 ± 0.86[defg]	1,514.03 ± 28.2[defg]
	T4	2.85 ± 0.4[cdefg]	11.3 ± 2.6[abc]	124 ± 53.1[efgh]	28.99 ± 8.2[defg]	25.84 ± 2.1[def]	1,698.02 ± 82.5[defg]
	T5	2.49 ± 0.62[fgh]	8.83 ± 3.51[f]	27.7 ± 27.14[h]	15.14 ± 3.8[cdef]	25.05 ± 2.8[defg]	1,457.5 ± 21.2[defg]
	T6	2.84 ± 0.4[fgcdefg]	10 ± 3.5[abcdef]	90.3 ± 67.9[efgh]	35.19 ± 13.35[abcd]	23.92 ± 1.41[bcd]	1,290.61 ± 96.8[fg]
	T7	2.98 ± 0.2[bcdef]	9.2 ± 2.3[bcdef]	154.7 ± 84.5[def]	27.19 ± 4.1[abc]	29.94 ± 2.13[bcd]	2,237.62 ± 96.6[cdef]
	T8	3.44 ± 0.13[abc]	12.5 ± 1.32[ab]	250 ± 48.1[bcd]	62.7 ± 6.6[ab]	41.2 ± 3.1[a]	3,274.4 ± 43.5[ab]
	T9	1.94 ± 0.3[h]	9 ± 2.65[bcdef]	12.7 ± 2.9[fh]	11.63 ± 6.6[g]	14 ± 2.73[h]	6,07.32 ± 34.03[g]
	Mean	2.989	9.62	122.67	33.994	28.43	1,774.2
	CV (%)	13.69	24.74	43.03	41.15	12.4	41.29
	LSD (0.05)	ns	ns	ns	ns	ns	ns

CV: coefficient of variation, LSD: least significant difference, and ns: not significant. Different letters indicated significant difference among treatments.

Table 3. The water use efficiency (kg/ha/mm) and HI % of maize under different treatments.

Water – management	HI%	WUE%
W_1	0.54^{a}	13.14^{a}
W_2	0.47^{a}	12.24^{b}
Mean	0.51	12.69
C.V	44.42	42.72
LSD	ns	*
Soil – Management	**HI%**	**WUE%**
T1	0.43 ± 0.4^{abc}	8.3 ± 4.7^{de}
T2	0.42 ± 0.15^{abc}	11.7 ± 2.9^{bcd}
T3	0.54 ± 0.2^{abc}	13.17 ± 5.5^{bcd}
T4	0.58 ± 0.12^{abc}	14.78 ± 5.4^{bc}
T5	0.55 ± 0.3^{abc}	11.26 ± 1.8^{bcde}
T6	0.41 ± 0.14^{bc}	8.54 ± 1.96^{cde}
T7	0.62 ± 0.1^{ab}	16.98 ± 2.95^{b}
T8	0.68 ± 0.3^{a}	24.53 ± 5.5^{a}
T9	0.33 ± 0.1^{c}	4.98 ± 2.5^{e}
Mean	0.51	12.69
CV (%)	44.42	42.72
LSD (0.05)	*	*

CV: coefficient of variation, LSD: least significant difference. * And ** indicates significance level at $P < 0.05$ and $P < 0.01$, respectively. Different letters indicated a significant difference among treatments.

Table 4. Interaction between the two water levels and soil management.

