



Research article

Differential performance in height growth rate and yield components to enhance cane yields of various sugarcane types during early drought and post-recovery

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Article Info

Article history:

Received 30 July 2024

Revised 3 October 2024

Accepted 28 October 2024

Available online 28 February 2025

Keywords:

Agronomic traits,
Drought-tolerance genotypes,
Interspecific hybrid,
Recovery performance,
Sugarcane breeding

Abstract

Importance of the work: Drought stress reduces sugarcane yields. A deeper understanding of the growth and yield components across different sugarcane genotypes could improve the process of breeding sugarcane with tolerance to drought.

Objectives: To investigate the effects of various water regimes on the growth behavior, yield components and cane yield of different sugarcane genotypes.

Materials and Methods: The experiment was designed as a split plot in a randomized complete block design with three replications. The main plot involved two water regimes—(well-watered (WW) and early drought stress (DS) —during 2–6 mth after tillering (MAT; tillering and early stalk elongation phase). The subplot contained six diverse sugarcane genotypes. The stalk height was measured at 3, 6, 8, 10, and 12 MAT. The height growth rate (HGR) and stalk number per stool were recorded at 6, 8, 10, and 12 MAT. The cane yield and yield components were collected at harvest.

Results: Early drought reduced the cane yield, stalk length, single stalk weight and millable cane. Based on the cane yield, F03-362 (F1), KK09-0358 (BC1) and KK3 (commercial cane) were identified as drought-resistant genotypes. The high number of millable canes and plant height were important traits that promoted high cane yield in F03-362, while KK09-0358 and KK3 were derived from a medium number of millable canes and a high single stalk weight.

Main finding: HGR, during recovery periods (re-watered after 6 MAT until 12 MAT), impacted promoting cane yield. The drought-tolerant genotypes had greater values for HGR than the drought-susceptible genotypes. This perspective was beneficial as it emphasized the selection characteristics in sugarcane breeding efforts to enhance drought tolerance.

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<https://doi.org/10.34044/j.anres.2025.59.1.07>

Introduction

Approximately 80% of the world's sugar is produced using sugarcane as the primary raw material in manufacturing (Mabeta and Smutka, 2023). Sugar production byproducts, such as molasses and bagasse, have the potential to considerably increase economic value (Wani et al., 2023). Sugarcane is essential to the industry because it provides both sugar and a vital energy source (Solomon, 2011). Sugarcane production worldwide is experiencing drought stress, resulting in lower yields (Khaled et al., 2018; Tippha-art et al., 2025). Additionally, the industry benefited from mechanical harvesting due to reduced labor inputs during a labor shortage (Schmitz et al., 2020). Challenges in sugarcane breeding programs focus on developing drought-tolerant genotypes with desirable characteristics (based on stalk diameter and stalk number/stool) that make them suitable for use with mechanized harvesters (Schmitz et al., 2020; Wirojsirasak et al., 2023).

Most sugarcane plantations are in tropical and subtropical regions such as Brazil, Thailand, and India, where these crops frequently face drought stress due to erratic precipitation, which often impacts sugarcane yields (Pipitpukdee et al., 2020). Thailand's sugarcane production relies on rainfed water over 80% of sugarcane crop areas, with sugarcane planting typically commencing in October–November (the late rainy season) and continuing until residual soil moisture is depleted. Early growth is susceptible to droughts since rains cease intermittently between December and April (Pipitpukdee et al., 2020), which might affect growth and yield.

Drought stress negatively impacts sugarcane growth and productivity, reducing cane yield and biomass (Leanasawat et al., 2021). The water deficit restricts plant metabolism and reduces plant growth (Graça et al., 2010; Jangpromma et al., 2010; Barbosa et al., 2015). The cane's relative height growth rate (HGR) was reported to decrease during an early-season drought (Jangpromma et al., 2012). Not only does drought stress affect plant growth, but it could also reduce yield components at harvest, with such reductions could decrease the cane yield (Leanasawat et al., 2021). *S. spontaneum* showed drought tolerance and the lowest reduction percentages on agronomic traits, plant growth and cane yield (Leanasawat et al., 2021). Sugarcane genotypes have been developed from interspecific hybridization between *S. officinarum* and *S. spontaneum* to enhance drought tolerance. Additionally, the commercial cane is backcrossed with interspecific hybrids to improve its high biomass and sugar content

(Thirugnanasambandam et al., 2023). Drought-tolerant genotypes may maintain plant growth and high yields under drought-stress conditions (Khonghintaisong et al., 2021). Different agronomic traits may promote high cane yield under drought stress conditions on diverse sugarcane genotypes. However, no information has been reported comparing diverse sugarcane genotypes (F1, BC1, BC2 and commercial cane) in growth characteristic behavior and agronomic traits for promoting high cane yield at harvest under drought stress conditions. It is crucial for drought-tolerant breeding programs to obtain information on how growth characteristic behavior and agronomic traits respond to drought and contribute to cane yield.

Therefore, the current study aimed to determine plant growth, yield component traits and cane yield for a diverse set of sugarcane genotypes under well-watered and early drought-stress conditions in the tillering and early stalk elongation stages of sugarcane growth. Understanding water stress-response plant growth and important traits for cane yield promotion of diverse sets of sugarcane genotypes is important for drought-tolerant sugarcane breeding success.

