



RESEARCH ARTICLE

Physiological and yield responses of sweet corn (*Zea mays* L. *saccharata*) to growth enhancers under water stress conditions

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Abstract

Certain growth enhancers can mitigate the effects of drought stress and damage on sweet corn (*Zea mays* L. *saccharata*). For this purpose, a field experiment was conducted to investigate the effect of several enhancers on the physiological characteristics, growth and yield of sweet corn under drought and saline soil conditions in a tropical region over 2 years. The factors included irrigation at 50, 65 and 80 % of the crop-available water content in the soil (no drought stress, mild drought stress and severe drought stress respectively) and growth promoters (control, superabsorbent A200 (SA200), polyacrylamide (PAM), humic acid (HA), smoke water (SW), salicylic acid (SA) and potassium silicate (PS). The experiment was designed as a split-plot in base on a randomised complete block design. The 2 year results showed that growth-enhancing treatments had positive and significant effects on superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), proline, SPAD, root dry weight, relative growth rate (RGR), crop growth rate (CGR), biomass and cob yield under moderate and severe drought stress conditions. The effect of growth promoters on cob yield in conditions control, moderate and severe stress were between 9.45-12.5, 8.43-10.77 and 7.6-9.51 t ha⁻¹ respectively. In general, SA200 is recommended for soil application, HA into irrigation system and SA for foliar application, to alleviate drought stress in sweet corn. So, these growth enhancers can be suggested as reducing the effect of drought stress for hot conditions and salty soil in the region.

Keywords: antioxidants; drought mitigation; humic acid; polyacrylamide; potassium silicate; salicylic acid; saline soil; smoke water; superabsorbent

Introduction

When the kernels of sweet corn (*Zea mays* group. *saccharata*) are soft and high in sugar, they are harvested during the milky stage. Sweet corn kernels retain their sweetness and excellent nutritional value because the sugar in their endosperm does not spontaneously turn into starch throughout the milky stage (1, 2). Sweet corn yields well in warm climates with plenty of water, although it is frequently linked to water scarcity and drought stress in hot climates. (3–6). In these conditions, leaf cells lose their turgor. Photosynthesis, absorption and transport of nutrients from the roots and gas exchange are impaired and growth slows down, ultimately reducing plant performance. Long-term stress may cause irreparable damage (7, 8). The effects of water stress on corn, when combined with sensitive growth stages such as tasselling, silking and pollination, can cause up to 50 % yield losses and the damage is significant even in drought-tolerant varieties (6).

Various growth promoters have been evaluated to mitigate the impacts of drought. Superabsorbent (SA200) and polyacrylamide (PAM) are types of polymers capable of retaining water significantly more than their weight (up to 200 times) and then slowly delivering it to the plant roots. These polymers are commonly utilized in arid regions and during periods of drought stress and research indicates they enhance crop growth and yield (9–11).

Smoke water, which is obtained from the smoke produced by burning plant materials, is used to strengthen and stimulate growth. Water smoke is composed of various compounds, such as karrikinolides, amines, acids, alcohols, phenols and other elements that facilitate growth (12, 13). Salicylic acid, when used as a foliar spray in small amounts, can help to stabilise membranes, boost photosynthesis and enhance antioxidant responses, ultimately leading to better corn performance during periods of water shortage (14, 15). Potassium silicate acts as a growth enhancer by supplying silicon and potassium, which help to fortify cell walls, manage stomatal function and boost water use efficiency. Studies have indicated that its application has diminished oxidative damage and enhanced crop yield under stress conditions in the field (16). Humic acid, a plant biostimulant derived from organic materials, is utilised as both a foliar spray and a soil application, containing various nutrient compounds, including nitrogen (17, 18). The application of humic acid during periods of drought stress has led to an increase in hormones, chlorophyll, antioxidants, cell membrane stability and the effectiveness of nutrient absorption (19, 20).

Therefore, this study aimed to compare the efficacy of 6 growth enhancers superabsorbent polymers, polyacrylamide, smoke water, salicylic acid, potassium silicate and humic acid during summer cultivation in a tropical area with saline soil on various

physiological traits, growth and yield of sweet corn. We hypothesised that the application of growth enhancers under dry conditions, by increasing the activity of antioxidant enzymes, proline, photosynthetic pigments and root growth, leads to increased drought resistance and consequently enhances cob yield and biomass yield. No study with this experimental combination has been conducted in the mentioned regions so far; therefore, this subject can be considered an innovative aspect of this research.

Materials and Methods

Study site

This study took place at the Al-Mouradia Research Station's farm, which is part of the Ministry of Agriculture in Babylon, Iraq, located at a longitude of 44°39' E and latitude of 32°3' N, during the years 2022 and 2023. The climatic and soil conditions of the region throughout the sweet corn cultivation period for both years are presented (Table 1, 2).

Experimental design and factors

The split-plot experiment was carried out in a randomised complete block design (RCBD) with three replications over 2 years. The factors involved different levels of drought stress (irrigating at 50 (control), 65 (moderate stress) and 80 % (severe stress) depletion of the crop-available water in the soil) implemented via a drip irrigation system in the main plots, alongside plant growth enhancers in the subplots, which included a control, superabsorbent A200 at 100 kg ha⁻¹, Polyacrylamide polymer at 100 kg ha⁻¹, smoke water at 1 L ha⁻¹ (21), salicylic acid at 0.5 mmol l⁻¹, potassium silicate at 3 mL l⁻¹ and humic acid at 300 mL l⁻¹ (22). Superabsorbent A200 and Polyacrylamide were mixed with the soil before planting (soil depth 10 cm), humic acid was also used by irrigation system at 5-leaf stage and the others were used as foliar sprays (500 L ha⁻¹ of water). Smoke water, potassium silicate and salicylic acid were foliar sprayed twice at the 5 and 9-leaf stages. Foliar spraying was done early in the morning on all vegetative parts of the plant.