Water level	Treatment	HI%	WUE%
Well - watered	T1	0.51 ± 0.4^{ab}	7.992 ± 4.7^{cdef}
	T2	0.52 ± 0.2^{ab}	11.6 ± 2.92^{def}
	T3	0.56 ± 0.2^{ab}	14.2 ± 5.5^{bcde}
	T4	0.6 ± 0.12^{ab}	15.92 ± 5.43^{bcd}
	T5	0.59 ± 0.3^{ab}	10.83 ± 1.8c^{def}
	T6	0.46 ± 0.2^{ab}	10.75 ± 1.9^{cdef}
	T7	0.66 ± 0.1^{ab}	19.2 ± 2.9^{abc}
	T8	0.69 ± 0.3^{a}	22.77 ± 5.5^{ab}
	T9	0.31 ± 0.1^{b}	5.1 ± 2.5^{f}
Water - stressed	T1	0.35 ± 0.2^{ab}	8.6 ± 1.9^{cdef}
	T2	0.36 ± 0.2^{ab}	11.8 ± 3.7^{cdef}
	T3	0.52 ± 0.1^{ab}	12.2 ± 3.44^{cdef}
	T4	0.56 ± 0.2^{ab}	13.64 ± 4.6^{cdefg}
	T5	0.51± 0.2^{ab}	11.71 ± 1.7^{cdef}
	T6	0.35± 0.4^{ab}	6.4 ± 1.6^{ef}
	T7	0.58± 0.1^{ab}	14.8 ± 5.6^{bcde}
	T8	0.66± 0.4^{ab}	26.3 ± 2.8^{a}
	T9	0.35 ± 0.2^{ab}	4.88 ± 2.7^{f}
	Mean	0.51	12.69
	CV (%)	44.42	42.72
	LSD (0.05)	*	**

CV: coefficient of variation, LSD: least significant difference. * and ** indicates significance level at $P < 0.05$ and $P < 0.01$, respectively. Different letters indicated a significant difference among treatments.

Percentage of elements concentration in plants and nutrients use efficiency

The grinded samples from roots, stems, leaves, and grains were analyzed using a near-infrared spectrometer (NIR) to determine the percentage of (N, P, K, Ca and Mg in both W_1 and W_2 blocks. The results indicated significant differences in root composition at T_8 treatment, with higher percentages of N (27.33%), K (20.9%), and Mg (4.6%) compared to other treatments. However, there were no significant differences in P% (1.03) and Ca% (5.98) among the treatments in the W_1 block (Table 5). The stem samples were also subjected to the same element concentration analysis, and similar patterns were observed. In T_8, the stem composition showed significant differences for (2.05% P), (14.9% K), and (15.04% Ca), while no significant differences were found for (7.12% N) and (3.8% Mg). However, these values were still relatively higher compared to other treatments in the W_1 block (Table 5). Similar trends were observed in the analysis of leaf samples from the W_1 block. In T_8, significant differences ($P \leq 0.05$) were found for (13.22% K), (9.36% Ca), and (3.51% Mg), while no significant differences were observed for (4.93% N) and (1.32% P). However, the values of N% and P% were higher compared to other treatments (Table 6).

Table 5. The percentage of the concentration of the root element within treatments of the well-watered block.

	Elements concentration in roots (%)					Elements concentration in stem (%)				
Treatment	N	P	K	Ca	mg	N	P	K	Ca	mg
T1	16.9^{cd}	0.9^{bc}	15.6^{c}	4.98^{c}	2.6^{d}	4.32^{c}	1.4^{bc}	11.99^{cd}	11.3^{c}	2.95^{d}
T2	9.98^{e}	0.9^{c}	10.1^{d}	3.6^{e}	2.7^{d}	1.74^{d}	1.8^{a}	6.01^{f}	9.9^{d}	2.72^{ef}
T3	14.6^{d}	1.03^{a}	15.6^{c}	5.8^{ab}	2.6^{d}	2.1^{d}	1.82^{a}	3.4^{g}	11.2^{c}	3.35^{b}
T4	16.2^{cd}	0.9^{c}	17.2^{b}	5.12^{c}	2.37^{d}	5.3^{bc}	1.7^{ab}	9.4^{e}	12.9^{b}	2.82^{de}
T5	16.5^{cd}	0.5^{d}	14.3^{c}	3.51^{e}	3.5^{bc}	2.2^{d}	1.1^{c}	2.9^{g}	9.03^{de}	2.62^{f}
T6	11.3^{e}	0.9^{c}	10.8^{d}	4.1^{d}	2.7^{d}	5.13^{bc}	0.7^{d}	12.3^{c}	7.3^{f}	3.2^{c}
T7	19.3^{b}	0.9^{b}	17.6^{b}	5.6^{b}	2.8^{cd}	6.1^{ab}	1.02^{cd}	13.5^{b}	9.7^{d}	3.7^{a}
T8	27.3^{a*}	1.0^{a}	20.9^{a*}	5.98^{a}	4.6^{a*}	7.12^{a}	2.1^{a*}	14.9^{a*}	15.1^{a*}	3.8^{a}
T9	18.4^{bc}	0.9^{c}	15.3^{c}	4.3^{d}	4.1^{ab}	2.93^{d}	1.03^{cd}	11.5^{d}	8.3^{e}	2.5^{g}
Mean	16.72	0.93	15.26	4.77	3.08	4.09	1.39	9.53	10.52	3.1
CV (%)	8.12	3.74	5.46	3.78	13.33	17.35	16.75	4.17	5.33	2.85
LSD (0.05)	*	ns	*	Ns	*	ns	**	*	*	ns

