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RESEARCH ARTICLE

Exploring the impact of heat waves on early crop growth in sugarcane clones

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Abstract

Sugarcane, a vital crop for sugar production and increasingly important for biofuels, faces challenges due to frequent and unusual weather patterns as well as rising temperatures. Heat stress poses a significant threat to plant health, leading to dehydration, reduced photosynthesis, stunted growth and ultimately diminished yields. This study evaluates heat stress tolerance in 32 sugarcane clones selected from a group of 1,261 clones based on their high Brix percentage and early vigour. Plant height was recorded at 15-day intervals and revealed a significant reduction between days 76 to 90, with an average increase of only 7.8 cm in plant height compared to an overall increase of 32.7 cm. This period coincided with an eight-day severe heat wave reported by the Indian Meteorological Department. Despite the stress, five clones exhibited normal growth during this period, demonstrating their potential resilience. The study identified these promising heat-tolerant clones as candidates for breeding programs aimed at developing varieties with enhanced heat stress resilience.

Keywords

heat stress; heat tolerant; heat waves; high temperature; plant height; sugarcane

Introduction

Sugarcane is one of the most important crops in the world and provides the majority of the sucrose needed to produce sugar. It is also a major component of the bioenergy and bio-based product industries. It is cultivated in nearly 100 countries, with an annual production of 1.9 billion tons. This accounts for 80% of global sugar and 40% of bioethanol, representing a market value of $80 billion (1). The production and productivity of sugarcane determine its profit margin with sucrose being a key component. Unusual weather patterns can significantly affect crop growth, even though the higher sucrose content is necessary. Disruption of proper growth can result in significant losses and poor harvest quality. Unexpected frosts, unusually high rainfall, droughts and heat waves are examples of these abiotic anomalies, each posing distinct risks to the crop production stability. Rising temperatures have exposed most of the world's crops to heat stress at various points of their life cycle. The uncertainty in predicting the expected agricultural implications of climate change presents a significant challenge (2, 3).

The UN Secretary-General declared July 2023 as the start of the "Era of Global Boiling"**.** This shift from global warming to global boiling denotes increased average temperature and more frequent severe heat waves, which disrupt the ecosystem and economy (4). Heatwaves pose a serious hazard to crop health and frequently made worse by climate change. For instance, temperatures above 34°C can trigger stomatal closure to prevent water loss. This reduces photosynthesis, disrupts energy production and ultimately impairing growth and yield potential. Severe heat waves can result in heat stress, which can impede plant growth and in the worst situations, killing the plant. Strategies to mitigate the negative impacts of these climatic abnormalities include adjusting planting schedules, choosing hardy crop varieties and implementing improved irrigation systems. The Intergovernmental Panel on Climate Change (IPCC) report predicts that temperatures will rise by at least 1.5°C by 2040, even in low-CO_2 emission scenarios (5).

Thus, cultivating crop varieties with increased resilience to these stresses is imperative. Achieving this objective requires a thorough comprehension of how plants react to heat stress. Identifying clones that can withstand heat stress could greatly expand the gene pool. Empirical evidence suggests that 1°C rise in seasonal temperature during the twenty-first century will lead to direct yield losses ranging from 2.5% to 16% in agronomic species (6, 7).

Yield losses due to heat stress from temperatures exceeding 33°C are common in many regions worldwide (8). Given that sugarcane is a C4 plant, its photosynthetic pathway enhances the uptake of carbon dioxide as temperature rises up to 34°C (9, 10). Sugarcane grows best at 32–33°C; however, beyond this range, yields are significantly reduced (11). When exposed to drought and heat stress, plants react in different ways. Plants close their stomata to conserve water when the soil becomes dehydrated. On the other hand, plants open their stomata to improve transpiration and cool their leaves in reaction to rising temperatures. Plants respond to these stresses at molecular and physiological level (12). The influence of heat stress is based on its intensity and duration (13).

Compared to other crops, sugarcane requires more space, a longer crop cycle and it relies heavily on flowering for improvement. The selection cycle is lengthy, requiring 12 to 15 years. Each year, thousands of fluffs (seeds) are collected and grown, with an average selection rate of one in 2,300 seedlings (14). This process demands significantly more agricultural inputs, such as land, labour, capital, fertilizers and pesticides than other crops.

