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Growth and physiological responses to different paclobutrazol concentrations in the formative sugarcane developmental stage

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Abstract

Paclobutrazol (PBZ) is a plant growth retardant that inhibits gibberellin synthesis. PBZ is probably used to resist drought through root growth promotion and inhibiting aboveground growth. However, the growth and physiology of early-stage sugarcane with PBZ need to be established. The objective of this study was to determine the responses of growth and physiology to the formative sugarcane developmental stage with different PBZ concentrations (0, 50, 100, 150, 200, and 250 mg/L). PBZ application affected plant height, tiller number, chlorophyll content, root characteristics, and biomass. This compound decreased plant height, whereas tiller number, chlorophyll content, root dry weight, and biomass increased. A PBZ concentration of 100 mg/L was identified as an appropriate concentration in formative sugarcane; this concentration retarded sugarcane height until 135 days after planting (DAP) but promoted drought resistance traits, namely SCMR and root dry weight, and improved final biomass and yield components, such as tiller number. The responses of drought resistance traits to varying PBZ concentrations form the basis for further drought resistance investigations in cultural practice.

Keywords: Plant height, Biomass allocation, Chlorophyll content, Root traits, Plant growth retardant

1. Introduction

Sugarcane (*Saccharum officinarum* L.) plays an important role in world sugar production because it is used to produce more than 80% of the total sugar production in the world [1]. Brazil, China, India, and Thailand contribute 60% of the total raw sugar production [2]. Additionally, Thailand is the fourth-largest ranked sugarcane producer in the world and is the world's second-largest exporter of sugar [3]. With the increase of greenhouse gas emissions and global warming significantly affecting variations in rainfall, the growth and yield of sugarcane often face water deficit, which are considered to be a severe problem.

Most sugarcane production areas in Thailand are rain-fed, so the crop may experience drought stress. Generally, farmers start to plant in the late rainy season (October–November). Therefore, the planted sugarcane in this area feasibly faces drought stress at the formative developmental stage, around 2-4 months, depending on the dry season duration in each year [4]. As a major problem in sugarcane production, a water deficit in the early growth stage of sugarcane could reduce the yield by up to 60% [5,6].

A favourite cultivar that is widely used in Thailand is 'KK3,' which accounts for around 86% of the total sugarcane production area [7]. KK3 is considered a drought-resistant cultivar in terms of acclimation to water deficits at the formative stage [8]. In the early drought phase, KK3 can maintain root growth to maintain water and nutrient uptake by contributing to underground plant parts. The proportion of assimilates is a major concern for shoots, more than roots, in the recovery phase, which causes stalk growth to rapidly increase [9]. Currently, KK3 is the most used sugarcane cultivar in the Thailand sugarcane production system. This presents a risk to the sugarcane production system if there is an incident of a new disease or unpredictable environmental stress.

Therefore, it is necessary to use diverse sugarcane cultivars in the production system. Despite genetic improvement being an approach to generate new cultivars that provide drought acclimation similar to KK3, breeding strategies are laborious, time-consuming, and costly. Plant growth retardants are used to resist drought through root growth promotion and inhibition of aboveground growth.

Paclobutrazol (PBZ) is a plant growth retardant that can partly inhibit gibberellin synthesis. Its role is to decrease plant height, cell elongation, cell division, and shoot elongation [10]. Currently, 50 mg/L PBZ applied to rice (*Oryza sativa* L.) at the heading stage can inhibit plant height and promote the number of spikelets per panicle [11]. 150 mg/L PBZ applied to wheat (*Triticum aestivum* L.) at the tillering stage, decreases plant height and stem length [12]. Moreover, the use of PBZ has the possibility of increasing biomass production in sesame. PBZ has benefits to plant growth, development, and yield [13].

In sugarcane, [14] it is reported that 150 mg/L PBZ, which was used to treat plantlets derived from in vitro culture to prepare seedlings before transplant, promoted the strength of plants and increased the tiller number, root length, and SPAD chlorophyll meter reading (SCMR) value, whereas stem height was decreased. Furthermore, a sugarcane stalk sett soaked with 50 mg/L PBZ improves the tiller number in the formative stage [15]. Thus, the sugarcane response to PBZ is a decrease in height while increasing tiller number, SCMR, and root could be adapted to resist drought stress. The hypothesis of this study is that PBZ could improve the traits which relate to early drought resistance in sugarcane, such as reducing water loss, maintaining chlorophyll content and efficiency, and contributing assimilation to the roots to find water in drought conditions. Thus far, information about the response of rooting, SPAD index, and growth to PBZ in the formative sugarcane developmental stage has been very limited in the literature. The previous reports thus far have been limited to experiments in vitro and soaking sett conditions. In a realistic sugarcane production system, sugarcane usually encounters drought stress 1-4 months after planting. Moreover, the response of growth, rooting, and physiological traits of the formative sugarcane stage with various PBZ concentration levels are not well understood and have not been studied extensively. Hence, the objective of this study was to determine the responses of growth and physiology in the formative sugarcane developmental stage to different PBZ concentrations. The investigation of PBZ doses that affect the drought resistance traits of sugarcane will provide useful information for further investigating PBZ application to resist drought conditions.