Table 6. The percentage of the concentration of the leaves element within treatments of the well-watered block.

	Elements concentration in leaves (%)					Elements concentration in seeds (%)				
Treatment	N	P	K	Ca	mg	N	P	K	Ca	mg
T1	-0.2^{c}	0.91^{c}	5.6^{d}	3.9^{c}	3.3^{g}	13.4^{cd}	3.3^{bc}	2.5^{d}	7.4^{c}	-1.9^{b}
T2	-0.95^{d}	0.97^{c}	3.7^{f}	3.4^{cd}	3.3^{fg}	11.3^{e}	3.2^{bc}	5.6^{d}	1.54^{e}	-0.7^{c}
T3	3.62^{b}	1.2^{b}	12.5^{b}	8.1^{b}	3.5^{b}	13.2^{d}	3.2^{a}	3.6^{c}	7.1^{ab}	-0.8^{d}
T4	4.7^{a}	1.21^{b}	12.2^{b}	8.4^{b}	3.3^{f}	13.7^{cd}	3.4^{c}	2.1^{c}	6.4^{c}	-0.5^{e}
T5	$-0.^{5}$	0.95^{c}	4.8^{e}	3.6^{c}	3.4^{c}	12.4^{cd}	3.4^{d}	0.2^{bc}	2.9^{e}	-1.4^{bc}
T6	4.84^{a}	1.3^{ab}	11.1^{b}	8.5^{b}	3.4^{e}	13.7^{e}	3.5^{c}	1.2^{d}	4.1^{d}	-0.8^{bc}
T7	4.7^{a}	1.3^{ab}	12.6^{b}	9.1^{a}	3.4^{d}	9.4^{b}	3.5^{b}	-8.6^{d}	8.5^{b}	-1.9^{b}
T8	4.93^{a}	1.32^{a}	13.22^{a}	9.3^{a*}	3.5^{a*}	14.4^{a*}	3.6^{a}	3.4^{a*}	9.9^{a*}	-0.4^{a}
T9	-0.98^{d}	0.8^{d}	3.9^{f}	3.01^{d}	3.5^{a}	8.6^{bc}	2.9^{c}	$-2\ d^{c}$	6.9^{d}	-3.3^{c}
Mean	2.24	1.1	8.85	6.37	3.4	16.72	0.93	15.26	4.77	3.08
CV (%)	8.66	4.28	3.23	5.49	0.5	8.12	3.74	5.46	3.78	13.33
LSD (0.05)	ns	ns	*	*	**	*	ns	*	*	*

CV: coefficient of variation, LSD: least significant difference. * And ** indicates significance level at $P < 0.05$ and $P < 0.01$, respectively. Ns: not significant. Different letters indicated a significant difference among treatments.

The grain grinded samples were analyzed using NIR, revealing significant differences in element concentration among the treatments. However, in T_8, no significant difference was observed for P% (3.61%), although it had a higher value than other treatments. A negative value of -0.4% was also observed for Mg% in T_8, the lowest among the treatments (Table 6). Further statistical analysis showed highly significant differences in root diagnoses for K% (24.44%) and Mg% (8.2%) (Table 7). Similarly, in stem diagnoses, highly significant differences were observed among all treatments of the W_2 block, particularly in T_8. Notably, N% (10.04%), P% (2.307%), K% (19.21%), Ca% (14.86%), and Mg% (3.803%) exhibited the highest values compared to other treatments (Table 7).