Materials and Methods

Experimental design and cultural practices

The field experiment took place from November 2020 to November 2021 at the Khon Kaen Field Crops Research Center, Tha-phra Station, Khon Kaen province, Thailand (16°20'N, 102°4'E, elevation 166.7 m above sea level). The experiment was set up using split plots within a randomized complete block design with three replications. The main plots were allocated to two water regime management conditions: 1) well-watered condition (WW) that was watered at field capacity (FC) with a 12.4% soil moisture content; and 2) early drought stress condition (DS), where sugarcane was planted under early drought stress conditions (2–6 mth after tillering; MAT), during the tillering and early stalk elongation phase, then re-watered in even recovery periods (6–12 MAT). The sub-plots consisted of six sugarcane genotypes, made up of four interspecific hybrids between *S. officinarum* x *S. spontaneum*—F03-362 (F1), TPJ04-768 (BC1), KK09-0358 (BC1) and KK09-0939 (BC2)—as well as two commercial genotypes—KK3 (adaptive) and UT12 (drought susceptible), according to Khonghintaisong et al. (2021).

The sugarcane was placed inside a plastic bag to generate uniform sugarcane seedlings. The sugarcane plants were transplanted to the field 21 d after planting. The main plot was divided into six sub-plots, each measuring eight rows that were 12.0 m long. The plants within each sub-plot were spaced 0.5 m apart in one direction and 1.5 m apart in the other. The soil had a sandy loam texture (78.2% sand, 15.3% silt and 6.5 clay), the FC was 12.4%, the permanent wilting point (PWP) was 2.1%, the bulk density was 1.6 g/cm³ at 0–30 cm and the pH was 5.35 for all samples. Furthermore, the electrical conductivity (EC) was 0.014 dS/m, available phosphorus was 51.8 mg/kg, exchangeable potassium was 46.0 mg/kg, exchangeable calcium was 77.6 mg/kg and exchangeable manganese was 8.4 mg/kg. A chloroacetanilide herbicide (Alachlor 48% weight per volume, emulsifiable concentrate: 2-chloro-2',6'-diethyl-/V-methoxymethy) was used to control weeds by applying it before they emerged.

A mini-sprinkler was used for crop establishment from transplanting to 1 MAT to obtain a consistent soil moisture content, with water provided uniformly to the trial field to FC. Later, the mini-sprinkler was replaced with a drip irrigation system. The WW remained at FC for the duration of the crop growth cycle. During DS, early drought was imposed by withholding water for 2–6 MAT (5 mth). After 6 MAT, the plant was re-watered using a drip irrigation system at FC and maintained at this level until harvest. Water quantities were recorded using a water meter to accurately determine water usage (the amount based on water crop requirements. Initially, the formula of Jangpromma et al. (2010) was used to determine the crop water requirement for sugarcane, as shown in Equation 1:

$$ET_{\text{crop}} = ET_o \times K_c \quad (1)$$

Where ET is evapotranspiration, ET_o is the amount of crop water required for sugarcane at different stages ($ET_o = K_p \times E_{\text{pan}}$, where K_p is the pan coefficient (class A pan with green fetch) and E_{pan} is the pan evaporation in millimeters per day)) and K_c is the crop water requirement coefficient for sugarcane, where $K_c = 0.55$ during the initial period (0–20 d after planting; DAP), $K_c = 0.80$ during the establishment stage (21–36 DAP), $K_c = 0.90$ during tillering (37–96 DAP), $K_c = 1.10$ during stem elongation (97–236 DAP), $K_c = 1.05$ during the yield formulation stage or sugar accumulation (237–336 DAP) and $K_c = 0.60$ during the maturity stage (337–365 DAP), according to Khonghintaiong et al. (2021).

Data collection

Soil moisture content

The soil moisture content (SMC) was measured at monthly intervals from 1 MAT to 12 MAT using a gravimetric method at depths of 0–60 cm. The soil samples were oven-dried at 105°C for 72 hr or until a consistent weight was recorded. The percentage of soil moisture content was calculated using Equation 2, according to Tippayawat et al. (2023):

$$SMC (\%) = \frac{[(\text{Wet soil mass} - \text{Dry soil mass}) / \text{Dry soil mass}] \times 100}{\quad} \quad (2)$$

Relative water content

The relative water content (RWC) was evaluated at 1 MAT, 4 MAT, 6 MAT, 8 MAT and 10 MAT at the bottom, middle and top positions on a fully expanded leaf. At each sampling time, the leaf was cut into 2 cm² pieces at 09:00–11:00 hours, placed in a tube and stored immediately in an icebox. After recording the fresh weight of the sample, it was soaked in distilled water for 24 hr, the leaf surface was blotted dry and then reweighed as the saturated weight of the leaves. After 48 hr of oven drying at 80 °C, the dry leaf weight was recorded. The RWC was determined using Equation 3, according to Silva et al. (2013):

$$RWC (\%) = \frac{[(\text{Leaf fresh weight} - \text{Leaf dry weight}) / (\text{Leaf saturated weight} - \text{Leaf dry weight})] \times 100}{\quad} \quad (3)$$

Plant growth

The stalk number per stool was collected from four representative stools per plot at 6 MAT, 8 MAT, 10 MAT and 12 MAT. The four uniform main stalks, tagged at 1 MAT from the four representative stools per plot, were used to determine the stalk height. Each stalk of the sample was measured from the ground to the upper exposed dewlap at 3 MAT, 6 MAT, 8 MAT, 10 MAT and 12 MAT. The HGR was calculated using Equation 4, according to Khonghintaiong et al. (2021):

$$HGR = (H_2 - H_1) / (T_2 - T_1) \quad (4)$$

where H_2 is the height at the second measurement and H_1 is the height at the first measurement and T is the time interval between the two measurements.