2. Materials and methods

2.1 Experimental design and details

This research consisted of two sub-experiments: 1) a preliminary trial to select a genotype and range of PBZ concentrations and 2) a varied PBZ concentration trial.

2.1.1 Sub-experiment 1

The preliminary pot experiment was conducted under open greenhouse conditions from August to December 2018 at the Field Crop Research Station, Agronomy Department, Faculty of Agriculture, Khon Kean University, Thailand. A 2×3 factorial experiment in a completely randomized design (CRD) was used with three replications. Two PBZ concentrations (0 and 500 mg/L) were assigned as Factor A, and Factor B were three sugarcane cultivars (KK3, KKU99-03, and UT13) with different drought characteristics. KK3 is a drought-resistant cultivar that has good performance for rooting traits under drought conditions [16]. 'KKU99-03' is an elite line with a high yield that is susceptible to drought stress [17], and 'UT13' is a wild-type genotype with a high root length density in the lower soil layer and is highly tolerant to water stress [18].

An insect-and disease-free sugarcane seed sett was planted into a black plastic bag. 20 days after planting, uniform seedlings in terms of plant height were selected and transplanted to experimental pots. A pot size of 43 cm in diameter and 33 cm in height was uniformly filled with 26 kg of dry soil, based on a 1.5 g cm^{-3} bulk density. At 30 DAP, PBZ was dissolved with distilled water and directly drenched into the soil. Chemical fertilizer 15-15-15 (N-P-K) applications were performed three times at 30, 60, and 90 DAP at a rate of 312.5 kg/ha. Watering was applied based on the daily crop water requirement (ETcrop) using the Equation 1 described by [19]:

$$\mathrm{ETcorp} = \mathrm{ETo} \times \mathrm{KC} \qquad (1)$$

when ET crop is the crop water requirement (mm day^{-1}), ETo is the evapotranspiration of a reference plant under specified conditions calculated by the pan evaporation method. Kc is the crop water requirement coefficient for sugarcane, which varies with genotype and growth stage.

2.1.2 Data collections

Stem height and tiller number were recorded at 7-day intervals from 30–120 DAP. At 30 DAP, before PBZ application, stem height was measured from the ground level to the last exposed dewlap of the main stem. In each pot, the main stem was marked, and all tillers were counted and recorded. Leaf chlorophyll content (SCMR) was collected in each pot at 30-day intervals from 30-120 DAP. Measurements were taken on the second fully expanded leaf from the top of the main stalk using a SPAD-502 meter (Minolta SPAD-502 meter, Tokyo, Japan). Each leaf sample was measured at three positions along the leaf length and then averaged.

The roots were measured at 90 DAP. In each pot, root samples were washed with water to eliminate soil particles from the samples. WinRhizo software program (WinRhizo Pro (s) V. 2004a, Regent Instruments, Inc.) was then used for analyzing root length, root volume, and root surface area. Root dry weight was determined by oven-drying at 80°C for 72 h or until constant weight.

2.1.3 Sub-experiment 2

A pot experiment was conducted under greenhouse conditions from February–September 2019 in the 1st year trial and repeated in the 2nd trial in 2020. A CRD with three replications was used, and the treatments comprised six different PBZ concentrations, namely 0, 50, 100, 150, 200, and 250 mg/L. KKU99-03 was used in this sub-experiment. (Based on the results from the 1st experiment; KKU99-03 revealed a clear difference in response to PBZ as providing the highest difference of height and tiller number between treated and un-treated PBZ during 51-120 DAP and it showed a good tendency to recovery of stem height at 120 DAP. The sugarcane sett, pot and soil preparations, transplant irrigation, and fertilizer were performed in the same way as in the first sub-experiment.

2.1.4 Data collections

Stem height, tiller number, and SCMR were measured similar to the first sub-experiment, but for the second sub-trial duration, data collection occurred from 30-240 DAP.

Biomass samples for aboveground and root parts were collected from each pot at 120 and 240 DAP. All dry matter of aboveground shoots (stems and leaves) was collected, and the dry weight was determined after oven-drying at 80°C for 72 h or until a constant weight. Root dry matter, root length, root volume and root surface area underwent the same methodology as with the 1st sub-experiment. The dry weights of stems, leaves, and roots were summarized and calculated into biomass.

2.2 Statistical analysis

The measured data were subjected to analysis of variance using Statistix10 software following a 2×3 factorial in a CRD for all observed traits [20] for the 1st sub-experiment and following a completely randomized design for the 2nd sub-experiment. The means were compared with the least significant difference (LSD) test for both sub-experiments.