The scheduling for irrigation timing and moisture treatments was established using soil texture and the standard method (23), along with soil sampling from a depth of 30 cm and allowing it to dry. The space separating the primary plots and blocks was 2 m, while there was a one-meter gap between the subplots. The sweet corn was grown from the Roi Soleal variety. Fertiliser was applied at a rate of 200 kg per ha based on the soil analysis (N-P-K, 20-20-20) (24). Sowing of the seeds took place over 2 years on August 15 in areas featuring a row distance of 60 cm and a spacing of 20 cm between

seeds, with irrigation occurring on the same day. After 20 days of germination, the plants were thinned to 10 plants/sq m.

Smoke water preparation

To prepare smoke water, 5 kg of dry plant material, consisting of a mixture of 2.5 kg of alfalfa aerial parts (*Medicago sativa*) and 2.5 kg of wheat straw and stubble (*Triticum aestivum*), was burned over a period of 5 hr. The smoke resulting from the combustion was produced in a controlled chamber and passed through one litre of distilled water using a suction device. The produced smoke water was brick red in colour with a pH = 5.5. Finally, this solution was diluted with water at a ratio of 1:500 and sprayed (21).

Measuring traits

Antioxidant enzymes

During the milking phase of sweet corn, leaf samples were collected and catalase activity was assessed following the standard method (25). The measurement of superoxide dismutase was conducted (26), while peroxidase activity was evaluated according to another approach (27).

Leaf proline content

During the milky stage, leaves were collected and the proline content was measured following standard method (28).

Leaf chlorophyll index (SPAD)

During the last leaf milking process, a minimum of 5 samples were collected and averaged from each plot using a SPAD meter (manufactured by Minolta, Japan) (29).

Root dry weight

At the physiological maturity stage, the dry weight of the roots from 3 separate plants was recorded. The roots from each plant were obtained using a specialised root drill (a hollow cylinder with a diameter of 20 cm and a depth of 40 cm) and after being soaked in water for 24 hr, they were rinsed under water pressure using a fine-mesh sieve (to reduce the loss of fine roots). The collected roots were then cleaned and dried for 48 hr at a temperature of 65 °C before being weighed (30).

Crop growth rate (CGR) and relative growth rate (RGR)

The crop growth rate (CGR) and relative growth rate (RGR) were determined (31).

$$\text{CGR (g g}^{-1} \text{ day}^{-1}) = (1/\text{SA}) \times [(W_2 - W_1) / (T_2 - T_1)]$$

$$\text{RGR (g m}^{-2} \text{ day}^{-1}) = (\text{Ln}W_2 - \text{Ln}W_1) / (T_2 - T_1)$$

Where, SA= soil area, W₁ and W₂ are plant dry weights at times T₁ and T₂.

Table 1. Weather conditions in the area throughout the sweet corn growing season over two years

Year	2022				2023			
Parameters	T. max	T. min	T. average	Rainfall	T. max	T. min	T. average	Rainfall
Month	(°C)	(°C)	(°C)	(mm)	(°C)	(°C)	(°C)	(mm)
July	45.19	25.57	35.38	9.10	47.50	25.64	36.57	8.68
August	46.06	28.34	37.20	8.23	48.02	26.97	37.49	7.98
September	43.07	23.57	33.32	7.78	44.31	22.86	33.58	6.40
October	38.37	18.08	28.22	4.99	36.10	18.77	27.43	4.34
November	27.49	11.89	19.69	2.77	27.16	12.98	20.07	2.82
December	21.04	7.83	14.43	1.76	22.54	8.91	15.72	1.93

T: temperature; Data from Ministry of Agriculture, Agricultural Meteorology Center, Babylon Governorate, Al-Kifl Station.

Table 2. Some chemical and physical properties of field soil (average of 2 years)

EC	pH	BD	P	K	N	OM	Sand	Silt	Clay	Soil Texture
(ds m ⁻¹)		(g cm ⁻³)	(mg kg ⁻¹)	(mg kg ⁻¹)			(%)			
6.8	7.4	1.3	8.4	200	0.0043	1.1	55	18	27	Sand Clay Loam

EC: electrical conductivity; BD: bulk density; OM: organic matter

Biomass yield and cob yield

During the harvest period of sweet corn, specifically at the beginning of the dough stage, samples of the plants were collected and the total dry weight of the entire plant, including the cobs and their husks, was measured and recorded as the economic yield (32).

Statistical analysis

The analysis of data was conducted with GenStat 12 statistical software and mean values were compared using the least significant difference (LSD) test at a 5 % significance level.

Results and Discussion

Antioxidant enzymes activities

The impact of drought stress, growth enhancers and interaction between them on of SOD, POD and CAT enzymes in the leaves during the milking stage of sweet corn was significant during 2022 and 2023 (Tables 3, 4).

The mean of the main effects for drought stress during 2 years showed that with increasing drought stress intensity, the activity of SOD, POD and CAT enzymes increased. The values of antioxidant activity increase were different, such that under severe drought stress, the rate of increase in SOD activity was higher than that of POD and CAT. In the control, as well as in the moderate and severe drought stress treatments, average 2-year measurements for SOD were 41.7, 60.9 and 74.7-unit mg^{-1} protein respectively, while POD values were 47.4, 54.0 and 70.1-unit mg^{-1} protein respectively and CAT levels measured 40.8, 51.7 and 60.7-unit mg^{-1} protein, respectively. Interaction means showed that, a notable increase in SOD, POD and CAT levels compared to the control under drought stress conditions (Table 3, 4). Despite the absence of a notable difference among the growth enhancers, the impact of SA200, SA

and HA treatments was more pronounced compared to the other treatments, whereas SW exhibited the least effect. Furthermore, the influence of growth promoters varied across different stress levels (Tables 3, 4).