Cane yield and yield component

The field-grown sugarcane in the two middle rows of each plot were manually harvested the millable cane stalk number and cane yield (tonnes of cane per hectare) were determined. Ten samples per plot were collected and measurements were made of the stalk diameter at 1 m above the ground, the stalk lengths and the single stalk weight.

Statistical analysis

A split-plot design was used for each characteristic to analyze variance (Gomez and Gomez, 1984). The least significant difference (LSD) test was used for mean comparisons. The Statistix 10 software program was used to perform the calculations (Analytical Software; Tallahassee, FL, USA).

Results

Soil moisture and plant water status

At 1 MAT, the SMC was comparable for both the WW and DS settings, since the droughting had not yet begun (Fig. 1). On the other hand, during the drought period (2–6 MAT), at 4 MAT, the SMC was clearly differentiated between the drought and irrigated treatments. At 4–5 MAT, the SMC dropped to 4.2–3.8% of the drought treatment level, which reduced the FC value (to 66.1–69.4%). However, due to rainfall at the end of the drought period (at 6 MAT), soil moisture levels in DS increased by 8.1%. Then, with the recovery that began after 6 MAT, the values returned to FC at 8–12 MAT. The RWC under DS was no different from WW at 1 MAT, which explained why the sugarcane plant water status was equal to its value before initiating drought stress in the DS treatment. Nevertheless, during drought stress periods under DS, the RWC was reduced significantly ($p < 0.05$) at 4 MAT compared

to WW. There was no difference in the RWC between WW and DS during the recovery periods.

Genotypic variation and genotype $\times$ water regime interaction for plant height, height growth rate and number of stalks per stool

At 3 MAT, 6 MAT, 8 MAT, 10 MAT and 12 MAT, the plant height significantly ($p < 0.05$) differed in genotype (G) and water regime (W), with the $G \times E$ interaction also significant at 3 MAT, 8 MAT and 12 MAT (Table 1). There were significant ($p < 0.05$) differences in the HGR for G at 6 MAT, 8 MAT, 10 MAT and 12 MAT (Table 2). The HGR was significantly ($p < 0.05$) different for W and the $W \times G$ interaction effects were also significant at 6 MAT and 8 MAT. The number of stalks per stool was significantly ($p < 0.05$) different for W and G at 6 MAT, 8 MAT, 10 MAT and 12 MAT (Table 3). The $W \times G$ interaction effects were significant ($p < 0.05$) for the number of stalks per stool at 10 MAT and 12 MAT.

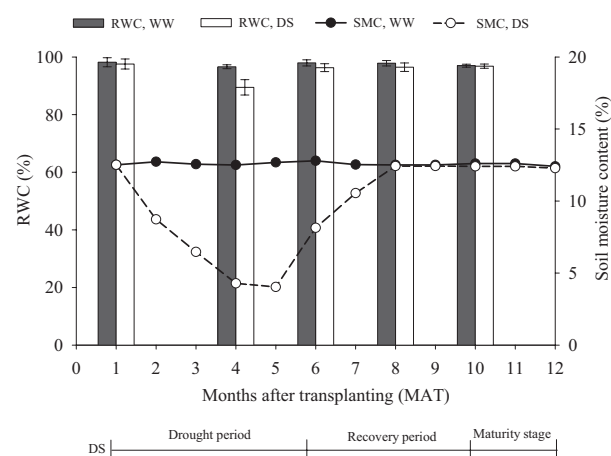


Fig. 1 Soil moisture content (SMC) at soil depth of 0–60 cm and relative water content (RWC) under well-watered (WW) and drought stress (DS) conditions during crop growth periods of sugarcane, where error bars = $\pm$ SD.

Table 1 Mean square statistics from analysis of variance for plant height at different months after tillering (MAT) under two water regimes with six sugarcane genotypes

SOV	DF	Plant height (cm)				
		3 MAT	6 MAT	8 MAT	10 MAT	12 MAT
Block	2	12.7	173.4	832.5	1,029.8	1,021.2
Water regime (W)	1	1,228.5 *	59,049.0 *	39,521.4 *	42,869.7 **	37,817.3 *
Error (a)	2	49.4	969.3	1986.1	483.9	747.7
Genotypes (G)	5	1,440.7 **	15,000.0 **	20,192.6 **	23,318.3 **	32,235.7 **
$W \times G$	5	158.1 **	995.5 ns	2,051.2 **	2,222.8 ns	2,458.0 **
Error (b)	20	17.0	521.0	221.4	864.8	385.6

ns = not significant; * = significant at $p < 0.05$; ** = significant at $p < 0.01$; DF = degrees of freedom; SOV = source of variation.