The determination of biomass allocation in different parts was calculated as a percentage of dry weight (g) of each biomass part (stem, leaves, and root) of an individual plant in each treatment, using the following Equation 2:

$$\text{Determination of biomass allocation part (\%)} = \frac{\text{Dry matter of each part (leaves/stem/root) (g)}}{\text{Total dry weight (g)}} \times 100 \quad (2)$$

3. Results

3.1 Sub-experiment 1

The analysis of variance showed significant differences between the PBZ treatments for plant height, tiller number, and SCMR. The differences among sugarcane genotypes were not significant for all traits. Application of PBZ x genotype (PBZ × G) interactions did not exist for all traits (data not shown), indicating that PBZ affects growth and physiology in all tested genotypes.

3.1.1 Determination of growth responses to PBZ within sugarcane genotypes

In general, the three sugarcane genotypes had different heights and tiller numbers in terms of increasing and peak patterns. In the PBZ-free treatment, the plant height of all three sugarcane genotypes gradually increased from 30-120 DAP; additionally, the plant heights of KK99-03 and UT13 were rapidly boosted from 72-120 DAP.

Although 500 mg/L PBZ initially retarded the height at 14 days after treatment with PBZ (44 DAP), it significantly reduced the height from 44-120 DAP (Figure 1A-1C).

In contrast, the application of 500 mg/L PBZ at the formative stage of sugarcane considerably increased the tiller number in all three sugarcane genotypes when compared with the PBZ-free treatment. A rapid increase in the tiller number of KK3 and KKU99-03 was revealed from 72-120 DAP, while UT13 boosted tiller number two-fold at 65 and 107 DAP. However, all sugarcane genotypes revealed a tendency to reduce the tiller number; the peak of tiller number of KK3 was observed at 107 DAP, while in KKU99-03 and UT13, the peak was observed at 120 DAP (Figure 1D-1F).