Proline

In this study, the impact of drought stress, growth promoters and interaction between them on the proline levels in leaves during the milking stage of sweet corn was significantly noteworthy (Table 4). The mean of the main effects for drought stress during two years showed that the level of proline rose with the increase in drought severity. In this base, over 2 years, the average proline levels under normal irrigation, moderate and severe drought stress were found to be 41.4, 56.0 and 66.2 $\text{mg } 100 \text{ g}^{-1}$ of fresh leaf weight respectively. The proline levels in the growth promoter treatments were significantly different from the control treatment; however, there were no significant differences among them under any level of drought stress. In the treatment with severe drought stress, the proline level in the HA treatment was greater than in the other treatments (Table 4).

Chlorophyll index (SPAD)

Table 5 indicated that the impact of drought stress, growth enhancers and interaction between them on the chlorophyll index (SPAD) in sweet corn was significant over 2 years (Table 5). The mean of the main effects for drought stress showed that the average chlorophyll index over the 2 years for no drought stress, moderate drought stress and severe drought stress was recorded at 40.8, 35.6 and 34.2 respectively. This means that, on average over 2 years, moderate drought stress led to a reduction of 12.7 % and severe drought stress resulted in a 16.1 % reduction compared to the control treatment. The application of growth promoters increased the chlorophyll index at each drought stress level compared to the control treatment. In conditions with no drought stress, there was no

Table 3. Interaction of water stress (WS) and growth enhancers (GE) on superoxide dismutase (SOD) and peroxidases (POD) activities of sweet corn during 2022 and 2023 and *p*-values

Water stress (WS)	Growth enhancers (GE)	SOD (unit mg^{-1} protein)			POD (unit mg^{-1} protein)		
		2022	2023	Mean	2022	2023	Mean
Control	Control	27.6 ^h	27.6 ⁱ	27.6	41.4 ⁱ	42.2 ⁱ	41.8
	Superab. A200 (SA200)	39.0 ^{fg}	51.2 ^g	45.1	52.3 ⁱ	46.8 ^{gh}	49.5
	Polyacrylamide (PAM)	38.9 ^{fg}	46.4 ^h	42.6	50.1 ⁱ	43.0 ⁱ	46.5
	Smoke water (SW)	38.2 ^g	46.7 ^h	42.4	50.2 ⁱ	45.7 ^{ghi}	47.9
	Salicylic acid (SA)	42.1 ^f	47.2 ^{gh}	44.6	52.4 ⁱ	47.5 ^{fg}	49.9
	Potassium silicate (PS)	40.5 ^{fg}	50.2 ^{gh}	45.3	50.7 ⁱ	43.3 ^{hi}	47.0
Moderate	Humic acid (HA)	40.4 ^{fg}	48.4 ^{gh}	44.4	50.6 ⁱ	47.9 ^{efg}	49.2
	Control	54.2 ^e	55.6 ^f	54.9	56.7 ^{gh}	51.4 ^e	54.0
	Superab. A200 (SA200)	65.3 ^{cd}	58.3 ^{ef}	61.8	63.3 ^{ef}	47.5 ^{fg}	55.4
	Polyacrylamide (PAM)	64.6 ^d	61.4 ^{de}	63.0	53.6 ^{hi}	50.6 ^{ef}	52.1
	Smoke water (SW)	64.1 ^d	60.9 ^{de}	62.5	59.6 ^{fg}	45.5 ^{ghi}	52.5
	Salicylic acid (SA)	61.7 ^d	63.8 ^d	62.7	60.7 ^f	47.9 ^{efg}	54.3
Severe	Potassium silicate (PS)	62.1 ^d	58.3 ^{ef}	60.2	60.0 ^{fg}	51.3 ^e	55.6
	Humic acid (HA)	62.0 ^d	60.9 ^{de}	61.4	61.7 ^f	46.9 ^{gh}	54.3
	Control	68.8 ^c	61.1 ^{de}	64.9	67.0 ^{de}	58.3 ^d	62.6
	Superab. A200 (SA200)	78.2 ^{ab}	77.3 ^a	77.7	71.5 ^{bc}	71.6 ^{ab}	71.5
	Polyacrylamide (PAM)	76.9 ^b	72.6 ^{bc}	74.7	76.6 ^a	65.4 ^c	71.0
	Smoke water (SW)	77.0 ^b	69.5 ^c	73.2	73.3 ^{abc}	69.0 ^{bc}	71.1
LSD (0.05)	Salicylic acid (SA)	81.4 ^a	75.9 ^{ab}	78.6	76.9 ^{cd}	69.0 ^{bc}	72.9
	Potassium silicate (PS)	77.2 ^b	72.5 ^{bc}	74.8	74.8 ^{ab}	66.5 ^c	70.6
	Humic acid (HA)	82.0 ^a	76.8 ^{ab}	79.4	70.4 ^{cd}	73.3 ^a	71.3
Treatments		3.86	4.32	-	3.76	3.65	-
p-value of the main effects and their interactions							
Water stress (WS)		$p \leq 0.01$	$p \leq 0.01$		$p \leq 0.01$	$p \leq 0.01$	
Growth enhancers (GE)		$p \leq 0.01$	$p \leq 0.01$		$p \leq 0.01$	$p \leq 0.01$	
WS $\times$ GE		$p \leq 0.05$	$p \leq 0.01$		$p \leq 0.05$	$p \leq 0.01$	

Superab. A200 (superabsorbent A200); $p \geq 0.05$, $p \leq 0.05$ and $p \leq 0.01$ are non-significant, significant at 5 and 1 % probability respectively. Means followed by a common letter are not significantly different at $p < 0.05$ according to the LSD test.