Table 2 Mean square statistics from analysis of variance for height growth rate (HGR) at different months after tillering (MAT) under two water regimes with six sugarcane genotypes

SOV	DF	HGR (cm/day)			
		6 MAT	8 MAT	10 MAT	12 MAT
Block	2	0.02	0.05	0.05	0.13
Water regime (W)	1	5.73 **	3.31 *	0.10 ns	0.02 ns
Error (a)	2	0.02	0.06	0.02	0.11
Genotypes (G)	5	0.97 **	1.02 **	0.07 *	0.33 **
W × G	5	0.06 *	0.97 **	0.76 ns	0.04 ns
Error (b)	20	0.02	0.03	0.03	0.08

ns = not significant; * = significant at $p < 0.05$; ** = significant at $p < 0.01$; DF = degrees of freedom; SOV = source of variation.

Table 3 Mean square statistics from analysis of variance for stalk number at different months after tillering (MAT) under two water regimes with six sugarcane genotypes

SOV	DF	Stalk number (stalks/stool)			
		6 MAT	8 MAT	10 MAT	12 MAT
Block	2	2.94	0.14	0.05	0.83
Water regime (W)	1	26.54 *	40.96 *	17.81 **	12.23 *
Error (a)	2	1.02	0.88	0.16	0.52
Genotypes (G)	5	49.21 **	49.22 **	62.68 **	50.78 **
W × G	5	1.06 ns	2.28 ns	1.93 **	0.60 ns
Error (b)	20	0.69	1.38	0.36	0.50

ns = not significant; * = significant at $p < 0.05$; ** = significant at $p < 0.01$; DF = degrees of freedom; SOV = source of variation.

Responses of plant height, height growth rate, and stalk number under well-watered and drought-stress conditions and recovery periods of diverse set of sugarcane genotypes

Early drought (during 2–6 MAT) significantly ($p < 0.05$) decreased the plant height by an average of 42% compared with WW at 6 MAT (Fig. 2). In addition, the KK3 genotype had fully recovered plant heights at 8–12 MAT, while F03-362 was recovering at 8 MAT, though every plant height was different between WW and DS in F03-362 during 10–12 MAT. Therefore, the TPJ04-768, KK09-0939 and UT12 genotypes that experienced early drought stress did not fully recover following re-watering (8–12 MAT).

All sugarcane genotypes showed differences in HGR between WW and DS at 6 MAT (Fig. 3). However, during the recovery periods, the HGR of the sugarcane increased under DS. The HGR under drought stress conditions was greater with early re-watering than WW, rapidly reduced during the maturity stage, and was not significantly ($p < 0.05$) different between WW and DS. During the recovery periods at 8 MAT, the HGR of the sugarcane genotypes could be classified into two patterns: 1) F03-362, KK09-0358 and KK3 had significantly ($p < 0.05$) higher HGR values for DS than for WW; and 2) TPJ04-768, KK09-0939 and UT12 were unable to enhance the HGR during DS compared to WW.

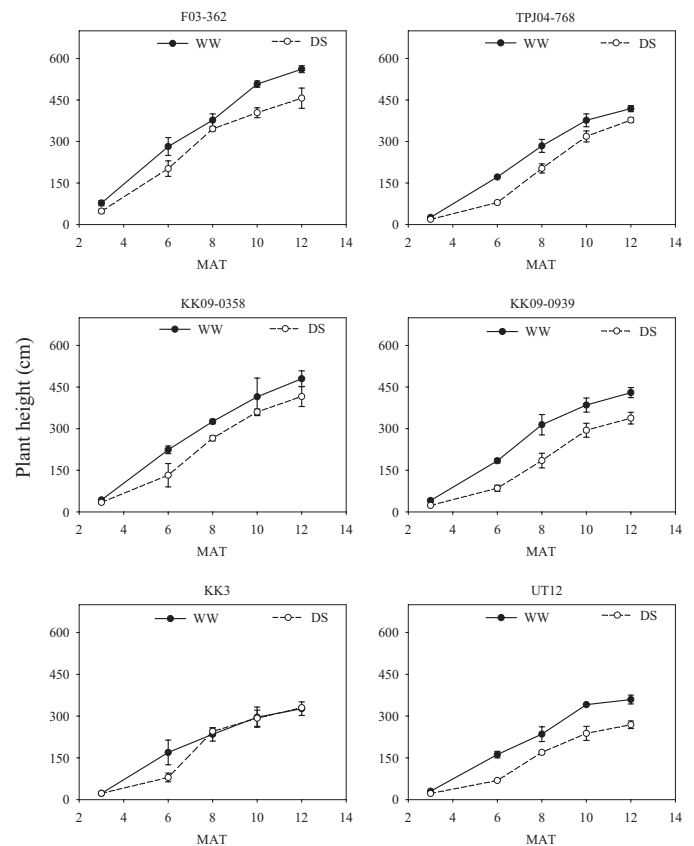


Fig. 2 Plant height of six sugarcane genotypes under well-watered (WW) and drought stress conditions (DS) at different months after tillering (MAT), where error bars = $\pm$ SD.