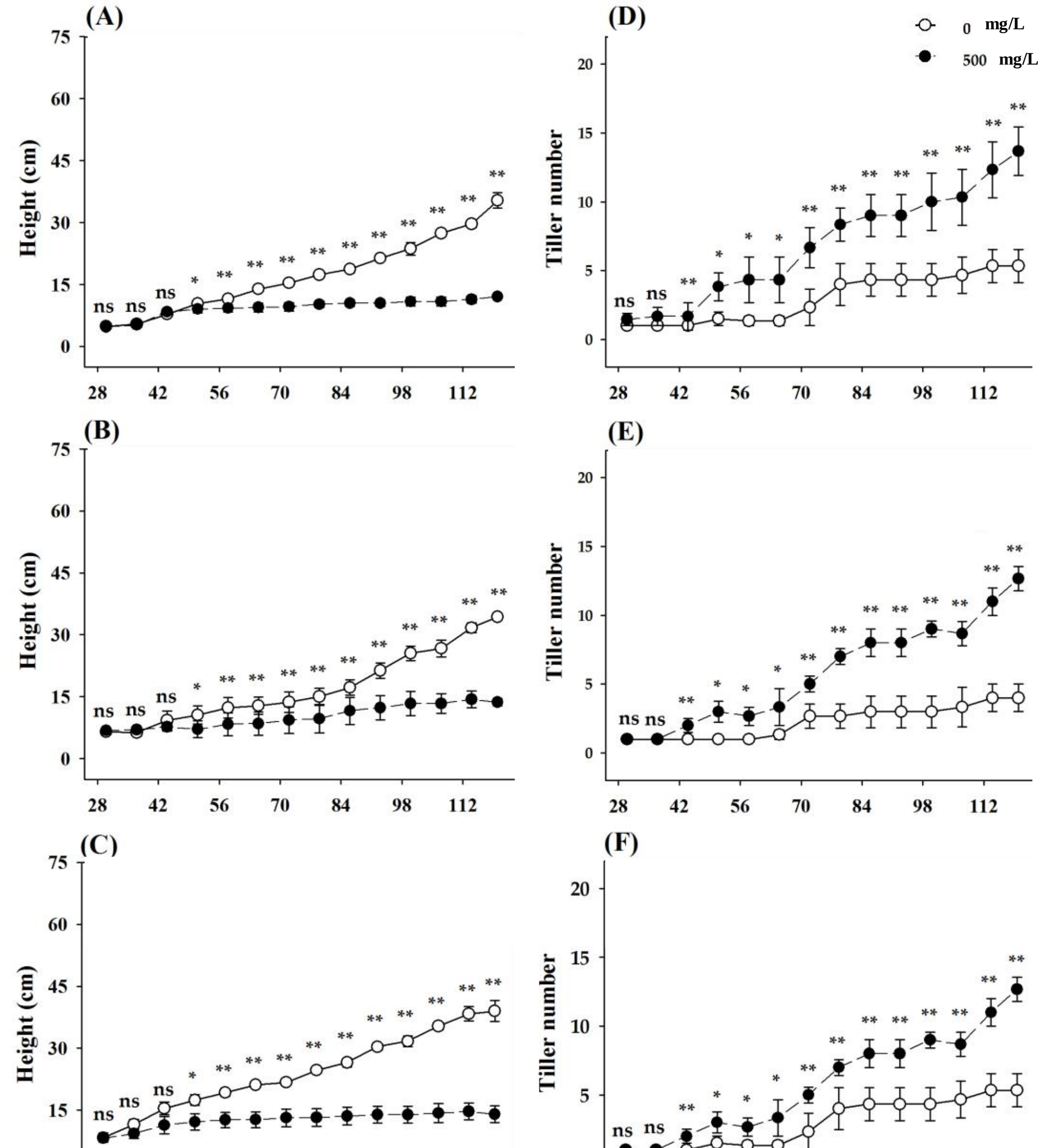

Figure 1 Height and tiller number between 0 and 500 mg/L PBZ from 30-120 days after planting (DAP) in three sugarcane cultivars, namely 'KK3,' 'KKU99-03,' and 'UT13.' Plant height of 'KK3'(A), 'KKU99-03'(B), and 'UT13'(C) between 0 and 500 mg L^{-1} PBZ Tiller numbers of 'KK3'(D), 'KKU99-03'(E), and 'UT13'(F) between 0 and 500 mg/L PBZ. **Significant at $p < 0.01$ probability level, *Significant at $p < 0.05$ probability level. Ns = non-significance.

Regarding illustrative features, PBZ decreased internodal elongation at 60 DAP. Three sugarcane cultivars revealed a shorter internode length under 500 mg/L PBZ compared to the PBZ-free treatment (Figure 2). Moreover, it is likely that KKU99-03 and UT13 were sensitive to PBZ in terms of limiting internode length.

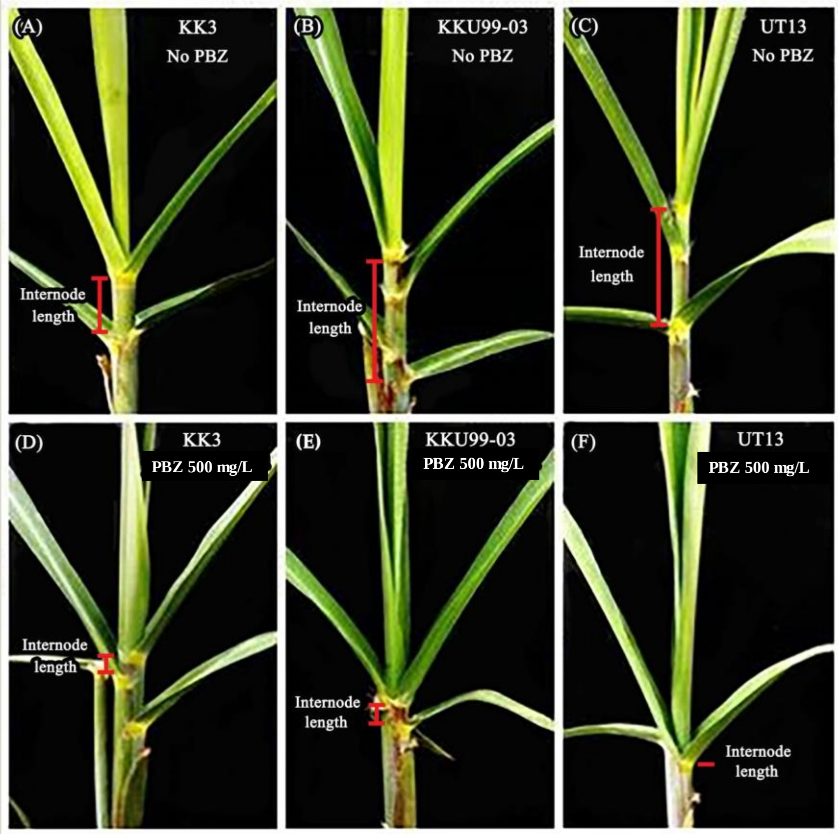

Figure 2 Internode length between 0 and 500 mg/L PBZ at 60 days after planting (DAP) in three sugarcane cultivars, namely 'KK3,' 'KKU99-03,' and 'UT13.' Internodal elongation under 0 mg/L PBZ 'KK3'(A), 'KKU99-03'(B), and 'UT13'(C) and intermodal elongation under 500 mg/L PBZ 'KK3'(D), 'KKU99-03'(E), and 'UT13'(F).