Plant growth is assessed by various traits, with plant height being the most direct and obvious. It is one of the important parameters that helps to analyse and predict the plant growth and can affect the final yield (15). This study investigates the relationship between plant height and the rise in temperature. The objective is to identify potential heat-tolerant candidates during the early crop growth, thereby establishing a cost-effective screening approach. This approach aims to enhance efficiency in selecting heat-tolerant varieties early in the growth cycle, ultimately leading to more resilient crop production.

In sugarcane breeding, this study serves as a valuable resource for achieving heat stress tolerance. In the coming years the weather patterns are expected to become more extreme, which will affect the normal growth of the plant. Unusual weather patterns in recent years have highlighted the growing need to develop sugarcane varieties with high yields and abiotic stress tolerance.

Materials and Methods

During November 2021, parental crosses were affected at the National Hybridization Garden (NHG), Sugarcane Breeding Institute, Coimbatore, India. At the Sugarcane Research Station, Cuddalore, the fluffs were germinated and planted to establish the ground nursery in 2022. Clones with desirable traits such as high Brix percentage, cane girth, cane height and non-flowering were advanced to clonal nursery I in 2023. Thirty-two elite clones with high Brix and early vigour were selected from clonal nursery I, which comprised 1,261 clones. These selected clones were raised at the Sugarcane Research Station, Cuddalore, in 2024 to conduct the present study. The clones were planted in 2-meter rows using the ridge-and-furrow method. Plant heights of each clone were recorded from 30th day after planting and every 15 days thereafter, in three replications *viz*., 30th, 45th, 60th, 75th, 90th, 105th, 120th and 135th day. Plant height was measured from base of the cane to the tip of the leaf. Minimum, maximum and average temperatures were obtained from the Sugarcane Research Station, Cuddalore; the Tamil Nadu Agriculture Weather Network; the Indian Meteorological Department and Climate data. Mean values were calculated over a fifteen-day period to align with the plant height measurements taken during the same period. All statistical analyses were performed using RStudio software, version 4.3.1, with the "variability" package (16).

Results and Discussion

Results for the analysis of variance, coefficients of variation, heritability, and genetic advance as a percentage of the mean are detailed in Tables 1, 2 and 3. As per the classification (17), the genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) are grouped into three levels: low (0–10%), moderate (10–20%), and high (above 20%). The GCV and PCV values were moderate for all plant height measurements across the various days, except for the 30th day, when they were high. This increase in variability on the 30th day could be attributed to the onset of rapid growth or environmental factors that might have influenced plant development more significantly at that stage. This indicates the potential for significant

Table 1. Analysis of variance for plant height across various time intervals of 32 sugarcane clones

S. No.	Source of variation	Mean sum of squares		
		Replication (df= 2)	Genotype (df=31)	Residuals (df=62)
1.	Plant height at 30th day	25.79	631.5*	9.6
2.	Plant height at 45th day	36.72	1089.17*	30.43
3.	Plant height at 60th day	3	2107.29*	29.15
4.	Plant height at 75th day	0.79	2676.06*	23.81
5.	Plant height at 90th day	22.92	2673.14*	24.41
6.	Plant height at 105th day	9.4	5332*	25.7
7.	Plant height at 120th day	55.4	5712.6*	18
8.	Plant height at 135th day	27.5	5734.5*	17.4

*significant at 5% interval

Table 2. Range, mean, environment variance (σ^2e), genotypic variance (σ^2g), and phenotypic variance (σ^2p) for plant height across various time intervals of 32 sugarcane clones