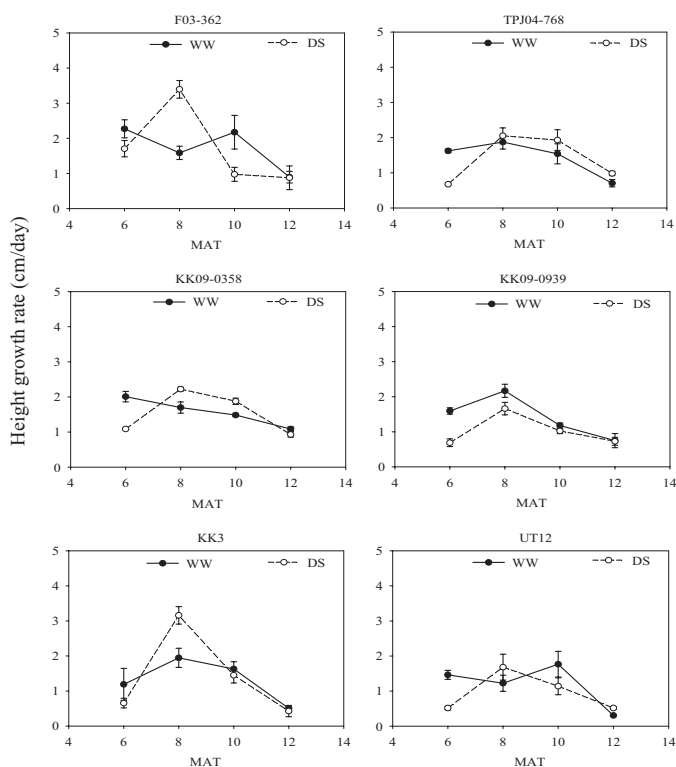


Fig. 3 Height growth rate of six sugarcane genotypes under well-watered (WW) and drought stress conditions (DS) at different months after tillering (MAT), where error bars = $\pm$ SD.

DS decreased the number of stalks per stool by an average of 22% compared to WW at 6 MAT (Fig. 4). The interspecific hybrid sugarcane genotypes had more stalks per stool than the commercial sugarcane genotypes under both watering conditions. After re-watering, the stalk number per stool increased in all genotypes under DS. However, the KK3 and F03-362 genotypes had fully recovered their numbers of stalks per stool at 12 MAT. Notably, the KK09-0358, TPJ04-768, KK09-0939 and UT12 genotypes that experienced early drought stress did not fully recover following re-watering at 12 MAT.

Cane yield and yield component under well-watered and drought-stress conditions and recovery periods of diverse set of sugarcane genotypes

There were significant ($p < 0.05$) differences in stalk length and single stalk weight between WW and DS; however, there was no significant difference for stalk diameter (Table 4). However, there were significant ($p < 0.05$) differences in stalk length, diameter and single stalk weight among the sugarcane genotypes. F03-362 had the highest stalk length, followed by KK09-0358 under both conditions. The KK3 genotype

produced the lowest stalk length under WW. However, there was no difference in the stalk length for the KK3 and KK09-0358 genotypes between the water regimes. While UT12 had the lowest stalk length under DS, it had the largest stalk diameters, followed by KK3, TPJ04-768, KK09-0358, KK09-0939 and F03-362, respectively. There were significant ($p < 0.05$) differences in the single stalk weight among the sugarcane genotypes. KK3 and UT12 had high single stalk weights under both water conditions. At the same time, KK09-0358 had a high single stalk weight only for DS. DS had the most impact on reducing single stalk weight in KK09-0939 compared to its potential under WW.

Under DS, the number of millable canes decreased significantly ($p < 0.05$), by an average of 15%, compared with WW. The average millable cane values among genotypes were significantly ($p < 0.05$) different. The millable cane number was highest in F03-362, followed by KK09-0939, KK09-0358 and TPJ04-768, with KK3 and UT 12 producing the lowest numbers of millable canes (Table 5). There were no significant differences for F03-362, KK09-0358, KK3 and UT12 between the numbers of millable canes between WW and DS for each sugarcane genotype.