3.1.2 Determination of SCMR and rooting responses to PBZ within the sugarcane genotype

In general, PBZ could boost the chlorophyll content represented by the SCMR value at 1 month after PBZ application (60-120 DAP). SCMR among the three sugarcane cultivars showed different responses to 500 mg/L PBZ when compared to the PBZ-free treatment. PBZ-treated KK3 and KKU99-03 had a significantly increased SCMR at 60-120 DAP (Figure 3A-B), whereas UT13 showed a significant difference at 60 and 120 DAP (Figure 3c). Despite different responses among genotypes in terms of sensitivity of the SCMR value to PBZ, all genotypes conclusively had a high chlorophyll content at the formative sugarcane developmental stage. PBZ did not significantly affect rooting traits in all cultivars, but KKU99-03 increased root traits when 500 mg/L PBZ was applied (Figure 4A-C).

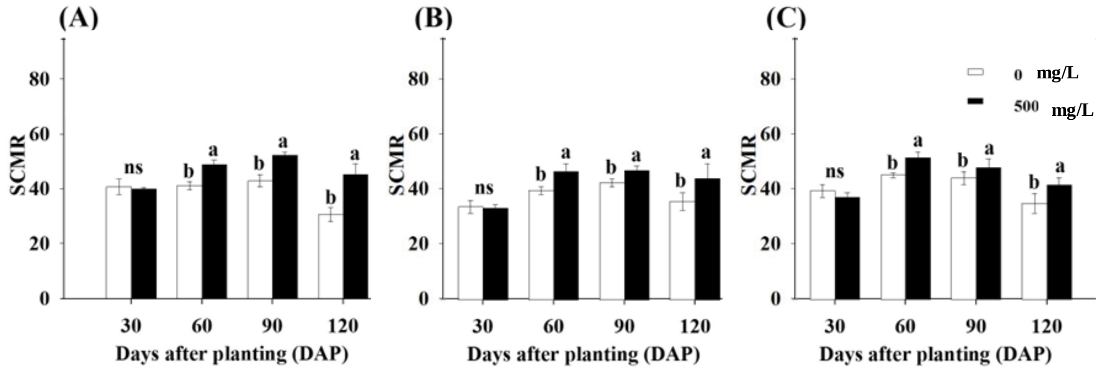

Figure 3 SCMR of two concentrations of paclobutrazol at 30-120 days after planting (DAP) of three sugarcane cultivars, namely 'KK3'(A), 'KKU99-03' (B), and 'UT13'(C). The bar mean standard deviation is followed by the LSD test differences among PBZ concentrations that are significant at $p < 0.05$. ns = non-significance.

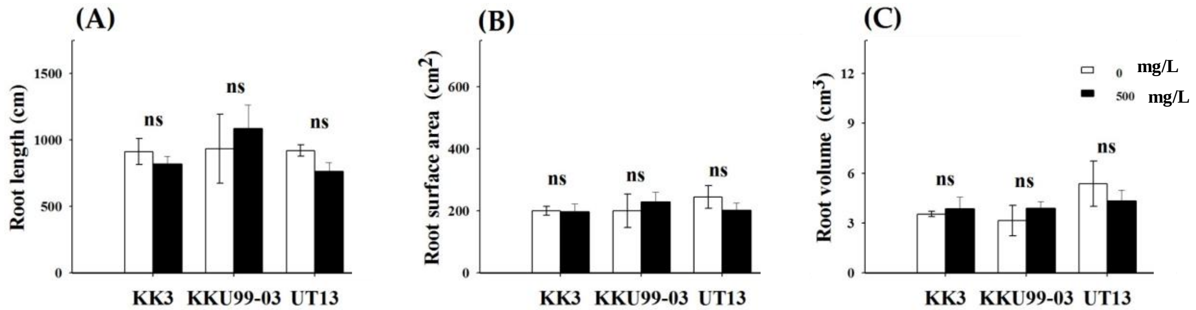

Figure 4 Root length (A), root surface area (B), and root volume (C) of two concentrations of paclobutrazol (0 and 500 mg/L) at 90 days after planting (DAP) of three sugarcane cultivars, namely 'KK3,' 'KKU99-03,' and 'UT13.' The bar mean standard deviation is followed by the LSD test differences among PBZ concentrations that are significant at $p < 0.05$. ns = non-significance.

3.2 Sub-experiment 2

3.2.1 Determination of growth responses to varied PBZ doses

The responses of KKU99-03 to PBZ differed between the two trials. In the 1st year, the 5 PBZ treatments evidently retarded plant height at 58 DAP when compared with the PBZ-free treatment, whereas plant height was retarded at 37 DAP in the repeated trial. In the 1st year, 50 mg/L PBZ was an appropriate dose to control plant height in the early growth stage (58-135 DAP), and then plant height recovered to the same level as the PBZ-free treatment (Figure 5A). The retardant effects were sorted based on the rate of PBZ, as a high dose of PBZ highly inhibited plant height (Figure 5A). In the 2nd trial, a clear difference in plant height was shown among PBZ treatments. The PBZ-free treatment had the highest height, followed by PBZ 50, 100, 150, 200, and 250 mg/L (Figure 5B). In the recovery aspect, plant height in the PBZ treatments was reached at 150 DAP, representing a rapid increase in height when compared with the height at 58-135 DAP (Figure 5B).

