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RESEARCH ARTICLE

Optimal potassium fertilization mitigates drought stress effects on sugarcane growth and physiology

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Abstract

Sugarcane is a key global crop, providing up to 60% of raw sugar material. However, abiotic stress factors, especially water scarcity, significantly limit its productivity by reducing nutrient uptake and transport within the plant. Ensuring proper nutrition is essential to improve stress tolerance and maintain sugarcane yield. This study conducted a two-factor experiment following a completely randomized design in a greenhouse to evaluate the effects of potassium application (in soil) on the growth and physiology of a sugarcane cultivar named ROC27 (ROC27 cv.) under a drought condition. The first factor was potassium application (in the form of potassium oxide) with 4 different rates, including K1 (0 kg/ha), K2 (100 kg/ha), K3 (150 kg/ha) and K4 (200 kg/ha), while the second factor was irrigation with 2 treatments: control (normal irrigation daily); drought (no irrigation from 100-120 days after planting). Here, we revealed that drought significantly affected sugarcanes' growth and physiological characteristics as it decreased plant height, stem diameter, chlorophyll content, photosynthetic efficiency, total plant dry weight and stem fresh weight. Different rates of potassium oxide application in the soil also showed different influences on the growth and development of sugarcane. Applying 100 kg/ha potassium oxide resulted in the highest growth and physiological performance under drought conditions. Furthermore, plants from this treatment also recorded the highest stem fresh weight of ROC27 at the end of the recovery period (20 days of re-watering after drought treatments). Taken together, these results indicate that an appropriate amount of potassium oxide application significantly enhanced sugarcane physiological traits and mitigated the adverse effects of drought on plant growth and development.

Keywords

drought stress; plant growth; potassium; sugarcane

Introduction

Sugarcane (*Saccharum officinarum* spp.) is a globally important crop known for its high sugar accumulation capacity, contributing up to 60% of the raw material for sugar production (1). Additionally, with its substantial biomass yield potential, sugarcane plays a crucial role in bioenergy production (2). Among various environmental factors affecting sugarcane growth, drought is considered the most critical factor, potentially causing up to a 60% reduction in yield (3). As a C_4 crop with strong photosynthetic capabilities, sugarcane requires a substantial water supply during its growth period compared to other crops. Consequently, sugarcane production worldwide tends to concentrate in regions with favourable irrigation and high rainfall conditions (4). Sugarcane cultivation is primarily located in tropical and subtropical areas (5). However, rainfall in many regions does not provide adequate moisture for sugarcane growth and photosynthesis. Therefore, water scarcity remains the most severe limiting factor for sugarcane productivity. Moreover, even in tropical growing regions, uneven rainfall distribution throughout the months can create adverse conditions for sugarcane.

In Vietnam, the coastal areas of the Central region are among the largest sugarcane-growing regions, accounting for 51% of the total land area and 48% of national production (6). However, due to the influence of climate change and prolonged drought conditions, sugarcane yields in recent years have shown a significant decrease, directly impacting the income of sugarcane farmers. In addition to providing adequate irrigation and selecting suitable sugarcane varieties, research on appropriate fertilizer dosages under limiting conditions also plays a vital role in maintaining sugarcane productivity. Water scarcity reduces nutrient permeability from the soil to the root surface, leading to decreased nutrient uptake. Furthermore, nutrient transport from the roots to the stem and leaves is also disrupted (7). Therefore, ensuring proper nutrition for the crop is crucial for enhancing drought tolerance and sustaining crop productivity. Potassium (K) is a significant nutrient element influencing crop growth and yield. K enhances crop resilience under limiting conditions by stabilizing cell membrane permeability, promoting root system development, regulating water uptake and gas exchange, increasing photosynthetic efficiency, reducing the impact of substantial oxidative stress caused by drought (ROS) and decreasing the excessive uptake of ions such as Na and Fe (8-12). In this regard, potassium supplementation is necessary for ensuring crop productivity and quality. However, over-fertilization poses environmental risks, including biodiversity loss, heavy metal buildup, water eutrophication, toxicity to beneficial microorganisms and the release of nitrogen and sulfur gases that contribute to global warming and the greenhouse effect. Therefore, determining the optimal dosage under current cultivation conditions in Vietnam is essential.

This study aims to evaluate the impact of potassium fertilization at different dosages on sugarcane growth under artificial conditions, thereby determining the appropriate fertilization level to minimize the adverse effects of limiting conditions on sugarcane growth and yield. In the context of global warming, which threatens the production of globally essential crops due to the increasing frequency of abiotic stress, this study offers valuable insights into maintaining crop productivity, particularly for sugarcane, under challenging environmental conditions.

Materials and Methods

Experimental materials

The experiment was conducted on the ROC27 sugarcane variety (originating from Taiwan) and arranged using a Completely Randomized Design (CRD). The first factor involved 4 potassium (K_2O) fertilizer levels, corresponding to no fertilizer (K_1), 100 kg/ha (K_2), 150 kg/ha (K_3) and 200 kg/ha (K_4). The second factor was the drought treatment (H), which included H_0: Maintaining field moisture (70-80%) by regular irrigation (control) and H1: No irrigation.