S. No.	Characters	Range	Mean	σ^2e	σ^2g	σ^2p
1.	Plant height at 30th day	27 - 100	65.2	9.6	207.3	216.9
2.	Plant height at 45th day	61 – 167	112.8	30.43	352.91	383.35
3.	Plant height at 60th day	102 – 217	154.8	29.15	692.71	721.86
4.	Plant height at 75th day	115 - 257	177.3	23.81	884.08	907.9
5.	Plant height at 90th day	127 - 266	185.1	24.41	882.9	907.32
6.	Plant height at 105th day	148 - 318	223	25.72	1768.77	1794.5
7.	Plant height at 120th day	169 – 332.4	241.9	18.01	1898.2	1916.2
8.	Plant height at 135th day	183 – 349.2	261.2	17.38	1905.7	1923.09

Table 3. Environmental coefficient of variance (ECV), genotypic coefficient of variance (GCV), phenotypic coefficient of variance (PCV), heritability broad sense (h^2), genetic advance (GA) and genetic advance as percent of mean (GA) for plant height across various time interval of 32 sugarcane clones

S. No.	Characters	ECV	GCV	PCV	h^2 as %	GA	GA as % of mean
1.	Plant height at 30th day	4.75	22.08	22.59	95.57	29	44.47
2.	Plant height at 45th day	4.89	16.65	17.35	92.06	37.13	32.9
3.	Plant height at 60th day	3.49	17.01	17.36	95.96	53.11	34.31
4.	Plant height at 75th day	2.75	16.77	17	97.38	60.44	34.09
5.	Plant height at 90th day	2.67	16.05	16.27	97.31	60.38	32.62
6.	Plant height at 105th day	2.27	18.86	19	98.57	86.01	38.57
7.	Plant height at 120th day	1.75	18.01	18.09	99.6	89.33	36.923
8.	Plant height at 135th day	1.6	16.71	16.79	99.1	89.5207	34.27

improvements through the selection of superior genotypes (18).

The variability analysis showed that the PCV was higher than the GCV. The difference is minimal (0.08 to 0.5%), indicating a limited environmental influence and a significant additive gene effect, which suggests these traits can be selected for improvement under stress conditions (19).

The traits from the present study exhibited high heritability (20). These finding are consistent with those of (21, 22). A high heritability value indicates that environmental or non-genetic factors have minimal influence on the expression of traits, making them more responsive to selection.

All traits exhibited high genetic advance as a percentage of the mean (>20%). High heritability values should be accompanied by high genetic advance to achieve effective trait selection and reliable predictions of anticipated genetic improvements (23). Therefore, high heritability and high genetic advance as a percentage of mean indicate additive gene effects, enabling simple and direct selection for future improvement of the trait.

Plant height for 32 clones was measured starting from the 30th day and subsequently at fifteen-day intervals, with a total of eight time intervals. These measurements were averaged across three replicates, as represented in Table 4. The plant height on the 135th day showed that clones C 230739 and C 230031 exhibited the highest and lowest plant height of 344.4 and 185.7 cm respectively, with an average plant height of 261.2 cm. Seventeen clones exhibited the plant heights above the average, while fifteen clones showed below-average plant height.

Among the eight time intervals, the 76-to-90 days interval (27.04.2024 to 12.05.2024) revealed reduced average plant height compared to the other intervals, as shown in Table 5. The increase in average plant height across all intervals was recorded at 32.7 cm. The average increase in plant height during the 76-to-90 days interval was 7.8 cm, representing only 23.9% of the growth relative to the average increase in plant height across all intervals combined (32.7 cm).

In association with temperature, the 76-to 90-days interval recorded the highest minimum temperature of 28.05°C, as depicted in Fig. 1. Research indicates that high

Table 4. Plant height increase (cm) from days after planting for every 15-days interval