A similar trend was also used in leaf diagnoses. The highly significant differences tested in T_8 of the W_2 block, the percentage of the N, K, Ca, and Mg were (4.51%), (12.3 %), (8.813 %) and (3.59 %), respectively, while in P% did not find significant differences among the treatments. In contrast, in $T_{8,}$ the percentage of the P% still was high (1.33%) than in the rest of the treatments in the same block (Table 7). The grain diagnoses results showed significant differences simultaneously in T_8, the result noted in the percentage of N %, P %, K%, and Ca %, (15.64), (4.5), (2.12), and (18.81). In contrast, in part of the Mg % did not find significant differences among the treatments in w_2 blocks; it was found in negative status (-1.52 Mg %) at all treatments, especially in $T_{8,}$ found the least one (Table 8).

Table 7. The percentage of the concentration of the root element within treatments of the stress-watered block.

	Elements concentration in roots (%)					Elements concentration in stem (%)				
Treatment	N	P	K	Ca	mg	N	P	K	Ca	mg
T1	19.4^{c}	0.91^{b}	18.1d^{e}	4.5^{e}	3.03^{ef}	6.1^{c}	0.96^{f}	5.4^{f}	9.9^{e}	2.8^{e}
T2	10.45^{e}	0.74^{e}	12.6^{f}	3.3^{f}	2.6^{ef}	2.4^{f}	1.1d^{e}	14.8^{b}	9.97^{e}	3.8^{a}
T3	26.4^{b}	0.86^{bc}	20.2^{c}	4.9^{cd}	5.6^{b}	4.6^{d}	1.13^{d}	12.7^{d}	10.96^{d}	2.8^{d}
T4	30.7^{a}	0.98^{a}	22.7^{b}	5.53^{b}	4.5^{c}	3.12^{e}	1.1^{de}	11.13^{e}	10.4^{e}	2.38^{h}
T5	16.4^{d}	0.81^{cd}	18.2^{de}	5.02^{c}	3.43^{de}	2.6^{f}	1.05^{e}	11.54^{e}	7.6^{f}	3.11^{b}
T6	18.7^{cd}	0.77^{de}	16.6^{e}	5.4^{b}	4.1^{cd}	6.2^{c}	1.95^{b}	13.98^{c}	13.2^{b}	2.9^{c}
T7	19.91^{c}	0.91^{b}	19.01^{cd}	5.83^{a}	3.4^{de}	8.82^{b}	1.4^{c}	14.6^{bc}	12.3^{c}	2.6^{g}
T8	31.12^{a}	1.03^{a}	24.4^{a*}	6.01^{a}	8.2^{a*}	10.1^{a*}	2.3^{a*}	19.2^{a*}	14.9^{a*}	3.8^{a*}
T9	12.96^{e}	0.8^{d}	13.8^{f}	4.7^{de}	2.4^{f}	2.96^{e}	0.9^{f}	4.9^{f}	6.97^{f}	2.7^{f}
Mean	20.7	0.87	18.4	5.01	4.13	5.20	1.32	12.03	10.67	2.99
CV (%)	8.01	3.8	5.42	2.73	14.47	2.59	2.93	3.19	3.25	0.51
LSD (0.05)	ns	ns	*	ns	*	*	ns	*	**	*

CV: coefficient of variation, LSD: least significant difference. * And ** indicates significance level at $P < 0.05$ and $P < 0.01$, respectively. Ns: not significant. Different letters indicated a significant difference among treatments.

Table 8. The percentage of the concentration of the leaf element within treatments of the stress-watered block.