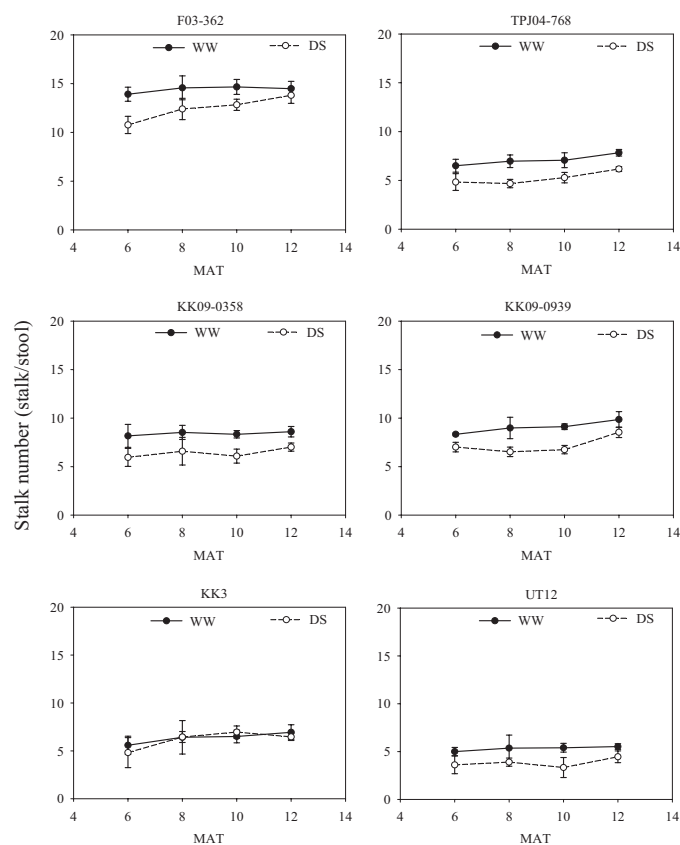


Fig. 4 Stalk number of six sugarcane genotypes under well-watered (WW) and drought stress conditions (DS) at different months after tillering (MAT), where error bars = $\pm$ SD.

Table 4 Stalk length, stalk diameter and single stalk weight under well-watered (WW) and drought stress (DS) conditions at harvest for six sugarcane genotypes

Genotype	Stalk length (cm)		Stalk diameter (cm)		Single stalk weight (kg)	
	WW	DS	WW	DS	WW	DS
F03-362	561.2 ± 12.4 ^{aA}	456.5 ± 36.6 ^{aB}	1.80 ± 0.09 ^{dA}	1.79 ± 0.02 ^{dA}	0.94 ± 0.08 ^{dA}	0.76 ± 0.05 ^{cA}
TPJ04-768	418.8 ± 10.9 ^{cA}	377.2 ± 8.1 ^{bcB}	2.27 ± 0.07 ^{cB}	2.44 ± 0.06 ^{bA}	1.49 ± 0.08 ^{cA}	1.29 ± 0.09 ^{bA}
KK09-0358	480.0 ± 28.7 ^{bA}	416.1 ± 36.3 ^{bA}	2.40 ± 0.07 ^{cA}	2.32 ± 0.10 ^{bA}	1.68 ± 0.13 ^{bA}	1.49 ± 0.16 ^{abA}
KK09-0939	430.0 ± 18.2 ^{cA}	338.0 ± 21.1 ^{cdB}	2.38 ± 0.04 ^{cA}	2.13 ± 0.10 ^{cA}	1.14 ± 0.12 ^{dA}	0.77 ± 0.03 ^{cB}
KK3	326.5 ± 24.3 ^{cA}	330.0 ± 2.1 ^{dA}	2.70 ± 0.23 ^{bA}	2.44 ± 0.15 ^{bA}	1.83 ± 0.18 ^{abA}	1.59 ± 0.23 ^{aA}
UT12	359.4 ± 15.9 ^{dA}	269.0 ± 13.6 ^{cB}	2.99 ± 0.06 ^{aA}	2.70 ± 0.15 ^{aA}	2.07 ± 0.21 ^{aA}	1.59 ± 0.09 ^{aA}
Mean	429.3A	364.5B	2.42A	2.30A	1.53A	1.25B
F test	**	**	**	**	**	**
CV (%)	4.01	5.98	4.58	4.21	11.44	9.7

CV = coefficient of variation.

Different lowercase superscripts indicate significant differences ($p < 0.05$) among mean values within each column, while different uppercase letters denote significant differences ($p < 0.05$) between the means of each trait under two irrigation treatments within each genotype, determined by the least significant difference (LSD) test.

Table 5 Millable cane and cane yield under well-watered (WW) and drought stress (DS) conditions at harvest of six sugarcane genotypes

Genotype	Millable cane (stalks/ha)		Cane yield (t/ha)		Cane yield reduction (%)
	WW	DS	WW	DS	
F03-362	193,162 ± 10,015 ^{aA}	170,707 ± 24,304 ^{aA}	158.0 ± 8.3 ^{abA}	129.2 ± 13.3 ^{aA}	17.9 ± 0.9 ^c
TPJ04-768	104,394 ± 4,474 ^{cdA}	82,202 ± 3,280 ^{cdB}	135.5 ± 12.8 ^{cA}	106.5 ± 11.6 ^{bB}	21.3 ± 2.3 ^b
KK09-0358	114,636 ± 7,189 ^{cA}	93,495 ± 5,590 ^{cA}	167.5 ± 11.9 ^{aA}	138.7 ± 6.4 ^{aA}	17.1 ± 0.7 ^c
KK09-0939	131,444 ± 10,877 ^{bA}	113,849 ± 7,167 ^{bB}	129.9 ± 10.2 ^{cA}	87.3 ± 7.8 ^{cB}	32.3 ± 2.9 ^a
KK3	92,576 ± 10,445 ^{dA}	86,141 ± 5,065 ^{cdA}	145.9 ± 9.0 ^{bcA}	136.0 ± 11.4 ^{aA}	6.3 ± 1.7 ^d
UT12	73,667 ± 3,939 ^{cA}	70,121 ± 2,841 ^{dA}	132.7 ± 13.7 ^{cA}	111.8 ± 10.0 ^{bA}	15.5 ± 1.1 ^c
Mean	118,313A	102,753B	144.9A	118.2B	18.4
F test	**	**	**	**	**
CV (%)	6.76	10.44	7.39	7.61	9.8

CV = coefficient of variation.