Technical procedures

Sugarcane stalks were cut from the top portion of 6-8 months old plants. Each standard stalk with one bud was treated with root-inducing hormones before being planted in a greenhouse. After the stalks sprouted and reached a height of 15-20 cm, each stalk was transplanted into a bag (25 cm in diameter, 35 cm in height, with a surface area of 0.125 m^2) containing 15 kg of river sand soil from the Red river delta (soil analysis data presented in Table 1). Before planting, the soil was enriched with 100 g of Song Gianh microbial fertilizer VS01 (manufactured in Vietnam, with 20% organic matter, 2% of humic acid, added with *Azotobacter* sp., *Aspergillus* sp., *Bacillus* sp., of 1 × 10^6 CFU/g each) per pot (equivalent to 10 tons/ha) and 5 g of lime per pot (equivalent to 500 kg/ha). The basal fertilizer application included 100 kg P_2O_5/ha applied once and the top dressing with 150 kg N/ha was split into 2 applications at 30 days and 60 days after planting (DAP). The K_2O corresponding to the experimental formulations was applied in 2 stages: 50% at 30 DAP and 50% at 60 DAP. The source of K_2O used in this study was obtained from the *Solu-K sulfate of the Potash* brand (with 51% of K_2O and 17.5% of S), imported from JMC, Korea.

Table 1. Summary of soil analytical criteria for sugarcane in the experiment

Soil analysis criteria	Value
pH	6.57
Total organic matter (%)	1.72
Total nitrogen (%)	0.09
Total phosphorus (%)	0.18
Total potassium (%)	1.32
Calcium (%)	0.07
Inorganic N (mg/100 g) 4.27	4.14
Inorganic P (mg/100 g) 50.02	47.52
Inorganic K (mg/100 g) 11.80	10.8

Drought treatment

The drought treatment began 100 DAP by ceasing irrigation and lasted 20 days. In the control formulations, plants were irrigated daily to maintain soil moisture at 70-80%. Soil moisture in the drought and control formulations was measured every 10 days using a Takemura DM15 soil moisture meter (Japan). At the end of the drought treatment (120 DAP), plants in the drought formulations were re-irrigated to restore soil moisture to 70-80%.

Parameters and monitoring methods

After the plants were transferred from the nursery to the larger pots, 5 randomly selected plants from each formulation were marked to monitor growth parameters, including plant height (cm) and stem diameter (cm). These parameters were recorded every 10 days. The SPAD index was measured using a SPAD-502 m (Minolta, Japan) on 5 plants per formulation per measurement. Multiple measurements were taken on each leaf and the values were averaged. The stomatal density on the upper and lower leaf surfaces was measured using the method described in a previous study (13). Stomatal density and size were assessed under the microscope using nail polish imprints from both the upper and lower leaf surfaces. Parameters related to photosystem II (fluorescence parameters) were measured using a handheld fluorescence measuring device (Opti-Sciences, OS30p$^+$, USA) following the methods described previously (14). Measurements were taken on fully developed leaves between 8:00 and 11:00 am and leaves were clamped during measurements for approximately 30 min. Measured parameters included maximum fluorescence (F_m), variable fluorescence (F_v) and maximum photochemical efficiency of photosystem II (F_v/F_m), which are related to the plants' ability to use light in photosynthesis (photosystem II).

Relative water content in the leaves was measured at the start, end of the drought treatment, and 20 days after reirrigation, corresponding to 100, 120 and 140 DAP. Leaf samples were collected randomly between 11:00 am and 1:00 pm. Ten samples were taken for each sampling, their fresh weight (FW) was measured and then they were soaked in distilled water for 24 hr. before being surface-dried to measure saturated leaf weight (TW). The leaf samples were oven-dried at 80 °C for 48 hr. until a constant weight was reached (DW). The relative water content in leaves (RWC) was calculated using the following formula: RWC (%) = [(FW-DW) / (TW-DW)] x 100. Leaf area (LA) was measured using an automated leaf area meter (AAM-8 Hayashi Denko Inc., Tokyo, Japan). Fresh stem weight was measured at the end of the drought treatment (120 DAP) and Brix was measured using a handheld refractometer Pal1-Atago (USA) at the end of the drought treatment. The Drought tolerance index (DTI) was calculated using the following formula: DTI = dry weight under stress conditions / dry weight under normal conditions (15).

Statistical analysis

All experiments were conducted with 5 plants per treatment. R software performed The data analysis (Ver. 4.3.1, the R foundation for statistical computing, Vienna, Austria). The dataset did not satisfy normality; thus, the non-parametric data analysis Kruskal-Wallis test was used. For the post hoc test, the Dunn test with the Benja-mini-Hochberg correction was applied. The bar and line plots were produced using the 'ggplot2' package in R 4.3.1.

Results

Influence of different potassium fertilization levels on the plant height and stem diameter of sugarcane under drought stress conditions

Soil moisture in the drought treatment gradually decreased over the experimental period and reached its lowest point at the 20 days irrigation cessation point. However, soil moisture rapidly recovered within 1-2 days after resuming irrigation (Fig. 1). The imposed drought conditions led to a reduction in plant height (Fig. 2 and 3A) and stem diameter (Fig. 2 and 3B). The impact of drought on plant height was observed to manifest earlier and more prominently than its effect on stem diameter.