Table 4. Interaction of water stress (WS) and growth enhancers (GE) on catalase (CAT) and proline of sweet corn during 2022 and 2023 and *p*-values

Water Stress (WS)	Growth enhancers (GE)	CAT (unit mg ⁻¹ protein)			Proline (mg 100 g ⁻¹ FW)		
		2022	2023	Mean	2022	2023	Mean
Control	Control	30.1 ^h	47.6 ^{hi}	38.8	33.8 ^k	40.0 ^g	36.9
	Superab. A200 (SA200)	41.0 ^g	42.5 ^{jk}	41.7	44.6 ^j	39.9 ^g	42.2
	Polyacrylamide (PAM)	38.7 ^h	42.8 ^{jk}	40.7	43.1 ^j	42.5 ^g	42.8
	Smoke water (SW)	38.8 ^g	40.3 ^k	39.5	42.5 ^j	44.4 ^g	43.4
	Salicylic acid (SA)	41.0 ^g	42.7 ^{jk}	41.8	44.7 ^j	40.8 ^g	42.7
	Potassium silicate (PS)	39.4 ^g	43.5 ^{ijk}	41.4	44.9 ^j	44.7 ^g	44.8
	Humic acid (HA)	41.3 ^g	43.1 ^{jk}	42.2	42.4 ^j	32.7 ^h	37.5
Moderate	Control	45.9 ^f	45.8 ^{gh}	45.3	51.4 ⁱ	57.8 ^{def}	54.6
	Superab. A200 (SA200)	52.5 ^{de}	50.8 ^{def}	51.6	57.9 ^{gh}	53.3 ^f	55.6
	Polyacrylamide (PAM)	50.8 ^{de}	55.6 ^{cd}	53.2	59.7 ^{fg}	57.9 ^{def}	58.8
	Smoke water (SW)	48.8 ^{ef}	57.8 ^{cde}	53.3	54.2 ^{hi}	56.3 ^{ef}	55.2
	Salicylic acid (SA)	49.9 ^e	57.1 ^{fg}	53.5	55.4 ^h	53.1 ^f	54.2
	Potassium silicate (PS)	54.2 ^d	52.0 ^{efg}	53.1	56.4 ^{gh}	62.6 ^{bcd}	59.5
	Humic acid (HA)	50.9 ^{de}	53.3 ^{gh}	52.1	56.3 ^{gh}	53.0 ^f	54.6
Severe	Control	54.0 ^d	50.9 ^{bc}	52.4	62.4 ^{ef}	61.0 ^{bcd}	61.7
	Superab. A200 (SA200)	64.1 ^{ab}	61.1 ^a	62.6	72.5 ^{ab}	66.3 ^{bcd}	69.4
	Polyacrylamide (PAM)	59.6 ^c	65.9 ^{cde}	62.7	65.2 ^{de}	60.7 ^{cde}	62.9
	Smoke water (SW)	58.3 ^c	56.9 ^{ab}	57.6	66.7 ^{cd}	60.1 ^{cde}	63.4
	Salicylic acid (SA)	60.9 ^{bc}	62.6 ^{ab}	61.7	74.7 ^a	64.4 ^{bc}	69.5
	Potassium silicate (PS)	61.8 ^{bc}	63.8 ^{ab}	62.8	69.2 ^{bc}	63.5 ^{bc}	66.3
	Humic acid (HA)	66.4 ^a	63.8 ^{ab}	65.1	67.9 ^{cd}	72.6 ^a	70.2
LSD (0.05)		3.74	4.63	-	3.77	6.61	-
Treatments		<i>p</i> -value of the main effects and their interactions					
Water stress (WS)		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01	
Growth enhancers (GE)		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01	
WS × GE		<i>p</i> ≤ 0.05	<i>p</i> ≤ 0.01		<i>p</i> ≤ 0.05	<i>p</i> ≤ 0.01	

Superab. A200 (superabsorbent A200); $p \geq 0.05$, $p \leq 0.05$ and $p \leq 0.01$ are non-significant, significant at 5 and 1 % probability respectively. Means followed by a common letter are not significantly different at $p < 0.05$ according to the LSD test.

significant difference between growth enhancer treatments and the control; however, the most pronounced changes in chlorophyll index among the growth enhancer treatments were observed under moderate and severe drought stress conditions (Table 5).

Root dry weight

The root dry weight of sweet corn at the physiological maturity stage was influenced by drought stress, growth enhancers and interaction between them over 2 years (Table 5). Under no drought, moderate

Table 5. Interaction of water stress (WS) and growth enhancers (GE) on chlorophyll index (SPAD) and root dry weight of sweet corn during 2022 and 2023 and *p*-values