Different lowercase superscripts indicate significant differences ($p < 0.05$) among mean values within each column, while different uppercase letters denote significant differences ($p < 0.05$) between the means of each trait under two irrigation treatments within each genotype, determined by the least significant difference (LSD) test.

Under DS, the cane yield decreased significantly ($p < 0.05$), by an average of 118.2 t/ha under DS compared to WW (144.9 t/ha), as shown in Table 5. The cane yield for F03-362 and KK09-0358 was significantly ($p < 0.05$) higher under WW; additionally, F03-362 and KK09-0358 had high cane yields under DS, whereas KK3 had a high cane yield only under DS. KK09-0939 had low cane yield under WW and DS (with the lowest potential and the highest reduction percentage), with the cane yield decreasing by 32.3%.

Discussion

Impact of drought on yields and components of diverse set of sugarcane genotypes

Early drought stress reduced the stalk length, single stalk weight and the number of millable canes, which reduced the

cane yield in the different sugarcane genotypes (F1, BC1, BC2, and commercial genotypes). Leanasawat et al. (2021) reported that drought stress reduced the cane yield in interspecific and commercial sugarcane genotypes. In addition, Misra et al. (2022) and Tripathi et al. (2022) found that drought stress reduced biomass accumulation, cane length, cane weight, cane girth and overall dry matter production, resulting in decreased cane yields.

The diverse set of six sugarcane genotypes in the current study indicated that the high cane yield under drought stress conditions was due to two reasons: 1) the high potential cane yield under WW and the quite low reduction in cane yield under DS (F03-362 and KK09-0358); and 2) with medium potential cane yield there was a low reduction in yield (KK3). At the same time, the drought-susceptible genotype (KK09–0939) showed low potential and a high reduction in cane yield. The F03-362 (F1), KK09-0358 (BC1) and KK3 (commercial cane genotype) were drought tolerant and had high cane yields

under DS. Begum and Islam (2012) and Dhansu et al. (2021) reported drought-tolerant commercial cane genotypes produced high cane yields under DS, Leanasawat et al. (2021) and Xu et al. (2023) found that interspecific sugarcane genotypes had drought tolerance and good cane yields under drought stress conditions. The drought-tolerant genotypes in commercial cane genotypes and interspecific sugarcane genotypes (F1, BC1 and BC2) may have differences in growth and post-agronomic traits to compensate for their disadvantages, resulting in high cane yields under drought stress conditions for a diverse set of sugarcane genotypes. The current study prioritized the HGR pattern and cane yield of drought tolerance genotypes of diverse sets of sugarcane genotypes; additionally, it considered quality-related yield components, such as sugar yield, CCS and fiber content. According to Alarmelu et al. (2014), the quality characters tended to continuously increase in Brix%, sucrose and CCS in BC1 and BC2, which could be used for dual purposes (to enhance sugar and fiber).

Differences in agronomic traits for promoting high cane yields of diverse set of sugarcane genotypes

The KK3 (commercial cane) genotype is a cross between clone 85-2-352 (commercial cane) and K 84-200 (commercial cane) (Mother x Father) (Cha-Um et al., 2012). From *S. officinarum*, KK3 has a large stalk diameter and single stalk weight (Su et al., 2020). While, KK09-0358 (BC1) has many millable canes and a high single stalk weight. KK09-0358, which is derived from a backcross between 95-2-317 (commercial cane) and F03-381 (F1), is a drought-resistant genotype, with shorter stalks and fewer millable canes than F03-362. However, it did better than the commercial cane genotypes in terms of stalk length and the number of millable canes, as well as being about the same size and weight as commercial cane under drought-stress conditions. Often, BC1 interspecific hybrid sugarcane exhibits more commercial traits than F1 hybrids because the backcrossing process helps reintroduce desirable commercial characteristics that may have been diluted in the F1 generation (Alarmelu et al., 2018).

The interspecific hybrids, F03-362 (F1), are crosses between 88-2-401 (commercial cane) and ThS98-178 + ThS98-264 (bulk pollen) (wild type; *S. spontaneum*). The characteristics of *S. spontaneum*, such as stalk diameter and stalk number, can be inherited by interspecific genotypes. Thus, the F03-362 (F1 hybrid of interspecific sugarcane genotype) was the smallest in stalk diameter and had many millable canes, contributing to the genetic improvement of sugarcane

genotypes (da Silva et al., 2017; Xu et al., 2020; Pathy et al., 2022). However, according to Xu et al. (2023), the most significant number of millable canes of interspecific hybrid sugarcane genotypes to compensate for small stalk size through increased stalk population is an interesting phenomenon. Notably, the performance and suitability of these hybrids can vary depending on various factors such as the specific parent species, growing conditions, and management practices (Yang et al., 2020). Future sugarcane breeding programs should prioritize enhancing drought tolerance, decreasing stalk diameter and increasing stalk number to maintain yield along with mechanized sugarcane harvester suitability.