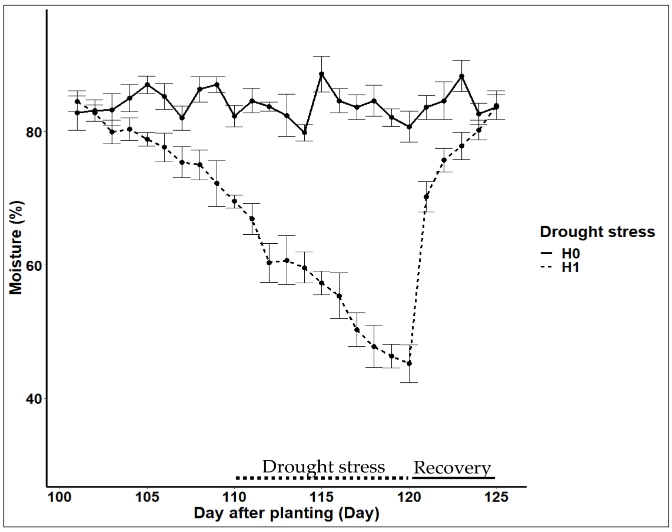

Fig. 1. The moisture levels at the experimental formulations during the drought treatment and recovery irrigation.

At the 20 days irrigation cessation point, the highest plant height and stem diameter were observed in the K_3 and K_2 formulations, followed by K_1 and the lowest values were found in the K_4 formulation. Twenty days after irrigation resumed, different K fertilizer formulations still negatively affected plant height (Fig. 3). Specifically, at 140 DAP, the tallest plant height was attained in the K_2 and K_3 formulations, followed by K_1. At the same time, the lowest value was observed in the K_4 formulation. This indicates that judicious K fertilization can enhance sugarcane growth under limited conditions.

Influence of different potassium fertilization levels on leaf area and relative water content (RWC) in the leaves

The experimental results (Table 2) indicate that the drought treatment significantly reduced leaf area (LA) and the relative water content in the leaves (RWC). Specifically, at the end of the drought period (120 DAP), leaf area decreased from 14.93 dm^2 in control to 9.99 dm^2 in the drought-treated formulations. Correspondingly, the RWC in the leaves decreased from 74% in the control to 50% in the drought-treated formulations. The RWC in the leaves in the drought-treated formulations was significantly lower compared to the control at the end of the drought period. Twenty days after recovery irrigation, we observed some recovery in RWC values, although it remained significantly lower in the drought-treated formulations. Different potassium fertilizer formulations significantly affected the leaf area of sugarcane at the pre-drought treatment stage. The largest LA was observed in the K_2 and K_3 formulations. However, at the end of the drought period (120 DAP), po-

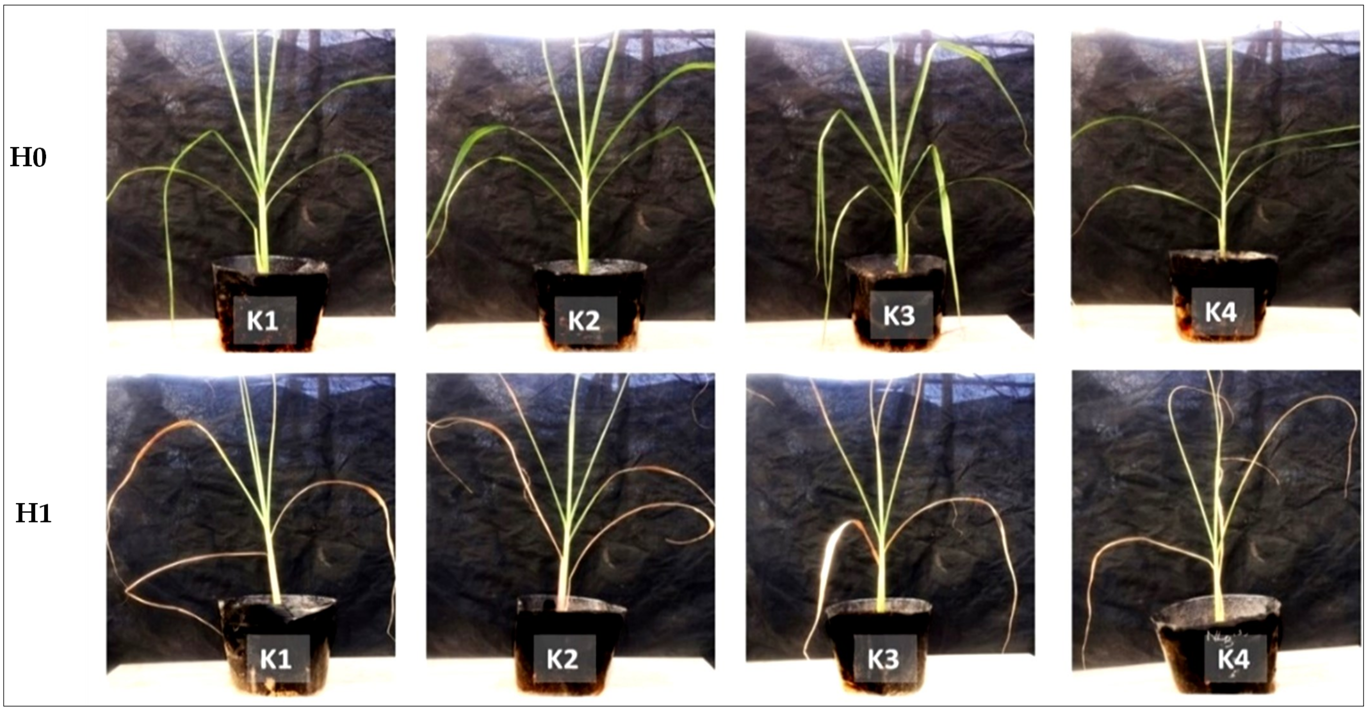

Fig. 2. Images of the experimental formulations (**b**) at the end of the drought period (120 days after planting).