At 120 DAP, the PBZ treatments had a higher tiller number than the PBZ-free treatment in the 1st year, whereas the 50 mg/L PBZ treatment had no significant difference from the PBZ-free treatment. The tiller number was lower than that in other treatments for the 2nd year of the trial. In addition, 250 mg/L PBZ had the highest tiller number at 72-156 DAP in both trials. However, at the end of the grand growth period, physiological maturity, 200 and 250 mg/L PBZ increased the stalk number compared to the PBZ-free treatment in both the 1st and 2nd trials, but not 50 to 150 mg/L doses (Figure 5C-5D).

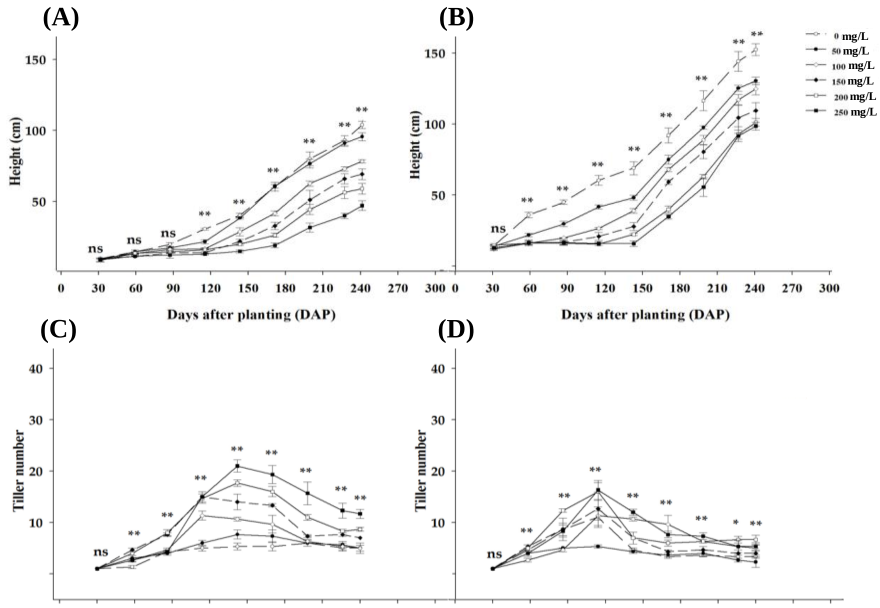

Figure 5 Plant height and tiller number after paclobutrazol treatment (0, 50, 100, 150, 200, and 250 mg/L) for 30-240 days after planting (DAP) in the 'KKU99-03' sugarcane cultivars over 2 years. Plant height of the 1st trial (A) and the 2nd trial (B), and tiller number of the 1st trial (C) and the 2nd trial (D).

3.2.2 SPAD chlorophyll meter reading; SCMR

The responses of SCMR to PBZ concentration were different between the two trials. For the 1st trial, the SCMR values of PBZ treatments were higher than that of the PBZ-free treatment at 30 and 60 DAP, and 50 to 200 mg/L treatment significantly increased the SCMR value compared with the PBZ-free treatment at 90 DAP. At 120 to 240 DAP in the 1st trial, the effect of PBZ decreased, as there was no significant difference between PBZ-treated and PBZ-free plants (Figure 6A). In the 2nd trial, the effect of PBZ on SCMR value at 30 DAP was unclear; the PBZ-free treatment did not significantly differ between 50, 100, 150, and 250 mg/L treatments. At 60-90 DAP, all PBZ treatments revealed an increased SCMR value compared with the PBZ-free treatment (Figure 6B). PBZ treatment increased SCMR during the formative sugarcane developmental stage in both years.