Height growth rate and plant growth under drought and recovery of diverse set of sugarcane genotypes

In this study, all six sugarcane genotypes had an average drop in stalk height and HGR due to early drought stress. Jangpromma et al. (2012) reported that the HGR of sugarcane was reduced under an early-season water deficit. According to Inman-Bamber and Smith (2005) and Farooq et al. (2009), the causes of the decline in plant development during droughts include changed plant water relations, decreased CO₂ absorption, cellular oxidative stress, membrane damage to damaged tissues and inhibition of enzyme activity. In addition, when plants experience water stress, they often shift their energy allocation to enhance survival. Typically, this involves prioritizing root growth over aboveground growth, allowing the plant to search for water more effectively. As a result, stem elongation and height growth slow down. This adaptive response helps plants cope with drought conditions but can impact overall biomass production and yield (Balasubramaniam et al., 2023; Roy et al., 2023). In addition, the drought stress response regarding the number of stalks per stool depends on the sugarcane, as early drought stress restricts the plant's ability to produce tillers, which directly limits the number of stalks that develop from each sugarcane stool. This reduction can lead to lower overall biomass and potentially reduce the yield at harvest (Tripathi et al., 2022).

In the current study, HGR during the recovery period was an important trait contributing to plant height and stalk length at the final harvest. The recovery phase was important to promote sugarcane productivity under water-deficit conditions during early sugarcane growth. According to Khonghintaiong et al. (2021), the height growth rate of sugarcane increased after re-watering under rain-fed conditions but rapidly decreased during the ripening stage. Therefore, it could be that HGR is

an indirect approach for selecting high cane yields under water deficit conditions in the formative stage. Thus, the growth characteristics of diverse sugarcane genotypes may differ under drought-stress conditions. Even after early re-watering, the drought-tolerant genotypes in the commercial cane and interspecific sugarcane genotypes (F1 and BC) had much better recovery in HGR than their susceptible counterparts.

However, the diverse set of drought-tolerant genotypes had different patterns for plant height, with the plant height of the drought-tolerant interspecific hybrid genotypes (F03-362 and KK09-0358) not recovering by harvest. Therefore, F03-362 and KK09-0358 had a trait producing high potential in plant height. KK3 (a commercial drought-tolerant genotype) was highly stunted in plant height during drought stress but could fully and rapidly recover its height even after recovery periods of 8–12 MAT. Furthermore, the assessment of drought tolerance in elite sugarcane hybrids based on yield traits under water-stressed conditions provides valuable insights into the relationship between morphological traits and drought tolerance, aiding in the selection of drought-tolerant genotypes (Xu et al., 2023)

The current study examined various sugarcane types (F1, BC1, BC2 and commercial cane) that considerably differed from commercial cane sugar (CCS) in terms of their classification ($F1 < BC1 < BC2 < \text{commercial cane}$) and fiber content ($F1 > BC1 > BC2 > \text{commercial cane}$). F03-362 (F1), KK09-0358 (BC1) and KK3 (commercial cane) were identified as drought-tolerant genotypes due to their high potential cane production and small reduction in yield percentage. Future sugarcane breeding programs should aim to improve drought resistance, reduce stalk diameter size and increase stalk number/stool to maintain yield while being suitable for mechanized harvesting. Sugarcane breeding programs can emphasize these features to generate new, drought-resistant genotypes by utilizing the proven resilience of genotypes such as KK09-0358 and F03-362. These genotypes could be used as parents or back crosses with high-yielding CCS commercial cane to increase sugar yield. Creating a new variety of cane with high fiber and sugar content may be beneficial to improve the efficiency and success of breeding for drought resistance and multipurpose cane.

Conclusion

Early drought reduced HGR, plant height, cane yield, stalk length, single stalk weight and number of millable canes were investigated in interspecific hybrid and commercial sugarcane genotypes. F03-362 (F1), KK09-0358 (BC1) and

KK3 (commercial cane) were identified as drought-resistant genotypes based on their high potential cane yield and low yield reduction percentage. The HGR during early recovery periods was essential to promote plant height even after re-watering in all types of diverse genotypes. Even after recovery, the drought-resistant genotypes (F03-362, KK09-0358, and KK3) showed greater HGRs than the drought-susceptible genotypes. The drought-resistant genotypes from the diverse set investigated showed traits promoting cane yield, with F03-362 having the highest number of millable canes. At the same time, KK09-0358 and KK3 had medium numbers of millable canes and high single stalk weights. Future sugarcane breeding programs should aim to improve drought resistance, reduce stalk diameter size, and increase stalk number/stool to maintain yield while being suitable for mechanized harvesting.

Acknowledgements

Funding was provided by: the National Science Research and Innovation Fund (NSRF) via the Khon Kaen University Fundamental Fund; and the Northeast Thailand Cane and Sugar Research Center (NECS) of Khon Kaen University (KKU). The Khon Kaen Field Crops Research Center provided research facilities under the Department of Agriculture.

Conflict of Interest

The authors declare no conflicts of interest.

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