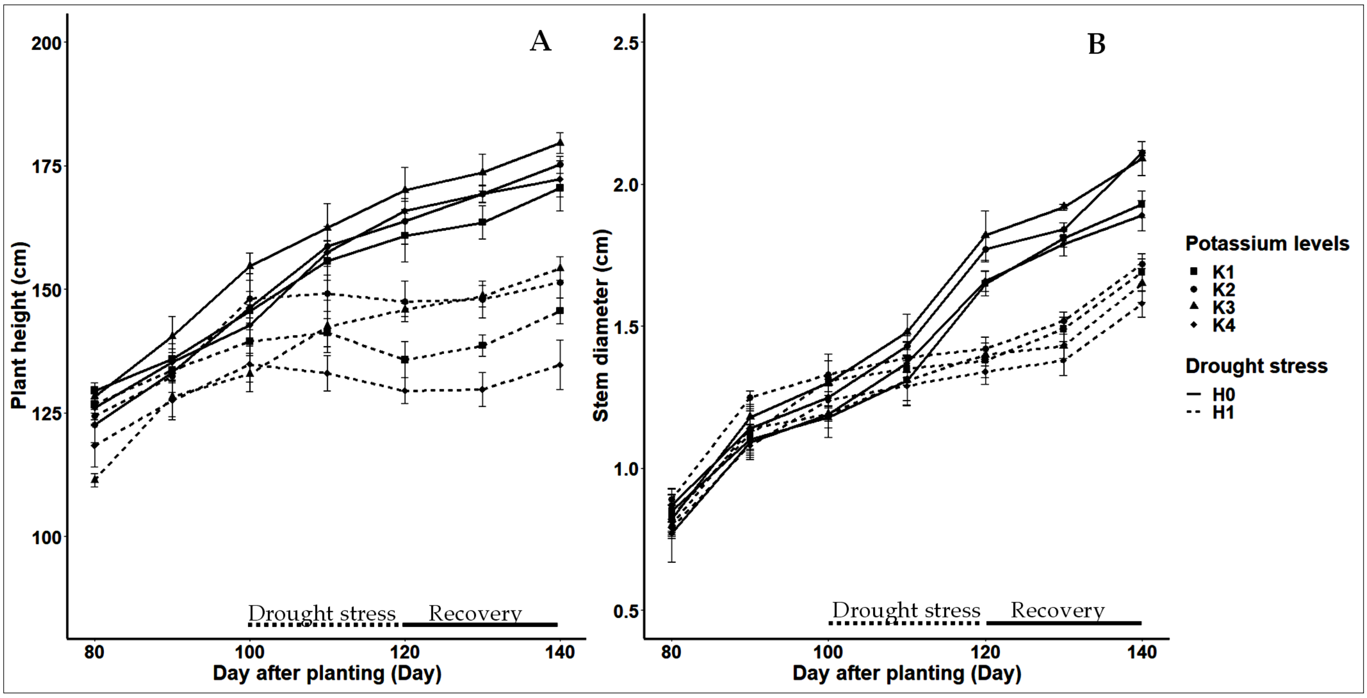

Fig. 3. The influence of different potassium fertilization levels and drought conditions on plant height (**A**) and stem diameter (**B**) of sugarcane.

tassium levels from K_1 to K_3 did not significantly influence LA. In contrast, the K4 formulation resulted in the smallest LA, substantially lower than the other potassium formulations. After 20 days of recovery irrigation (140 DAP), the different potassium fertilizer levels did not significantly affect LA or RWC values.

Influence of different potassium fertilization levels on the SPAD index and quantum yield of photosystem II (F_v/F_m)

The SPAD index is an essential indicator for assessing the growth of crops and is a rapid measure of chlorophyll content in leaves for various crop species, including sugarcane (16). Research results indicate that drought conditions significantly reduced this index, corresponding to 38.21 and 21.77 for the control and drought formula at 120 DAP respectively and maintained the same pattern at 140 DAP (37.70 in control plants versus 34.76 in drought-treated plants). At the end of the drought period, the highest SPAD index was observed in the K_2 formulation, followed by K_3 and the lowest in K_1.

The maximum quantum yield (F_v/F_m) is closely related to a plants' photosynthetic capacity and is an important indicator for assessing a plants' response to adverse conditions, including drought. Experimental results show a significant disruption of photosynthetic activities in plants under drought conditions, corresponding to 0.74 in the control formulations and 0.61 in the drought-treated formulations at 120 days after planting and 0.77 and 0.73

Table 2. Influence of different potassium fertilization levels on leaf area and relative water content in the leaves