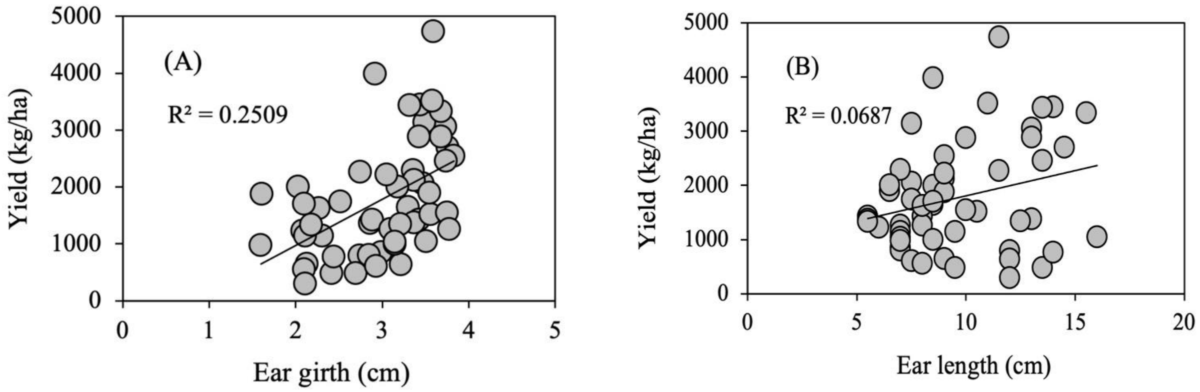
	Elements concentration in leaves (%)					Elements concentration in seeds (%)				
Treatment	N	P	K	Ca	mg	N	P	K	Ca	mg
T1	2.8^{d}	1.2^{c}	9.7^{d}	7.9^{c}	3.5^{c}	11.3^{d}	3.5^{f}	-12.2	9.75^{c}	-6.5
T2	0.18^{e}	0.9^{e}	5.9^{e}	4.4^{d}	3.4^{d}	10.5^{e}	3.5^{ef}	0.98	7.3^{g}	-2.2
T3	3.64^{c}	1.03^{d}	11.2^{b}	8.3^{b}	3.4^{e}	9.5^{f}	3.8^{d}	-15.3	12.9^{b}	-3.3
T4	3.6^{c}	1.2^{b}	10.07^{cd}	8.2^{b}	3.5^{b}	8.9^{g}	4.2^{b}	-20.7	12.5^{b}	-2.1
T5	-0.7	0.8^{g}	4.8^{g}	3.1^{e}	3.4^{d}	13.01^{b}	3.4^{g}	-4.3	9.1^{e}	-1.65
T6	-0.9	0.9^{f}	3.98^{h}	3.03^{e}	3.5^{b}	13.05^{b}	3.9^{c}	-10.7	12.5^{b}	-2.5
T7	3.9b	1.3^{a}	10.3^{c}	8.5^{b}	3.3^{f}	11.3^{d}	3.6^{e}	1.13	10.9^{c}	-2.5
T8	4.51^{a*}	1.3^{a}	12.3^{a*}	8.8^{a*}	3.6^{a*}	15.6^{a*}	4.5^{a*}	2.12^{a*}	18.8^{a*}	-1.52
T9	-0.23	0.8^{g}	5.24^{f}	2.9^{e}	3.2^{g}	12.6^{c}	3.2^{h}	-6.9	8.14^{f}	-2.1
Mean	1.87	1.05	8.2	6.13	3.42	11.74	3.73	-8.63	11.32	-2.7
CV (%)	3.64	2.18	2.67	2.78	0.5	0.7	1.48	-5.64	2.33	-3.7
LSD (0.05)	*	ns	*	*	*	*	**	*	*	ns