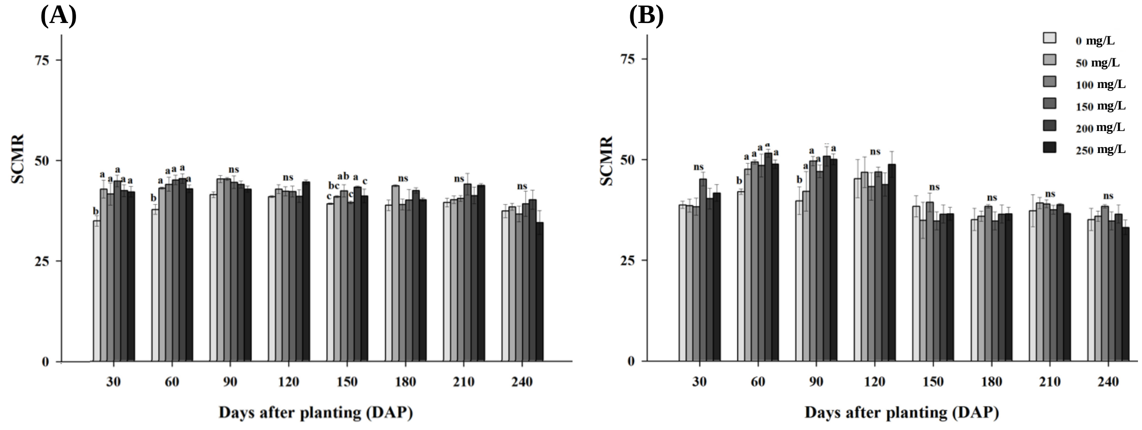

Figure 6 SCMR after paclobutrazol treatment (0, 50, 100, 150, 200, and 250 mg/L) at 30-240 days after planting (DAP) in 'KKU99-03' sugarcane over 2 years: 1st trial (A) and 2nd trial (B). The bar mean standard deviation is followed by the LSD test differences among PBZ concentrations that are significant at $p< 0.05$. ns = non-significance.

3.2.3 Determination of biomass allocation responses to PBZ treatment

The biomass allocation of sugarcane was affected by PBZ treatment in both years. High concentrations of PBZ, namely 100, 150, 200, and 250 mg/L, enhanced the dry weight proportion of the roots, but low doses of PBZ, such as 50 mg/L, did not significantly affect root dry weight allocation in the PBZ-free treatment in either year. However, in both trials, the stem dry weight proportion decreased with the 100 and 150 mg/L PBZ treatment and 150, 200, and 250 mg/L PBZ treatment in the 1st and 2nd trials, respectively. In addition, there were no significant effects of PBZ on leaf dry weight percentage in either year (Table 1). Consequently, PBZ application may change the partitioning of sugarcane dry weight by enhancing root allocation and reducing stem biomass.

Table 1 Determination of biomass proportion percentage responses to varied paclobutrazol (PBZ) at 120 days after planting (DAP) over 2 years.

Concentration of PBZ (mg/L)	1st year sugarcane trial (%)			2nd year sugarcane trial (%)		
	Stem dry weight	Leaf dry weight	Root dry weight	Stem dry weight	Leaf dry weight	Root dry weight
0	28.55^{a}	53.37	18.08^{c}	48.82^{a}	30.87	20.31^{c}
50	27.96^{a}	51.46	20.58^{cb}	48.84^{a}	29.85	21.31^{c}
100	20.77^{b}	54.87	24.36^{ab}	42.86^{ab}	31.45	25.69^{b}
150	20.84^{b}	52.62	26.54^{a}	39.83^{b}	31.06	29.11^{a}
200	22.81^{ab}	49.28	27.91^{a}	39.55^{b}	30.60	29.85^{a}
250	24.46^{ab}	47.18	28.36^{a}	40.74^{b}	29.62	29.64^{a}
F-test	*	ns	**	*	ns	**

Means followed by the same letter within each column are not different from each other by LSD 5% **Significant at $p < 0.01$ probability level, *Significant at $p < 0.05$ probability level, and ns = non-significance.

3.2.4 Responses of biomass to PBZ in the physiological maturity phase

At the physiological maturity stage (240 DAP) in the 2nd year, leaf dry weight increased under PBZ treatment, whereas stem dry weight was enhanced under 100 and 150 mg/L PBZ treatment. Except for root and stem dry weight, there was no significant difference between PBZ-treated and PBZ-free plants at physiological maturity. In general, PBZ seems likely to improve biomass productivity, representing an increase in total dry matter in PBZ application treatments (Figure 7).