S. No.	Clones	1 to 30 days	31 to 45 days	46 to 60 days	61 to 75 days	76 to 90 days	91 to 105 days	106 to 120 days	121 to 135 days	Total plant height (cm)
1	C 230031	31.0	34.3	43.7	10.0	14.3	32.7	8.0	11.7	166.0
2	C 230220	53.7	22.0	27.3	21.0	16.3	32.7	18.0	19.3	173.0
3	C 230245	54.3	48.3	51.0	20.0	8.9	36.3	16.0	30.3	218.9
4	C 230266	79.7	30.0	31.2	26.7	2.7	42.3	45.7	30.0	212.5
5	C 230274	64.0	44.0	43.7	41.0	16.0	63.3	16.3	23.3	272.0
6	C 230278	61.7	54.2	62.7	15.7	26.0	45.0	16.0	18.0	265.2
7	C 230280	56.3	46.2	52.0	16.0	7.8	54.7	10.0	4.0	233.0
8	C 230320	82.7	58.4	49.7	15.7	10.0	63.3	15.0	8.7	279.7
9	C 230321	72.7	61.2	53.3	16.3	8.0	57.3	39.3	25.3	268.9
10	C 230690	61.0	50.7	58.7	28.7	3.7	59.0	11.0	12.4	261.7
11	C 230709	83.3	65.1	54.7	14.3	5.7	89.0	9.0	5.7	312.1
12	C 230712	78.3	34.7	36.7	35.3	15.0	14.0	21.0	19.7	214.0
13	C 230717	62.3	44.3	59.0	30.3	1.5	51.7	13.7	22.0	249.2
14	C 230739	96.7	62.4	53.7	37.3	5.3	55.0	20.3	13.7	310.4
15	C 230771	72.7	48.3	53.0	29.7	0.3	51.0	29.3	12.7	255.0
16	C 230791	54.3	70.3	43.0	29.7	1.0	55.0	19.0	27.3	253.3
17	C 230803	84.7	27.7	35.4	12.0	11.7	69.3	17.7	31.7	240.7
18	C 230960	64.7	41.7	20.3	22.7	12.3	18.7	4.0	15.7	180.3
19	C 231034	80.3	41.7	24.7	37.0	2.0	19.7	24.0	38.3	205.3
20	C 231043	62.3	57.4	59.0	15.7	6.3	32.7	34.7	7.3	233.4
21	C 231050	60.3	55.3	42.0	13.7	2.7	27.0	11.7	9.7	201.0
22	C 231091	64.0	36.0	28.9	22.7	9.4	41.3	2.7	4.7	202.3
23	C 231107	70.7	48.0	29.0	16.0	18.0	25.0	11.7	7.0	206.7
24	C 231128	82.7	34.0	26.7	8.5	2.7	45.7	19.0	22.7	200.2
25	C 231190	57.7	57.4	43.4	21.7	0.3	8.3	13.3	30.3	188.8
26	C 231214	55.3	48.2	41.7	12.0	1.4	10.7	20.7	23.4	169.3
27	C 231226	59.7	27.3	25.7	14.3	2.5	36.0	17.7	6.3	165.5
28	C 231227	71.7	55.2	46.0	27.0	8.3	6.3	23.0	17.3	214.5
29	C 231231	68.3	57.2	53.2	32.7	9.7	23.3	27.7	26.3	244.4
30	C 231242	30.3	52.0	35.0	18.3	4.7	12.3	28.0	30.0	152.7
31	C 231251	47.7	59.3	21.3	19.7	4.0	19.3	24.7	34.0	171.3
32	C 231254	61.3	51.7	36.0	40.0	10.3	16.0	17.7	28.3	215.3

Table 5. Average increase in plant height for every 15-days interval

Days interval from planting	Mean increase in plant height (cm)
1 to 30	65.2
31 to 45	47.6
46 to 60	41.9
61 to 75	22.5
76 to 90	7.8
91 to 105	37.9
106 to 120	18.9
121 to 135	19.3

night time temperatures have a more significant impact on plant growth compared to daytime temperatures or mean daily temperatures (24, 25). Compared to the weather data from the previous year, the fifteen-day interval during the same month exhibited a statistically significant increase of 1.73°C, 2.41°C, and 2.07°C in minimum, maximum and average temperatures, respectively. Furthermore, the average temperature for this time interval has risen by 1.01°C compared to May over the three decades spanning 1991 to 2021 (26).

During the interval of 76 to 90 days, a specific eight-day (78 to 85 days) from 29.04.2024 to 07.05.2024 showed heat waves to severe heat waves, according to the data from the Indian Meteorological Department (27).