Water stress (WS)	Growth enhancers (GE)	Chlorophyll index (SPAD)			Root dry weight (g plant ⁻¹)		
		2022	2023	Mean	2022	2023	Mean
Control	Control	40.7 ^c	39.6 ^{bc}	40.1	20.38 ^{abc}	20.94 ^{ab}	20.66
	Superab. A200 (SA200)	40.8 ^{bc}	40.2 ^b	40.5	19.68 ^{abcd}	20.23 ^{abc}	19.95
	Polyacrylamide (PAM)	41.3 ^{bc}	40.2 ^b	40.7	19.28 ^{bcd}	20.20 ^{abc}	19.74
	Smoke water (SW)	42.9 ^{ab}	42.9 ^a	42.9	19.38 ^{bcd}	20.31 ^{abc}	19.84
	Salicylic acid (SA)	42.1 ^{abc}	38.7 ^{bc}	40.4	20.92 ^{ab}	22.14 ^a	21.53
	Potassium silicate (PS)	43.7 ^a	40.2 ^b	41.9	20.45 ^{abc}	22.04 ^a	21.24
	Humic acid (HA)	41.5 ^{bc}	37.8 ^{cd}	39.6	21.52 ^a	22.27 ^a	21.89
Moderate	Control	35.0 ^{gh}	31.5 ^j	33.2	16.42 ^{fg}	17.69 ^{def}	17.05
	Superab. A200 (SA200)	38.4 ^d	35.9 ^{def}	37.1	18.68 ^{cde}	19.62 ^{bcd}	19.15
	Polyacrylamide (PAM)	36.9 ^{def}	36.3 ^{de}	36.6	18.82 ^{cde}	18.53 ^{cde}	18.67
	Smoke water (SW)	37.3 ^{de}	35.5 ^{efg}	36.4	18.42 ^{cdef}	19.11 ^{bcde}	18.76
	Salicylic acid (SA)	36.4 ^{defg}	34.8 ^{efghi}	35.6	18.15 ^{def}	19.20 ^{bcde}	18.67
	Potassium silicate (PS)	37.1 ^{def}	35.6 ^{efg}	36.3	17.18 ^{ef}	18.35 ^{cde}	17.76
	Humic acid (HA)	36.0 ^{efg}	33.1 ^{ij}	34.5	17.08 ^{ef}	18.24 ^{cde}	17.66
Severe	Control	30.4 ⁱ	33.5 ^{hi}	31.9	11.58 ⁱ	13.52 ^h	12.55
	Superab. A200 (SA200)	34.5 ^{gh}	35.2 ^{efghi}	34.8	14.62 ^{gh}	17.07 ^{efg}	15.84
	Polyacrylamide (PAM)	35.8 ^{efg}	33.8 ^{ghi}	34.8	14.35 ^{gh}	15.55 ^{fgh}	14.95
	Smoke water (SW)	35.1 ^{gh}	34.3 ^{fghi}	34.7	12.85 ^{hi}	14.68 ^h	13.76
	Salicylic acid (SA)	34.3 ^{gh}	33.4 ^{hij}	33.8	14.38 ^{gh}	15.08 ^{gh}	14.73
	Potassium silicate (PS)	33.2 ^h	35.1 ^{efgh}	34.1	13.98 ^h	15.63 ^{fgh}	14.80
	Humic acid (HA)	35.5 ^{efg}	36.3 ^{de}	35.9	14.08 ^h	15.74 ^{fgh}	14.91
LSD (0.05)		2.19	1.90	-	2.08	2.32	-
Treatments		<i>p</i> -value of the main effects and their interactions					
Water stress (WS)		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01	
Growth enhancers (GE)		<i>p</i> ≤ 0.01	<i>p</i> ≤ 0.01		<i>p</i> ≤ 0.05	<i>p</i> ≤ 0.05	
WS × GE		<i>p</i> ≤ 0.05	<i>p</i> ≤ 0.05		<i>p</i> ≤ 0.05	<i>p</i> ≤ 0.05	

Superab. A200 (superabsorbent A200); $p \geq 0.05$, $p \leq 0.05$ and $p \leq 0.01$ are non-significant, significant at 5 and 1 % probability respectively. Means followed by a common letter are not significantly different at $p < 0.05$ according to the LSD test.

drought and severe drought conditions, the average root dry weight was 20.69, 18.24 and 14.50 g plant⁻¹ respectively (The mean of the main effects). As a result, moderate and severe drought stress led to reductions in root dry weight of 11.8 % and 29.9 % respectively, when compared to the control treatment. The root dry weight was higher in the severe drought stress and SA200 treatments (interaction means), showing a 26.5 % increase relative to the control treatment (2-year mean), while the other growth enhancer treatments during moderate drought stress and no drought stress did not show significant differences from the control (Table 5).

Relative growth rate (RGR) and crop growth rate (CGR)

The impact of drought stress on the RGR and CGR of sweet corn over 2 years was significant, whereas the influence of growth promoters and interaction between them was found to be insignificant (Table 6). The treatments for moderate and severe drought stress led to a reduction in the 2-year average RGR by 13.5 and 30.5 % respectively (Fig. 1A) and a decline in CGR by 18.2 and 29.4 % respectively (Fig. 1B), when compared to the control treatment.

Biomass and cob yield

The biomass and cob yield of sweet corn at the early dough stage of the kernels (the optimal time for harvesting sweet corn) were significantly influenced by drought conditions, the application of growth enhancers and interaction between them (Table 6). The mean of the main effects for drought stress over a 2-year period, showed that the average biomass for the treatments experiencing no drought stress, moderate drought stress and severe drought stress was 22.56, 20.41 and 17.25 t ha⁻¹ respectively, while the cob yield averaged 10.64, 9.50 and 8.46 t ha⁻¹ for the same conditions.

Interaction means showed that, across all drought stress levels, there was a significant difference in biomass between the treatments using growth promoters and the control treatment. The treatments without drought stress yielded the highest biomass, followed by those with moderate and severe drought stress (Fig. 2).

In this experiment, the most impactful growth enhancers on cob yield or economic yield (2-year mean) were SA200 and HA under moderate and no drought stress conditions when compared to the control, along with SA200 treatment during severe drought stress conditions (Fig. 3).