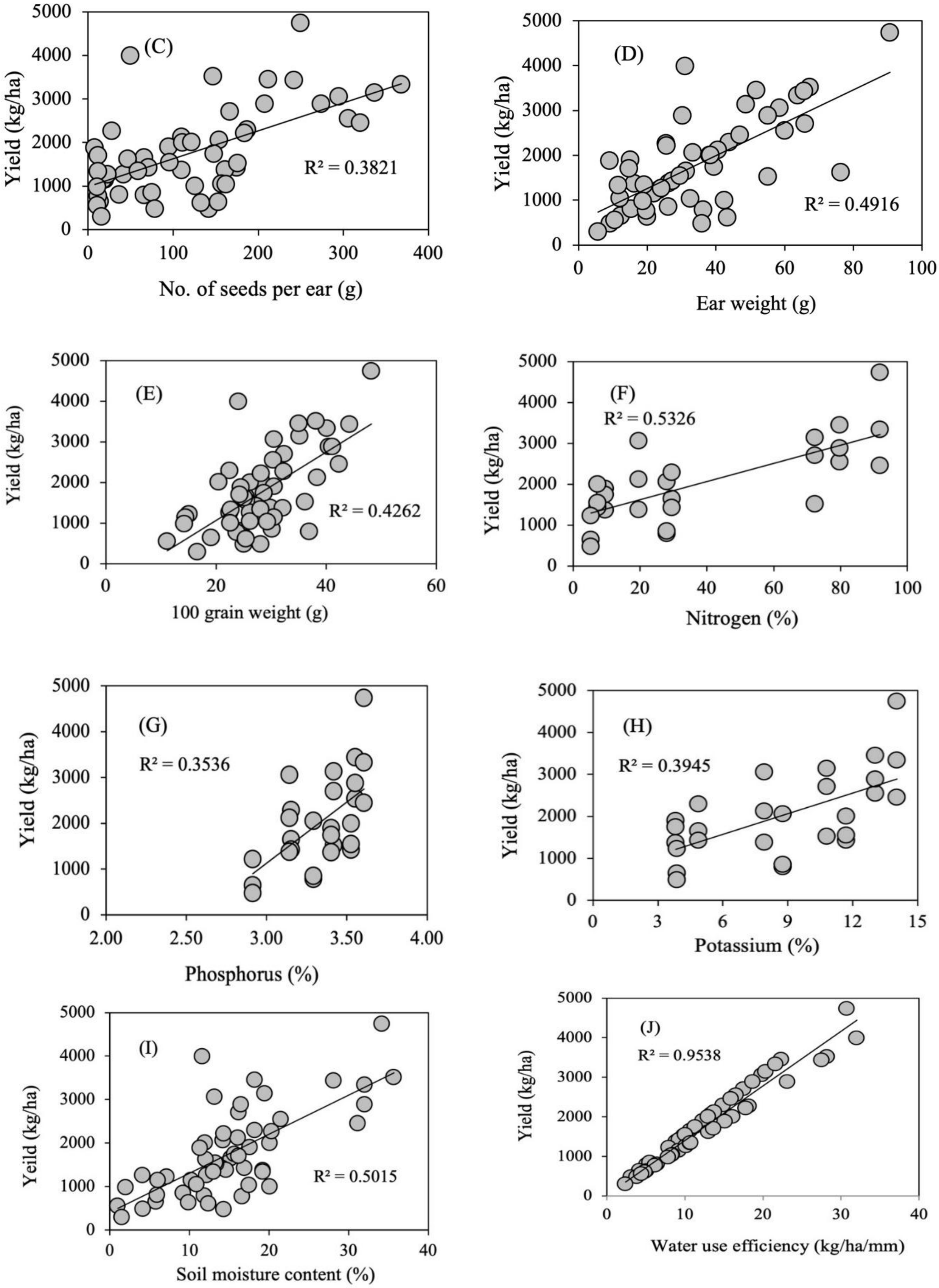
CV: coefficient of variation, LSD: least significant difference. * And ** indicates significance level at P < 0.05 and P < 0.01, respectively. Ns: not significant. Different letters indicated a significant difference among treatments.

Relationship of the Ears, WUE, NUE, SMC with yield

The relationship of phonological parameters such WUE, NUE, SMC, and ear related parameters measured. The results revealed that ear girth had positive relations (r^2=0.251) with yield as shown in Figure 2A, while ear length showed weak relationship (r^2=0.069) with yield under water-stressed conditions (Figure 2B).

A positive relationship observed between number of seeds per ear and ear weight with yield, while the r^2 value were 0.382 and 0.492, respectively (Figure 2C and D). Similar result observed for the correlation between the 100 grains weight with yield, which had strong positive correlation (r^2=0.426) as shown in Figure 2E. In term of phonological parameters such as soil moisture content, water use efficiency, and harvest index % have shown strong positive correlation with yield, while the relation strength were (r^2=0.865), (r2=0.954), and (r^2=0.502), respectively, as shown in Figure 2I, 2J, and 2K. In addition, there was positive relationship between NPK percentage and yield of maize under water-stressed conditions, as shown in Figure 2F, 2G, and 2I.