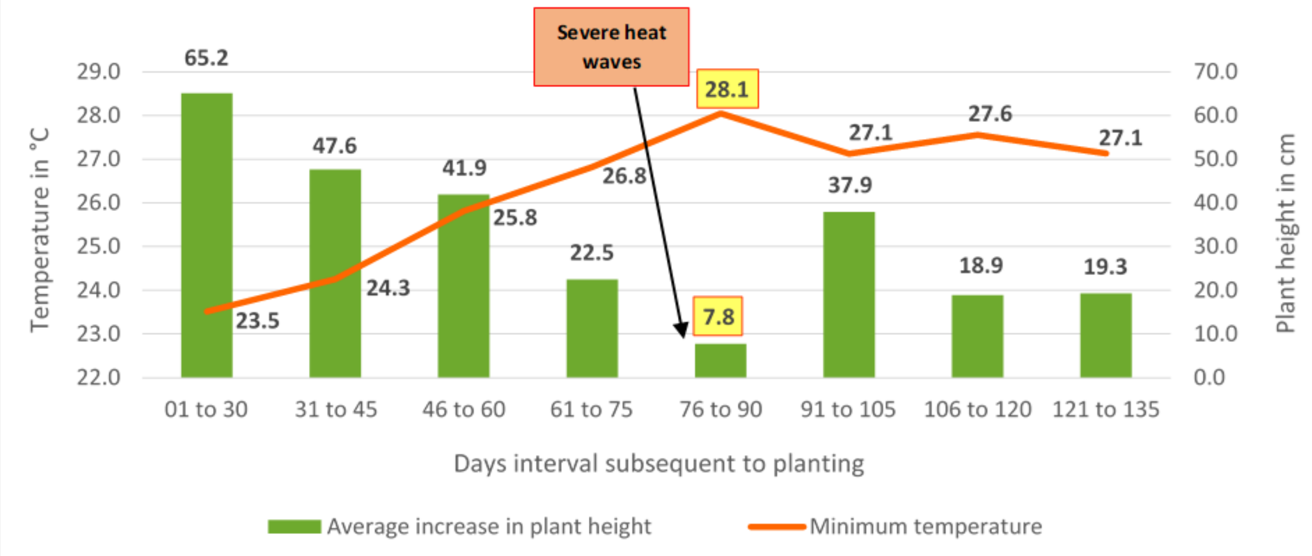

Fig. 1. Average increase in plant height in relation to minimum temperature over a 15-day interval.

Over the period of mentioned eight-days in 76-to-90 day interval of 2024, the recorded minimum, maximum, and average temperatures were 29°C, 36.28°C and 32.64°C, respectively. In comparison, a fifteen-day interval (days 76 to 90) in May 2023 recorded minimum, maximum and average temperatures of 28.05°C, 35.17°C, and 31.61°C as illustrated in Fig. 2. The increases in minimum, maximum and average temperatures between these intervals were 0.95°C, 1.11°C, and 1.03°C, respectively. A study revealed that sustained high temperatures of 33°C for five days led to a 15% reduction in the photosynthesis rate (28). In this study, the data clearly denote a considerable increase in temperature, which affected the normal growth of the plant.

During the 76-90-day period of crop growth (heat stress period), the average increase in plant height was reduced to 7.8 cm. During this time interval, out of 32 clones, only five clones exhibited increase in plant height more than 15 cm, while 13 clones showed less than 5 cm. These five clones (*viz.*, C 230220, C 230274, C 230278, C 230712 and C 231107) demonstrate potential as heat stress tolerant candidates. The average increase in plant height for the 5 clones and other clones was recorded as 18.3 cm and 5.8 cm, respectively. The five clones alone exhibited a 234.6% increase in average plant height, which accounted for most of the overall increase in average plant height (7.8 cm) during the heat stress. It was found that, under the heat stress, potential heat-tolerant genotypes and other genotypes experienced an average height reduction of 44.0% and 82.2%, respectively, in contrast to the overall average increase in plant height was 32.7 cm.

Clones C 230771 and C 231190 exhibited the lowest increase in average plant height (0.33 cm), indicating high susceptibility to heat stress compared to the other clones. This represents only 4.2% of the average increase in plant height observed during the 76-to-90 day interval (7.8 cm).