In this study, the activities of the antioxidant enzymes SOD, CAT and POD increased with the intensity of drought stress (Tables 3, 4). The distinction among the growth-promoting treatments was more pronounced under severe stress, with HA and SA treatments (2-year mean) showing greater increases compared to the others. Nonetheless, no significant differences were noted among the growth enhancers under conditions of moderate drought stress and normal settings (Tables 3, 4). Drought stress can interfere with the electron transport chain in both the chloroplasts and mitochondria of plants. In such situations, molecular oxygen starts to form, leading to the production of hydroxyl, superoxide and hydrogen peroxide radicals, which are potent oxidants that can harm the plant. Under these circumstances, plants generate antioxidants like superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), which are substances that neutralize reactive oxygen species (ROS) and prevent cellular damage (33). The level of antioxidant activity differs among species and is influenced by various treatments (34). Humic acid serves as a natural biostimulant that enhances enzyme activity and bolsters the defence mechanisms of plants. In addition to this direct enhancement of metabolism, humic acid also improves soil quality, aids in nutrient absorption and exhibits hormone-like effects, all of which lead to increased resistance against oxidative stress during drought conditions (35). One study demonstrated that the application of humic acid under drought stress led to a rise in antioxidant levels in corn compared to the control group (36). Another study revealed that using salicylic acid resulted in an increase of the antioxidants SOD, CAT and POD within the plant (37).

In this work, with the increase in drought stress intensity and the application of drought stress mitigators, the proline content

Table 6. Analysis of variance the effect of water stress (WS) and growth enhancers (GE) on relative growth rate (RGR), crop growth rate (CGR), biomass yield and cob yield of sweet corn during 2022 and 2023 (*p*-value of the main effects and their interactions)

Treatments	RGR		CGR		Biomass yield		Cob yield	
	2022	2023	2022	2023	2022	2023	2022	2023
Water stress (WS)	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$
Growth enhancers (GE)	$p \geq 0.05$	$p \geq 0.05$	$p \geq 0.05$	$p \geq 0.05$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$
WS $\times$ GE	$p \geq 0.05$	$p \geq 0.05$	$p \geq 0.05$	$p \geq 0.05$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$	$p \leq 0.01$

$p \geq 0.05$, $p \leq 0.05$ and $p \leq 0.01$ are non-significant, significant at 5 and 1 % probability, respectively.

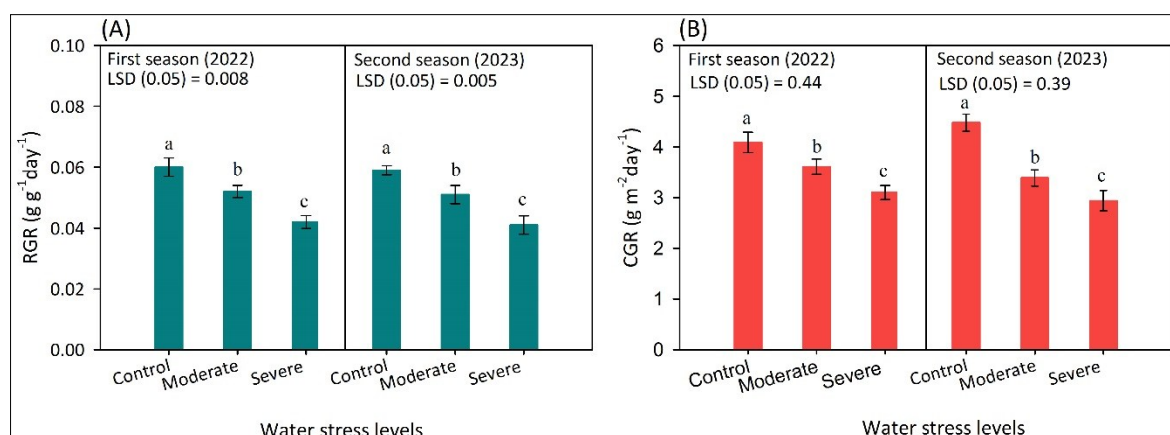


Fig. 1. Effect of water stress on relative growth rate (A) and crop growth rate (B) of sweet corn during 2022 and 2023. Means followed by a common letter are not significantly different at $p < 0.05$ according to the LSD test.