(C)
R² = 0.3821
Yield (kg/ha)
No. of seeds per ear (g)
(D)
R² = 0.4916
Yield (kg/ha)
Ear weight (g)
(E)
R² = 0.4262
Yield (kg/ha)
100 grain weight (g)
(F)
R² = 0.5326
Yield (kg/ha)
Nitrogen (%)
(G)
R² = 0.3536
Yield (kg/ha)
Phosphorus (%)
(H)
R² = 0.3945
Yield (kg/ha)
Potassium (%)
(I)
R² = 0.5015
Yeild (kg/ha)
Soil moisture content (%)
(J)
R² = 0.9538
Yield (kg/ha)
Water use efficiency (kg/ha/mm)

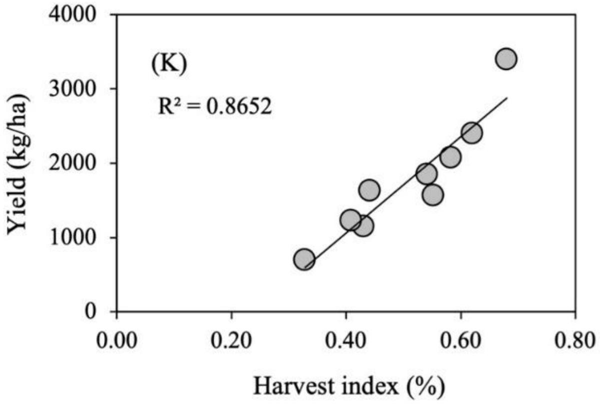


Figure 2. These collections of sub-figures shows the relationship of different parameters with the yield of maize under stress-water conditions. **A:** relationship of ear girth (cm) with yield, **B:** relationship of ear length (cm) with yield, **C:** relationship of the number of seeds per ear (g) with yield, **D:** relationship of ear length (cm) with yield, **E:** relationship of 100-grain weight (g) with yield, **F:** relationship of nitrogen % with yield, **G:** relationship of phosphorous % with yield, **H:** relationship of potassium with yield, **I:** relationship of soil moisture content % with yield, **J:** relationship of water use efficiency (kg/ha/mm), and **K:** relationship of harvest index % with yield.

DISCUSSION

Improvement in nutrient use efficiency cannot possibly be viewed only by fertilizers management. It will be governed due to the soil moisture contents and soil solution, while water stress limits soil nutrient use efficiency (Bossio et al., 2008). However, water cannot fulfill the plant's requirements alone; balancing applying the chemical and organic fertilizers with proper soil moisture contents increases nutrient and water use efficiency in terms of soil fertility and productivity, ultimately increasing grain yield (Ryan et al., 2009). In maize, vegetative and reproductive growth stages are the sensible stages. Drought stress at the flowering stage caused the ear and silk reduction, resultantly extending the gap between silking and anthesis (Jaleel et al., 2009; Sarobol.E.et al., 2004).

Nilson and Orcutt, (1996) stated that the effect of the drought stress one week before silking (R_2 --- R_4) decreased the grain yield by 53%, compared to non-drought threatened plants. Maize crop needs 50%– 70% soil moisture to maintain their normal physiological activities. The cereal productions rarely exceed 1.5 t/ha even when an ample number of fertilizers are used in drought-affected areas in developing countries, while in case of sufficient water of irrigation leads, the yield amount exceeds 8 t/ha (Thompson, 2012). So a strong positive correlation exists between WUE, NUE, and crop yield production (Lucas et al., 2007). Therefore, this study revealed that the use of chemical fertilizers within the combination of SAPs enhanced the water holding capacity, particularly water, nutrients use efficiencies, and maize yield. The current study elucidates that applying SAPs regularly increased water holding capacity and soil moisture content by 40 to 60% at water deficit conditions, prolonging the wilting period from 6 to 12 days and water holding capacity from 171 to 402%.