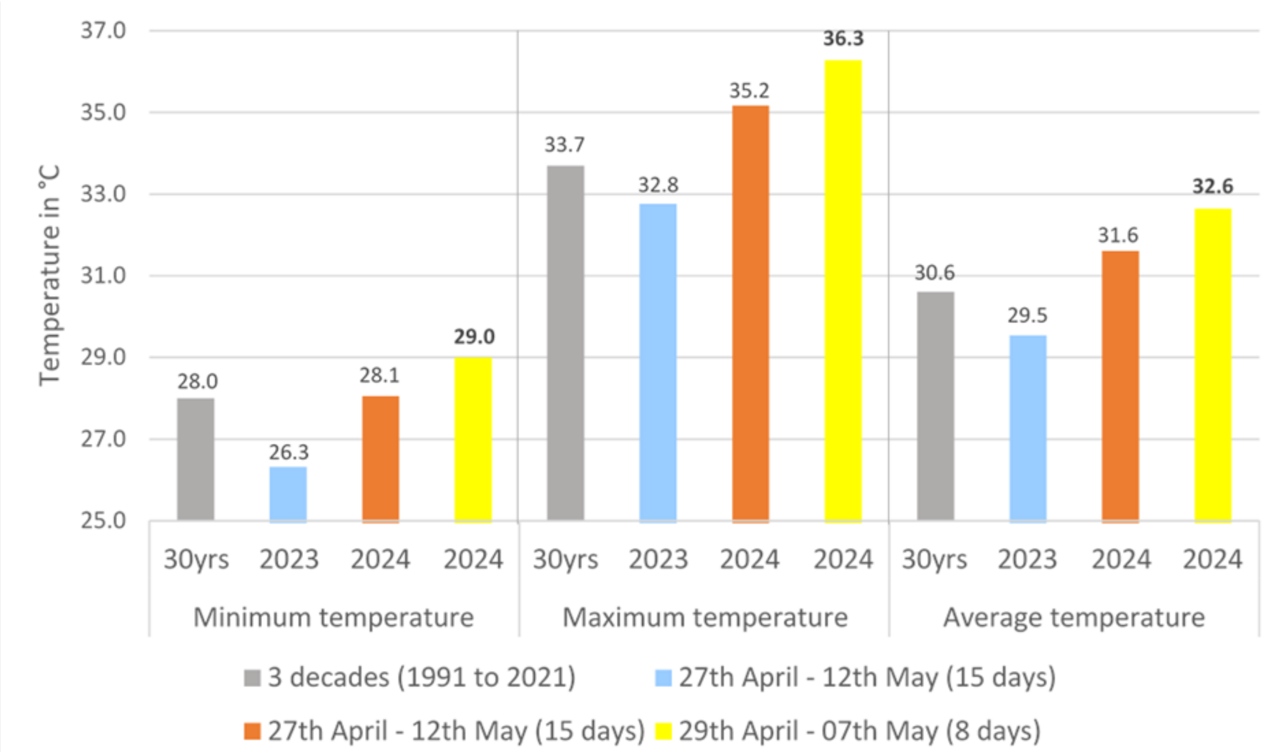

Fig. 2. Minimum, maximum, and average temperatures for the three decades, 15-day interval in 2023 and 2024, and 8-day intervals in 2024 during crop growth.

Clone C 230274 performed well under heat stress but has a shorter total height compared to clone C 230739, which does not perform well under heat stress. Nonetheless, clone C 230739 exhibited the highest overall height among the clones. This height achievement is attributed to its early vigour, growing to 83.33 cm within the first 30 days, as shown in Fig. 3. Plants exhibiting early vigour are typically better equipped to endure and recover from heat stress because their rapid growth and robust development enable them to establish stronger root systems and more extensive leaf canopies early in their lifecycle. These attributes enhance water uptake, nutrient absorption, and efficient photosynthesis, allowing the plants to better withstand and recover from the damaging effects of heat stress (29-31). Clone C 230274 is a promising candidate for further studies in abiotic resistance breeding.