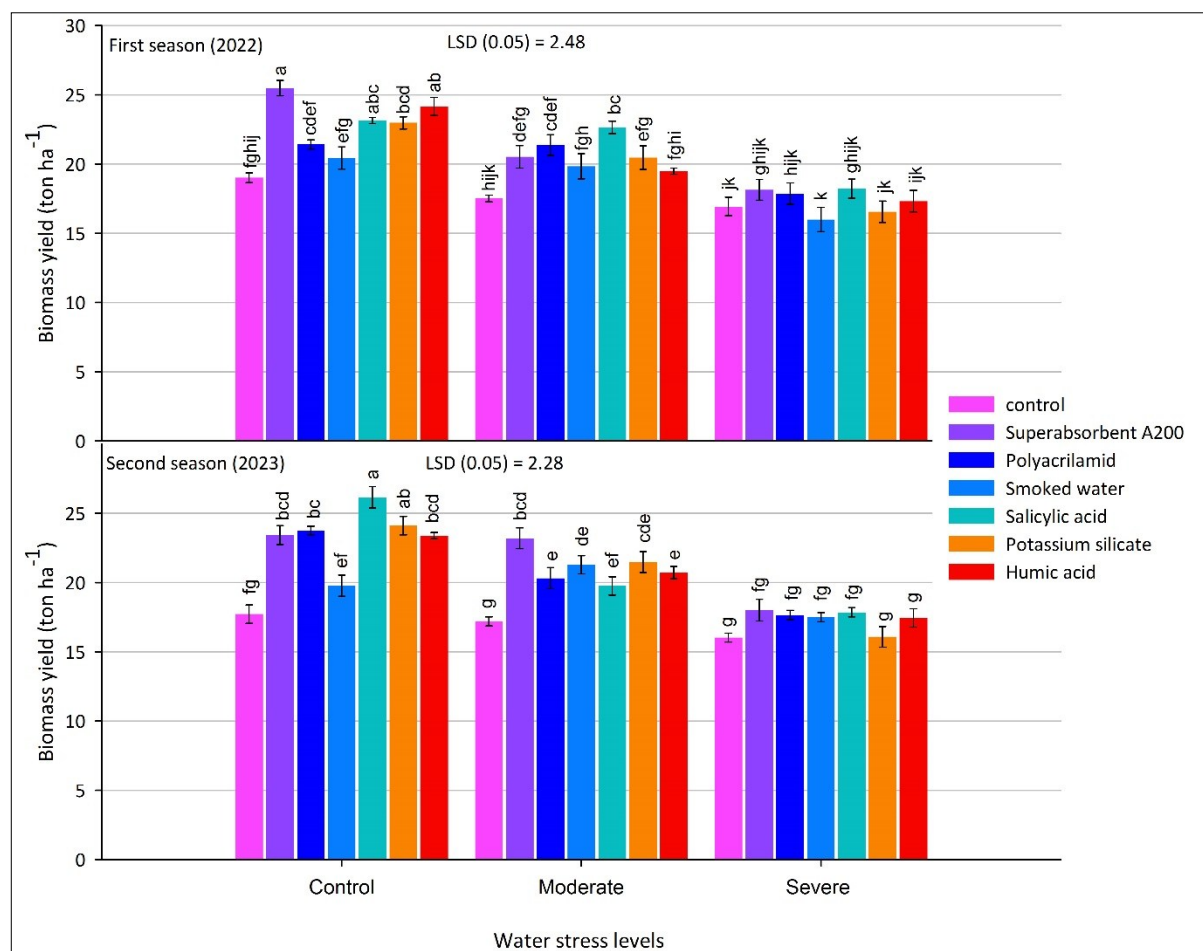


Fig. 2. Interaction of water stress and growth enhancers on biomass yield of sweet corn during 2022 and 2023. Means followed by a common letter are not significantly different at $p < 0.05$ according to the LSD test.

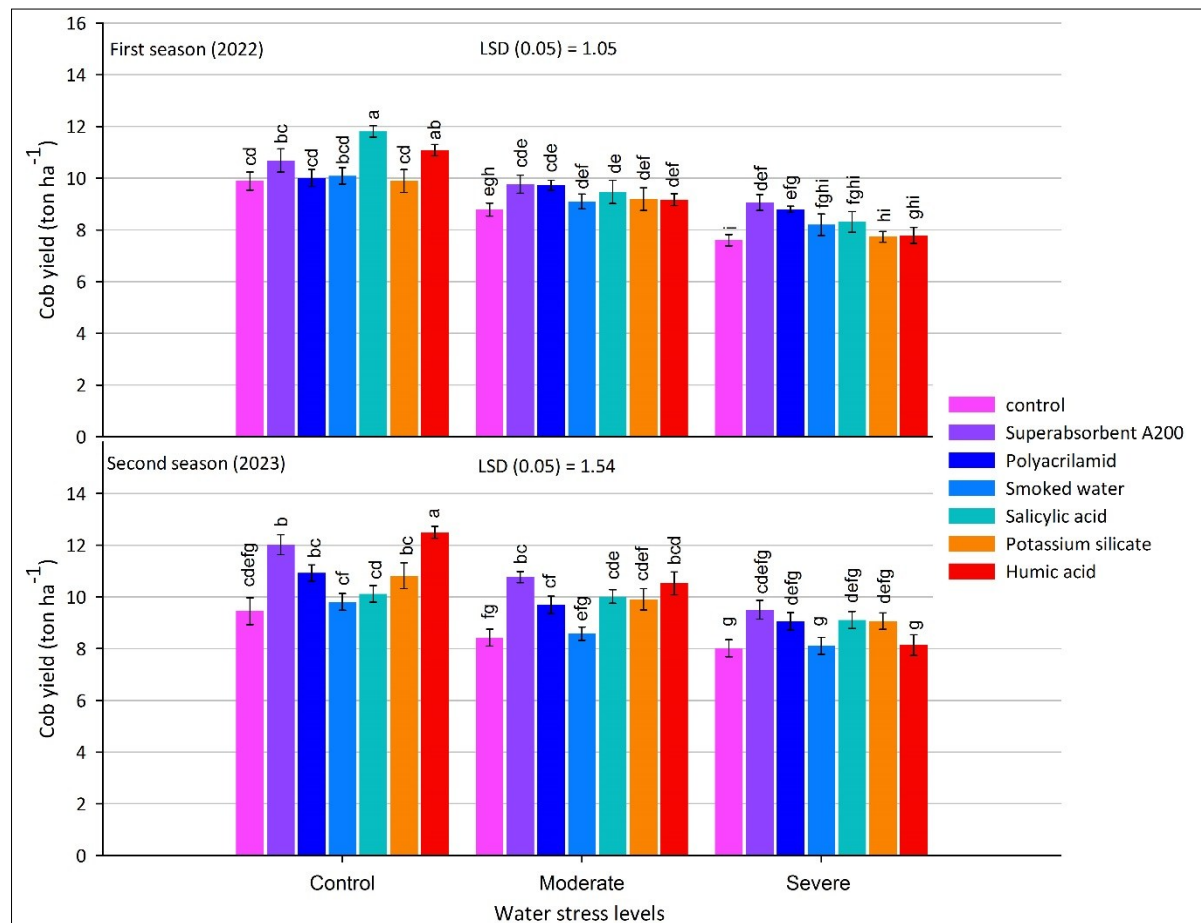


Fig. 3. Interaction of water stress and growth enhancers on cob yield of sweet corn during 2022 and 2023. Means followed by a common letter are not significantly different at $p < 0.05$ according to the LSD test.

increased. This indicates that proline plays a role in reducing the effects of drought stress on the plant. Among these, the SA200, SA and HA treatments (2-year mean) were more effective than the others (Table 4). In reaction to drought conditions, plants employ a mechanism for osmotic regulation. This process involves the accumulation of solutes, such as proline, within the cell to sustain turgor pressure even when the water potential is low. Proline is a small organic compound (38). Leaf proline functions as an osmolyte, safeguarding proteins and membranes and aids in the detoxification of reactive oxygen species (39). In a study conducted on corn, the findings indicated that a reduction in drought stress led to decreased levels of proline (40). The rise in proline during conditions of severe drought stress is influenced by various factors, including the plant species, cultivar, duration of stress, intensity of stress and other elements (38, 39).