Treatment		Leaf area			Relative water content		
		100 DAP	120 DAP	140 DAP	100 DAP	120 DAP	140 DAP
H0	H_0K_1	10.89^{b}	14.66^{ab}	16.21^{ab}	74.48^{a}	74.75^{a}	75.05^{a}
	H_0K_2	12.29^{a}	15.23^{ab}	16.85^{a}	77.16^{a}	76.10^{a}	74.00^{a}
	H_0K_3	11.67^{ab}	15.57^{a}	16.94^{a}	76.12^{a}	74.75^{a}	74.82^{a}
	H_0K_4	11.18^{ab}	14.25^{b}	15.23^{b}	75.15^{a}	71.74^{a}	72.67^{a}
H1	H_1K_1	11.41^{ab}	10.52^{cd}	13.02^{c}	75.17^{a}	55.42^{b}	64.82^{b}
	H_1K_2	11.89^{ab}	11.03^{c}	13.26^{c}	74.22^{a}	53.15^{bc}	65.80^{b}
	H_1K_3	11.63^{ab}	9.66d^{e}	11.50^{d}	74.57^{a}	46.62^{cd}	66.37^{b}
	H_1K_4	10.96^{b}	8.75^{e}	10.78^{d}	74.10^{a}	44.35^{d}	64.10^{b}
Effect of potassium	K_1	11.15^{b}	13.13^{a}	14.62^{ab}	74.82^{a}	64.75^{a}	69.93^{a}
	K_2	12.09^{a}	12.62^{a}	15.07^{a}	75.69^{a}	64.62^{ab}	69.90^{a}
	K_3	11.65^{ab}	12.59^{a}	14.22^{b}	75.34^{a}	60.68^{bc}	70.60^{a}
	K_4	11.07^{b}	11.50^{b}	13.01^{c}	74.62^{a}	58.04^{c}	68.38^{a}
Effect of drought stress	H_0	11.51	14.93	16.31	75.73	74.16	74.13
	H_1	11.476^{ns}	9.99*	12.145*	74.51^{ns}	49.88*	65.27*

Statistical analysis was performed using a Kruskal–Wallis test (p-value ≤ 0.05) followed by a Dunn–Benjamini–Hochberg post hoc test for multiple comparisons. Different letters indicate a significant difference between the 2 medians. **DAP**: days after planting.**ns**: Non-significant, *****: Significant T-Test, at p ≤ 0.05

Table 3. Influence of different potassium fertilization levels on the SPAD index and quantum yield of photosystem II (F_v/F_m)

Treatment		SPAD			F_v/F_m		
		100 DAP	120 DAP	140 DAP	100 DAP	120 DAP	140 DAP
H_0	H_0K_1	38.34^{ab}	36.12^{a}	36.57^{ab}	0.77^{a}	0.74^{a}	0.76^{abc}
	H_0K_2	44.31^{a}	41.38^{a}	39.60^{a}	0.77^{a}	0.76^{a}	0.78^{a}
	H_0K_3	40.90^{ab}	38.32^{a}	39.17^{ab}	0.76^{a}	0.74^{a}	0.78^{a}
	H_0K_4	37.05^{b}	37.02^{a}	35.47^{ab}	0.75^{a}	0.71^{a}	0.77^{ab}
H_1	H_1K_1	38.41^{ab}	19.16^{b}	35.51^{ab}	0.79^{a}	0.59^{c}	0.72^{abc}
	H_1K_2	37.01^{b}	22.93^{b}	36.53^{ab}	0.78^{a}	0.69^{ab}	0.75^{abc}
	H_1K_3	38.64^{ab}	24.66^{b}	34.37^{ab}	0.78^{a}	0.60^{c}	0.71^{bc}
	H_1K_4	39.26^{ab}	20.32^{b}	32.62^{b}	0.76^{a}	0.58^{c}	0.70^{c}
Effect of potassium	K_1	38.38^{a}	28.64^{bc}	36.04^{ab}	0.78^{a}	0.66^{b}	0.74^{a}
	K_2	40.66^{a}	32.16^{a}	38.06^{a}	0.78^{a}	0.72^{a}	0.77^{a}
	K_3	39.77^{a}	31.49^{ab}	36.77^{ab}	0.77^{a}	0.68^{bc}	0.75^{a}
	K_4	38.16^{a}	28.02^{c}	34.04^{b}	0.75^{a}	0.64^{b}	0.73^{a}
Effect of drought stress	H_0	40.15	38.21	37.70	0.76	0.74	0.77
	H_1	38.33^{ns}	21.77*	34.76*	0.77^{ns}	0.61*	0.73*

Statistical analysis was performed using a Kruskal–Wallis test (p-value ≤ 0.05) followed by a Dunn–Benjamini–Hochberg post hoc test for multiple comparisons. Different letters indicate a significant difference between the 2 medians. **DAP**: days after planting. **ns**: Non-significant, *****: Significant T-Test, at p ≤ 0.05

at 20 days after recovery irrigation. The impact of different potassium fertilizer formulations on the F_v/F_m index is evident at 120 DAP (i.e., end of the drought period), with the highest value recorded in the K_2 formulation, followed by K_1, K_3 and the lowest in K_4. However, 20 days after recovery irrigation, the impact of different potassium formulations was insignificant (Table 3).

Influence on stomatal density

Stomatal conductance plays a crucial role in controlling the exchange of CO_2 between the leaf surface and the atmosphere. It is also one of the critical indicators for assessing the impact of drought conditions on crops and the response of different varieties to the same drought conditions. The results show that drought conditions significantly increased stomatal density on the adaxial and abaxial leaf surfaces (Fig. 4). The impact of different potassium fertilizer formulations significantly affects stomatal density on the leaf surface. However, in the formulation with 100 kg/ha of potassium fertilizer, stomatal density was lower than the other two formulations on both the adaxial and abaxial sides.