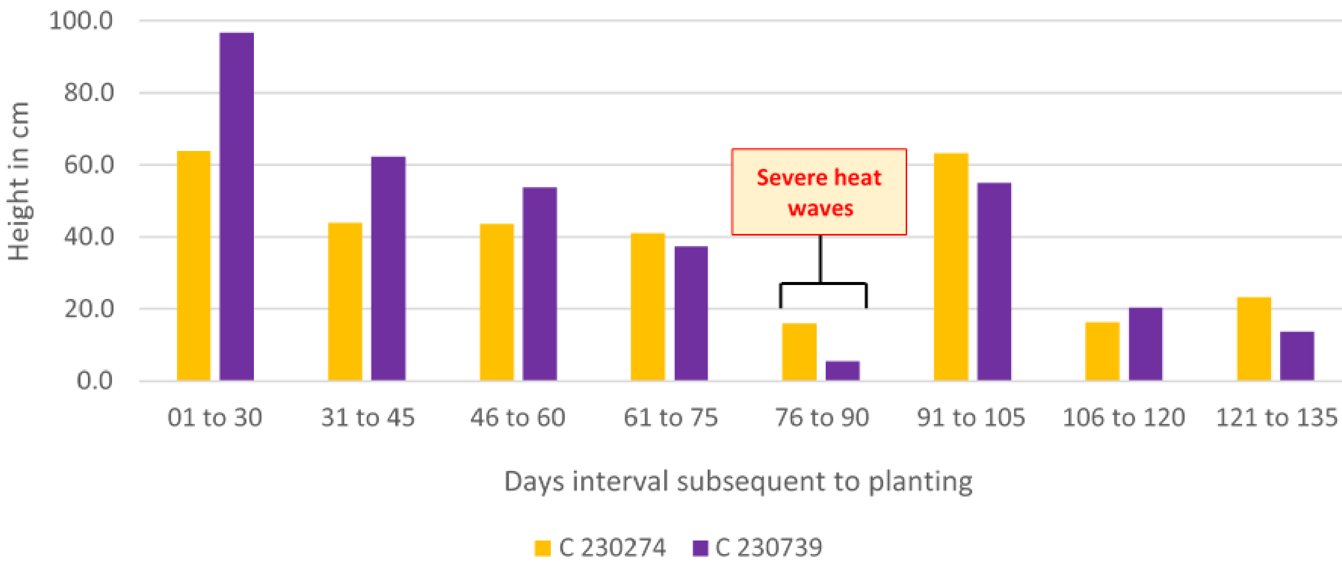

Fig. 3. Comparison of plant height increase between clone C 230274 (heat tolerant candidate) and C 230739 (early vigour) at a 15-day time interval.

Understanding plant responses to high temperatures necessitates a comprehensive analysis of key phytohormones, such as abscisic acid, cytokinins, jasmonic acid, salicylic acid and ethylene (32). These hormones play crucial roles in modulating heat stress responses. Additionally, investigations into heat shock proteins, reactive oxygen species, and the accumulation of osmoprotectants and antioxidants provide critical insights into the complex mechanisms plants employ to withstand thermal stress (33). The integration of these studies will collectively reinforce and offer further validation of the heat-tolerant clones.

Conclusion

This study highlights how unusual weather patterns, particularly elevated temperatures, destabilize the delicate balance required for optimal crop growth. To maintain food security, in the face of a changing climate, there is a growing need for continuous study and innovation in agricultural methods due to the rising frequency of extreme weather events. This study revealed a significant reduction in crop growth due to heat stress. Additionally, temporal measurement of crop growth coupled with temperature has served as an ideal approach to unravel the critical temperature and stage at which the plant growth was severely impaired due to heat stress. Hence, this approach can be effectively used to screen and identify heat-tolerant clones, aiding in the development of climate-resilient sugarcane varieties.

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Authors' Contributions

TT and AT prepared the original manuscript and oversaw the entire project. DS contributed to conceptualization, data curation, and oversight. ST, GP and RA contributed to both conceptualization and supervision. SC and SN managed statistical analysis and manuscript revisions. All authors have reviewed 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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