In the present experiment, the chlorophyll index was influenced by growth enhancing treatments under severe drought stress conditions and significant differences were observed; such that the HA and SA200 treatments (2-year mean) had the highest values (Table 5). Chlorophyll undergoes significant changes when exposed to drought and various treatments, which can reflect the internal status of the plant (41). The role of SA in maintaining chlorophyll levels, delaying senescence and channelling photosynthetic products to the seeds has been fully proven (15). Interestingly, under moderate drought conditions, SA200 was at the highest level, highlighting the importance of consistent soil moisture for the accumulation of photosynthetic products and overall productivity. Each of the enhancers contributes in a unique way; such that smoke water enhances chlorophyll production under favourable conditions (13), superabsorbent protects photosynthesis under moderate stress (9), potassium silicate protects chlorophyll under severe stress conditions (16) and salicylic acid improves performance by facilitating stress signalling (15).

In this study, both CGR and RGR were primarily influenced by water availability and showed minimal responses to growth enhancers. The highest levels of CGR and RGR were observed under non-stress conditions and decreased as drought stress intensified (Table 6). Physiological assessments of plant growth play a crucial role in predicting yield and serve to evaluate occurrences throughout the plant growth cycle. Key traits such as crop growth rate (CGR), relative growth rate (RGR), shoot dry weight and root dry weight reflect the fluctuations during the crop growth phase. Drought has a significant impact on these 2 traits by hindering leaf growth, photosynthesis and the flow of photosynthetic materials (42). These findings are consistent with previous research indicating that water shortage inhibits cell division, protein production and carbohydrate metabolism, thereby slowing growth (39). The limited impact of enhancers suggests that they can influence certain physiological traits, such as osmotic regulation or antioxidant defence, but are unable to fully compensate for the effects of severe water scarcity. Consequently, crop growth rate (CGR) and relative growth rate (RGR) are closely linked to soil moisture and carbon absorption. For sweet corn, water remains the primary factor, while enhancers act as beneficial but secondary aids (43).

In this research, the biomass and cob yield of sweet corn showed a favourable response to all the growth promoters used (Fig. 2, 3, Table 6). SA200 and SA (2-year mean) had the greatest impact on biomass yield for all drought stress treatments, but for cob yield, SA200 and HA were more effective. In other words, SA200

and PAM (2-year mean) created stable growth by maintaining and managing soil moisture, thereby mitigating the effects of drought stress (9–11). SW contributed to growth improvement through its karrikin and amine compounds (44). SA improved antioxidant defence by neutralising free radicals and minimising their harmful effects (15). PS influenced stomatal regulation and, by leveraging the synergistic effects of silicate and potassium on growth, enhanced drought resistance (16). HA improved conditions by developing roots and reducing the effects of drought (45). Collectively, these growth enhancers, by increasing antioxidant activity, proline and osmotic regulation, improving chlorophyll index and photosynthesis, increasing root weight and water absorption efficiency, as well as reducing drought complications, helped increase biomass and cob yield by delaying the effects of stress compared to the control.

Environmental, practical and economical aspects

SA200 and PAM are synthetic polymers whose beneficial effects remain in the soil for up to 5 years, after which they lose their properties and decompose. These compounds are biodegradable, do not cause problems for dry and saline soils and their use is recommended (46). Humic acid is the result of the decomposition of natural organic materials such as lignite and leonardite. This substance contains elements such as C, O, H, N and S; it also possesses amounts of micronutrients like Fe, Mg, Zn and Cu, which play an effective role in the growth and development of plants (47). SA and PS are applied via foliar spraying. Since these substances are not used in the soil, they are environmentally safe and their use is recommended (48, 49). Regarding the foliar spraying of smoke water, according to the conducted studies, no harmful environmental effects have been reported so far (50). In this experiment, the growth promoters SA200, SA and HA had the greatest impact on biomass and cob yield in saline and dry soils. SA200 is applied at the time of seed sowing along with fertiliser through the fertiliser tank. HA is mixed with irrigation water and used via drip irrigation. SA is also applied as a foliar spray in stages. However, overall, in terms of total cost for the farmer, the preparation and use of SA and HA are much more cost-effective than SA200.

Conclusion

In general, the findings regarding the impact of growth enhancers SA200, PAM, SW, SA, PS, HA under both moderate and severe drought stress conditions, compared to scenarios without drought stress, indicated that all these growth promoters mitigated the effects of drought in various ways during drought conditions, leading to an increase in cob yield. Among these, the contributions of SA200, SA and HA were particularly significant. Therefore, it is advisable to use these 3 growth promoters for sweet corn cultivation in hot conditions and saline soils of the area. However, considering the costs of purchasing and consuming growth enhancers, the use of SA and HA is cost-effective, practical and accessible for the farmer.

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Authors' contributions

This article is part of the Ph.D thesis of the first author. AOHA conducted the experimental research, performed data collection and contributed to drafting the manuscript. MEG, as the research supervisor, played a key role in designing the overall experimental plan, writing the paper and preparing the figures. SJH supervised the research and was involved in the design of the experiment and treatments. AHJ played an important role in designing the experimental setup and monitoring the correct implementation of the treatments. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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