During the reproductive growth stage (silking & pollen shed), drought reduced corn yield from 3 to 8% per day (Lauer, 2007). However, after two weeks, the mentioned stages of severe drought downed the yield by 6% per day (khalili et al., 2013). Drought stress negatively affected corn growth and yield, including reduced assimilate partitioning, decreased photosynthesis, and changes in protein abundance (Fahad et al., 2017). Bahamin et al., (2021) stated that drought could decrease nitrogen uptake from soil and reduce the N concentration in corn crop tissues. Drought reduced N concentration by 44-51% and P by 39-48% in drought-sensitive stages revealed by (Bista et al., 2018). However, drought at initial and severe times reduced N & P uptake rates by 46-72% and 54-80%, respectively (Tarighaleslami et al., 2012). (Alam, 1999) Investigated that drought reduced root development which caused limited nutrient uptake, especially N, P, and K. Dry and irregular soil moisture caused insufficient nutrient uptake. Based on the experiment result, nutrients uptake levels improved in the root, stem, leaf, and seeds for N (27.3, 7.12, 4.93, and 14.4%), P (1, 2.1, 1.32, and 3.6%), and K (9, 14.6, 13.22, and 3.4%) due to the application of SAPs in T_8 incorporated of the recommended dose of fertilizer of NPK. SAPs improved the soil moisture content, root better uptake level, and enough soil moisture and nutrient availability.

Applying SAPs increased water productivity by 12.8 to 17.2% (Abdullah et al., 2021). SAPs also increased relative water content, leaf water potential recorded higher in corn treated by SAPs, and increased biomass accumulation by 11.1, 39.0, and 98.7% at proper, moderate, and deficit irrigation, respectively (Zheng et al.,2023). Combine application of SAPs with cow manure increased N-uptake, CEC, and SMC in corn fields stated by (Khadem et al., 2010). (Singh et al., 2018) suggested that 15% of SAPs concentration increased 26.5% yield of corn over the control. A similar study (Krasnopeeva et al., 2022) revealed that 100 kg of SAPs ha^{-1} was the most appropriate rate, increasing corn yield and dry matter yield. The results of the current study revealed the water use efficiency of 24.53 kg ha^{-1} mm^{-1} and HI% (0.68) again in T_8 to declare that using SAPs in crops field during drought conditions could enhance vegetative and reproductive growth. Lastly, the corn crop yield applied 13 gr per pot based on the calculation 325 kg ha^{-1}, as literature revealed SAPs resulted based on their concentration rather than their types.

Asiimve et al., (2023) reported that SAPs incorporated with organic and inorganic fertilizers increased soil fertility and productivity. While 70% evaporated stress reduced 22% and 7% corn yield and soil moisture content (Wei et al., 2018). The cereal productions rarely exceed 1.5 t/ha even when ample amount of fertilizers are used in drought-affected areas in developing countries. In contrast, in case of sufficient water from irrigation leads, the yield amount exceeds 5 t/ha (Thompson, 2012). However, the number of rows, kernels row^{-1}, and overall seed per ear were recorded at 14, 20, and 250-300 without SAPs plots or stressed corn fields (Strachan, 2004).

This experiment's findings elucidated that applying SAPs enhanced the soil moisture content from 25% to 50%, while in control, recorded less than 20%. The proper soil moisture content with other extreme parameters improved by SAPs under the water deficit condition maximized the ear length (13 cm), the number of rows in one ear or cob was recorded from 16 to 18, number of kernels in one row was recorded from 25 to 30, and overall seeds per ear were 350 to 400, 100 seed weight 42.1 gr and finally yield per ha recorded 3390 kg in T_8 (SAPs + NPK). However, only NPK treatment in T_4 produced 2074 kg ha^{-1}. Several experiments were conducted to investigate the impact of Super Absorbent Polymers only and in combination with organic and inorganic fertilizers on soil physical and chemical properties. The results demonstrated significant enhancements in soil moisture content, water holding capacity, water retention power, leaching, percolation, and reduced surface runoff. These practices collectively stimulated corn root growth and improved nutrient uptake levels, leading to improved corn production parameters and ultimately increasing the yield of corn under drought conditions.

CONCLUSION

Using super absorbent polymers (SAPs) combined with manure and fertilizers showed significant improvements in maize growth and productivity. The integrated application of NPK fertilizers and SAPs resulted in higher values for ear-related parameters compared to other treatments. Additionally, it is exhibited the highest yield under both well-watered and water-stressed conditions. The application of SAPs contributed to improved soil moisture content, water use efficiency, and harvest index. Furthermore, SAPs positively influenced the concentration of essential elements in different plant parts. These findings emphasize the potential of SAPs in enhancing crop performance, particularly in water-limited environments.

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