Accumulated dry matter and drought tolerance index

The impact on accumulated dry matter and drought tolerance index at 120 DAP (i.e., 20 days of drought treatment) of the examined formulas is presented in Table 4. The results show that drought conditions significantly reduced

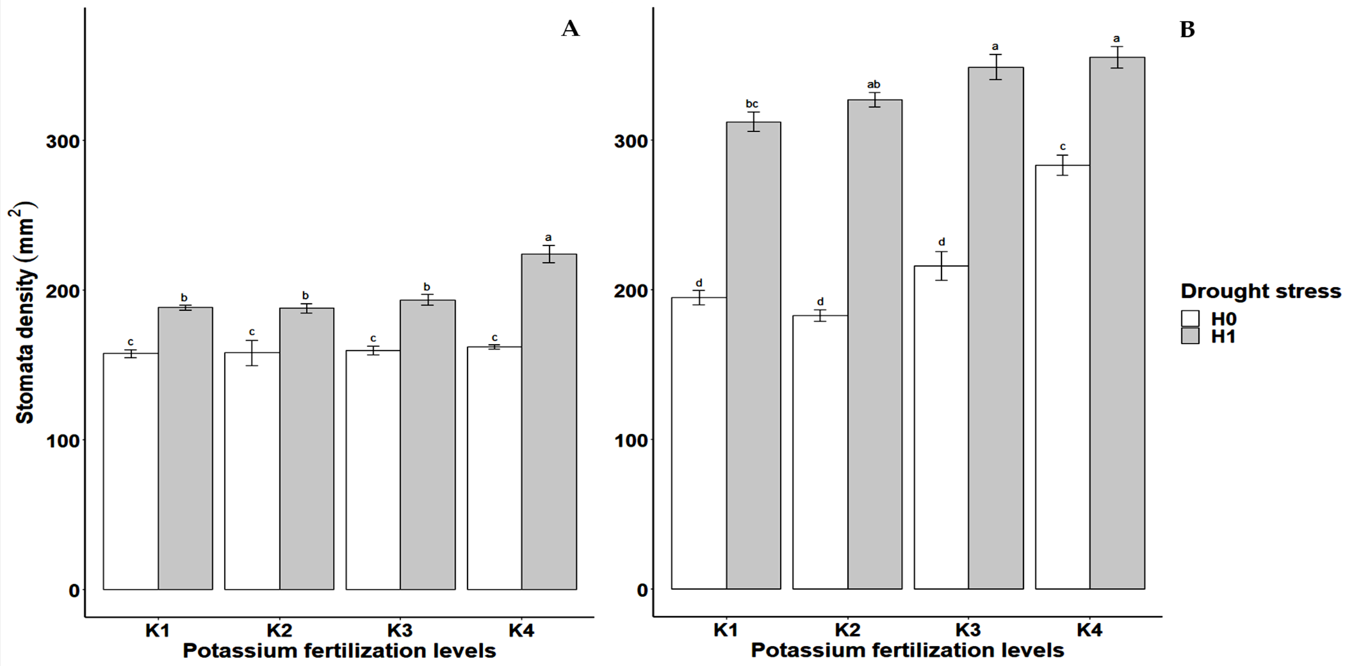

Fig. 4. Influence of different potassium fertilization levels and drought conditions on stomatal density on the adaxial (**A**) and abaxial (**B**) of sugarcane leaf surfaces at 120 days after planting (end of the drought treatment).

Table 4. Influence of various potassium fertilizer formulations on the ability to accumulate dry weight and drought tolerance index at the end of the drought treatment (120 days after planting)

Treatment	Dry weight (g)				Drought tolerance index (DTI)
	Root	Stem	Leaves	Whole plant	
H_0K_1	5.81	21.24	14.25	41.30^a	0.74
H_1K_1	5.44	15.22	10.20	30.86^c	
H_0K_2	6.05	21.13	15.12	42.30^a	0.77
H_1K_2	4.91	16.80	11.04	32.75^{bc}	
H_0K_3	5.44	19.30	13.23	37.97^{ab}	0.71
H_1K_3	3.88	15.98	8.71	28.57^c	
H_0K_4	3.58	18.23	9.61	31.42^{bc}	0.65
H_1K_4	2.97	10.63	6.75	20.35^d	
H_0				37.99^A	
H_1				28.13^B	
K_1				35.58^{AB}	
K_2				37.52^A	
K_3				33.27^B	
K_4				25.88^C	

Statistical analysis was performed using a Kruskal–Wallis test (p-value ≤ 0.05) followed by a Dunn–Benjamini–Hochberg post hoc test for multiple comparisons. Different letters indicate a significant difference between the 2 medians

the accumulated dry matter from 37.99 g/plant in the control formula to 28.13 g/plant in the drought-treated formulas. Different potassium fertilizer formulas also had other effects on the accumulated dry matter in plants. Among the formulas, K_2 achieved the highest dry matter (37.52 g/plant), followed by K_1 and K_3 with 35.58 and 33.27 g/plant respectively. K_4 achieved the lowest total plant dry matter at 25.88 g/plant. Regarding the drought tolerance index, the results showed that formula K_2 had the highest drought tolerance index, followed by K_1, K_3 and K_4 respectively. Thus, formula K_2 maintained the highest dry matter and drought tolerance index at the end of the drought treatment.

Impact of different potassium formulas on stem mass and Brix at 140 DAP

Stem mass is an essential parameter for sugarcane yield, while the Brix index is closely related to the quality of sug-

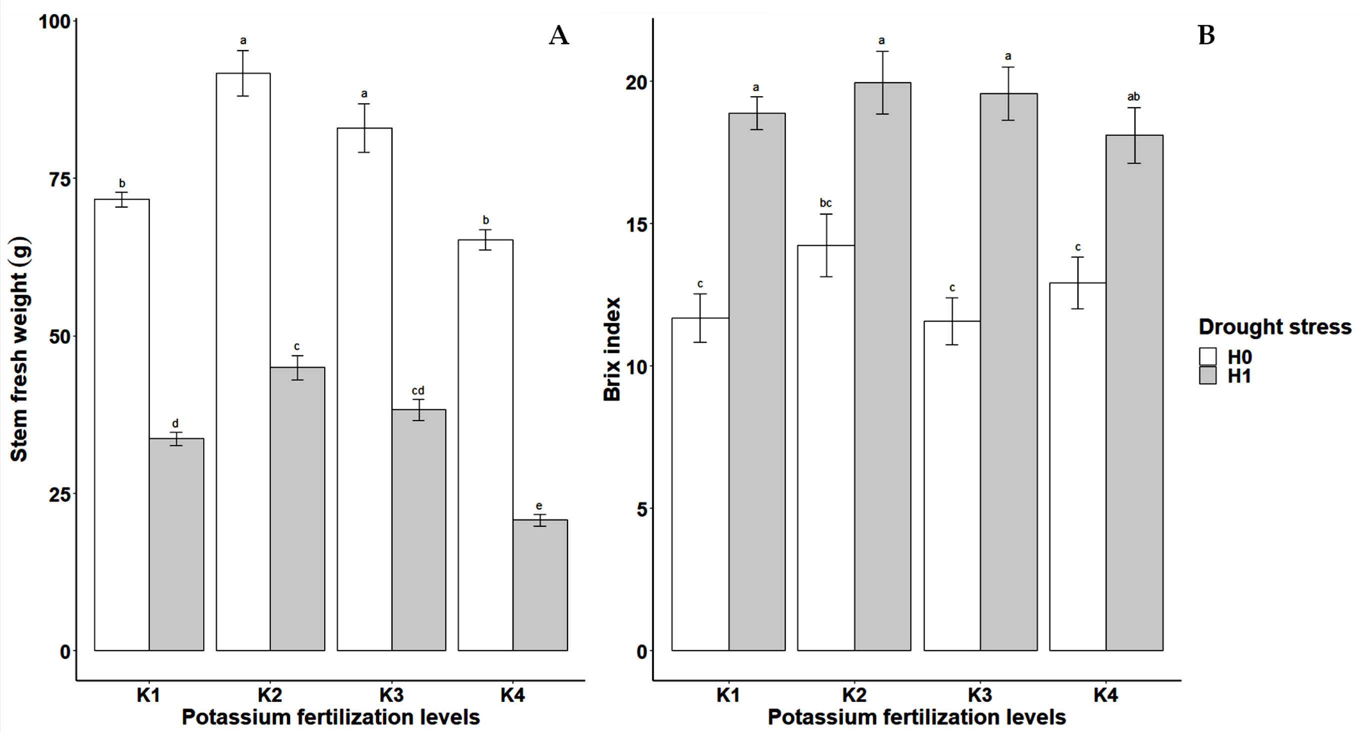

Fig. 5. Influence of different potassium fertilization levels and drought conditions on fresh weight (**A**) and Brix index (**B**) of sugarcane stems at 140 days after planting (20 days after rehydration).

arcane as a raw material. The experimental results (Fig. 5) show that drought conditions significantly reduced fresh stem mass at 140 DAP (20 days after rehydration). Conversely, the parameters related to sugar content in the stem (Brix index) tended to increase under drought conditions. Different potassium fertilizer formulas had varying effects on the fresh stem mass of sugarcane observed at 140 DAP. In the control conditions (H_0), the highest fresh stem mass was achieved in formulas K_2 and K_3. Meanwhile, in the drought conditions (H_1), potassium fertilizer formula K_2 provided the highest fresh stem mass, followed by K_3 and K_1.

Discussion

This study examined the effects of different potassium fertilizer dosages on sugarcane growth and development under water-deficit conditions. According to our results, droughts' impact manifested earlier and more prominently on plant height than on stem diameter. This finding aligns with previous studies, which indicated that drought diminishes both plant height and stem diameter, as well as elongation rates of sugarcane (5, 17). Another study also reported a 7% decrease in sugarcane stem diameter due to drought stress compared to the control (18). Furthermore, the degree of stem diameter reduction under drought conditions was considered significant among sugarcane varieties, subsequently influenced by the duration and intensity of the drought treatment (5). The reduction in stem height growth can be attributed to decreased soil water potential, resulting in reduced leaf size and leaf number on the plant (19). The experimental results (Table 2) indicate that the drought treatment significantly reduced LA and the leaves RWC, aligning with several previous sugarcane studies (5, 14, 20). Leaves play a crucial role in the growth and development of plants, directly influencing photosynthesis, respiration and transpiration processes. One of the early responses to limited irrigation and drought conditions in sugarcane leaves is leaf curling and rolling. This is considered one of the mechanisms that helps plants, especially C_4 plants with substantial biomass, reduce the leaf surface area exposed to the air and consequently, decrease water transpiration (21). This is also one of the reasons for the significant reduction in leaf area in sugarcane under drought conditions, alongside a decrease in leaf emergence rate (22). We observed some recovery in RWC 20 days after recovery irrigation, although it remained significantly lower in the drought-treated formulations compared to the control. This can be explained by drought conditions reducing cell turgor, permeability and cell wall strength. Therefore, even after 20 days of re-irrigation, drought treatment still resulted in lower leaf RWC in treated plants.

Consistently, drought treatment also negatively affected other physiological parameters of sugarcane, including the SPAD index, the maximum quantum yield and the stomatal conductance. The SPAD index is an essential indicator for assessing the growth of crops and is a rapid measure of chlorophyll content in leaves for various crop species, including sugarcane (16). The maximum quantum yield (F_v/F_m) is closely related to a plants' photosynthetic capacity and is an essential indicator for assessing plant response to adverse conditions, including drought. Maintaining a high and stable F_v/F_m value under limiting conditions helps the plant maintain better photosynthetic capability and material accumulation, thereby improving adaptation (5). Stomatal conductance plays a crucial role in controlling the exchange of CO_2 between the leaf surface and the atmosphere (23), thereby influencing the process of photosynthesis and other physiological processes of crops (24). Under drought conditions, maintaining an appropriate quantity and size of stomata helps plants better withstand stress (25). This is also one of the critical indicators for assessing the impact of drought conditions on crops and the response of different varieties to the same drought conditions. The results show that drought conditions significantly increased stomatal density on the adaxial and abaxial leaf surfaces (Fig. 4). These findings are consistent with research on *Leymus chinensis* (Trin.) Tzvel, which demonstrated that the plants' adaptation mechanism to drought conditions includes increased stomatal density and reduced stomatal size (23). Under drought conditions, sugarcane leaf area significantly decreases due to leaf curling and rolling, leading to increased stomatal density per unit leaf area; however, the size and total number of stomata on the leaf will decrease (23). Maintaining lower stomatal density helps plants reduce water evaporation and thus adapt better to water scarcity and drought conditions (25).

Drought stress reduced sugarcane accumulated dry matter, fresh stem mass and increased Brix index. Stem mass is an essential parameter for sugarcane yield, while the Brix index is closely related to the quality of sugarcane as a raw material. The decrease in fresh stem mass of sugarcane under drought conditions can be explained by the reduced ability to receive light, accumulate substances and water in the stem, growth rate and photosynthetic ability when the plant experiences water deficit (22). Conversely, the parameters related to sugar content in the stem (Brix index) tended to increase under drought conditions. This result is consistent with previous research (14, 26). Different potassium fertilizer formulas, such as potato, maize or sugarcane, had varying effects on the yield and development of crops from previous studies (27-29). Our results show that reasonable K fertilization can enhance sugarcane growth under limited conditions. The study on potatoes highlights that appropriate K fertilizer application promotes plant growth and yield (27). The K_2 formula displayed the best effects on sugarcane growth under stress conditions, as suggested by the most prominent LA as well as the highest dry matter, drought tolerance index and fresh stem mass compared to other formulas. This finding indicates that the addition of potassium (at the K_2 level) has a positive effect in mitigating the impact of drought conditions on the ability to accumulate dry matter in various plant parts, including roots, stems and leaves, thereby maintaining better overall plant dry matter. This result is consistent with the findings of previous studies on wheat and coffee (30, 31). The additional potassium helps the plant maintain a water balance within cells, regulate low-pressure conditions, perform various physiological activities, such as photosynthesis and open stomata in drought conditions (30, 32). Potassium is a macronutrient that plays a crucial role in the growth and development of plants. Under normal conditions, maintaining a balance of K^+ ions within plant cells is essential for natural plant growth (8). However, drought conditions can disrupt the K^+ ion balance within cells by increasing membrane permeability, thereby increasing the efflux of K^+ ions from the cells. This is caused by increased reactive oxygen species (ROS) (2). This leads to K^+ deficiency within cells, affecting the activity of K^+-dependent enzymes and disrupting various physiological metabolic processes in plants. Therefore, maintaining an appropriate K^+ ion level is crucial for a plants' drought tolerance. Adding 100 kg/ha of potassium in this experiment helped sugarcane achieve the highest stem mass. This demonstrates the significant importance of this potassium fertilizer in mitigating the adverse effects of drought conditions on sugarcane.

Conclusion

The artificial drought conditions significantly reduced the growth of the ROC27 sugarcane variety under greenhouse conditions. Drought reduced plant height, stem diameter, SPAD index, relative water content in the leaves, and the efficiency of photosystem II (F_v/F_m). Drought conditions also decreased stem weight and the ability to accumulate dry matter in sugarcane. Different potassium fertilizer formulations had varying effects on the adaptability of the ROC27 variety to artificial drought conditions. We observed that applying 100 kg K_2O/ha fertilizer among the formulations helped the plants adapt the best. This potassium dosage improved growth and physiological parameters during the drought period and supported better development during the recovery phase. Specifically, in terms of fresh stem weight at 20 days after reirrigation, the application of 100 kg K_2O resulted in the highest fresh stem weight, followed by the 150 kg formulation. This study provides a foundation for enhancing sugarcane performance under drought conditions. Drought significantly reduces sugarcane yield, thereby impairing the economic value of this globally important crop. The findings from this research offer a potential solution for sugarcane farmers worldwide to mitigate these adverse effects. As potassium fertilization has proven to be an effective strategy, expanding the study to other sugarcane cultivars and diverse growing conditions would further improve sugarcane production in the face of environmental challenges.

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Authors' contributions

TKB conceptualizes the study. NNC, NTV and THD contributed to conducting the experiments. ATL data analysis, writing—original draft preparation. TKB writing—review and editing. 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.

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