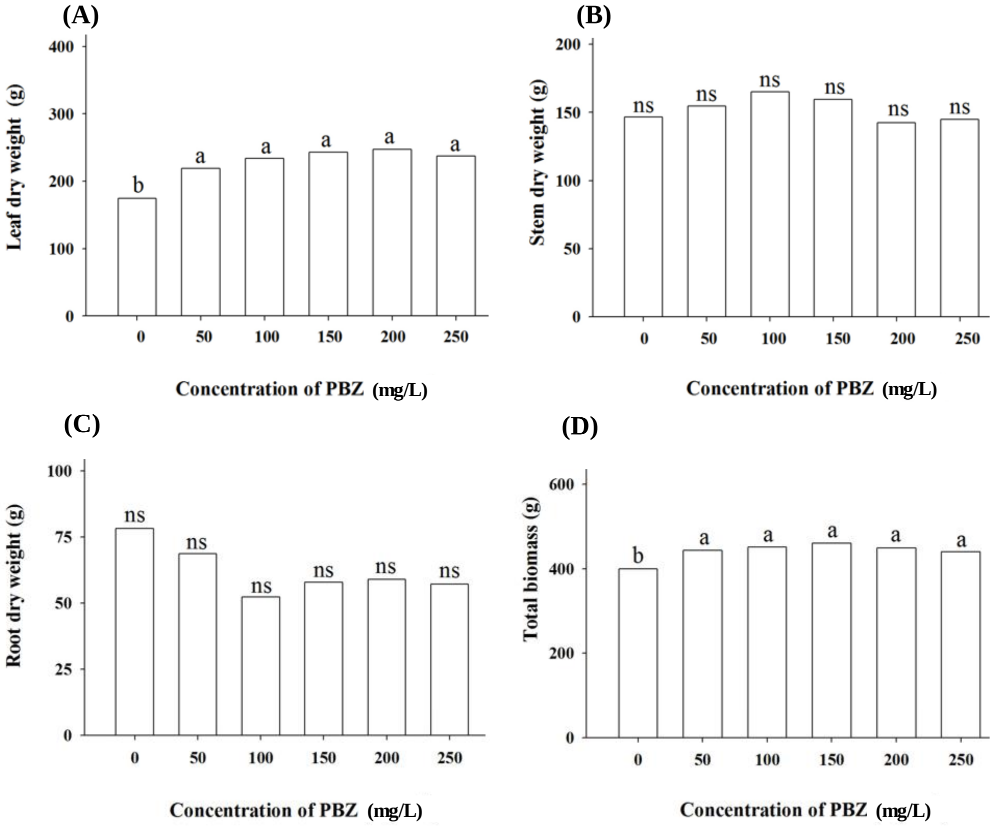

Figure 7 Biomass allocation in 2nd year to leaf dry weight (A), stem dry weight (B), root dry weight (C), and total biomass (D) under PBZ treatment at the recovery stage (240 days after planting (DAP)). The bar mean standard deviation is followed by the LSD test differences among PBZ concentrations that are significant at $p< 0.05$. ns = non-significance.

4. Discussion

Height, tiller number, SCMR, biomass allocation, and root weight of sugarcane at the formative stage were affected by PBZ application. These results agree with [14], who reported that sugarcane seedlings treated with PBZ in in vitro conditions increased SCMR, whereas plant height was inhibited. Moreover, the soaking seed approach reduces sugarcane plant height and enhances tiller number and chlorophyll content [15]. PBZ effects have been reported in many monocots, such as wheat [21], maize [22], barley [23], and rice [24]. The plant height of many crops is decreased via PBZ, which can block gibberellin as it functions to promote cell growth and cell elongation in plants [25]. PBZ directly inhibits the oxidation of ent-kaurene to ent-kauronoic acid in the gibberellin biosynthetic pathway [26]. In contrast, the inhibition of gibberellin synthesis enhances photosynthetic pigment production, as well as chlorophyll, and regulates phytohormone [27]. The reduction of gibberellin promotes the increase of auxin and cytokinin production, resulting in improvement of tillering performance in grass crops [28]. This study found that PBZ application in the formative phase of sugarcane remarkably increased the tiller number, confirming previous reports in rice [29]. In addition, [30] reported that PBZ is directly associated with restricting vegetative growth in rice. This current report also indicates that PBZ changed the proportion between root and shoot dry weight, as well as increased root allocation. Biomass production was associated with chlorophyll content; a positive correlation between biomass and chlorophyll content was reported in [31,32]. In sugarcane leaves, chlorophyll content plays an important role in the photosynthetic process, according to a strong correlation between the SPAD value and yield productivity [33]. Consequently, PBZ application potentially improves biomass production in sesame. PBZ has been reported to play an important role in plant growth, development, and yield [13].

During the formative period, this study found that 100 mg/L PBZ was an appropriate dose to use in sugarcane production systems, which often face drought at the formative stage. This concentration reduced plant height but increased the tiller number, chlorophyll content, and root dry weight allocation; meanwhile, it had a good performance on growth in the grand growth period (recovery phase) of sugarcane. In a previous report, however, 150 mg/L PBZ showed the best concentration with reduced height and increased diameter, root and shoot dry weight, and chlorophyll content of in vitro sugarcane seedlings [14]. Furthermore, seed soaking with 50 mg/L PBZ effectively dwarfs sugarcane in the seedling stage and improves tillering, chlorophyll content, soluble protein content, proline content, and POD activity [15]. Accordingly, spraying with 50 mg/L PBZ in rice at the heading stage has been shown to enhance grain yield [11]. In this context, the suitability of PBZ varies based on approach, objective, crop species, and growth stage development.

Furthermore, sugarcane that provides cane traits that enable a considerable recovery in physiological, rooting, and growth features, as well as a higher proportion of assimilates to the shoots during the recovery period, is desirable. Thus, the grand growth period of sugarcane is critical for promoting sugarcane productivity when early sugarcane development encounters severe drought stress [34]. In previous reports that studied PBZ effects on sugarcane, there is very little information on the recovery period and biomass production in physiological maturity; they only report at seedling and tillering stages. The aim of the previous reports focuses on providing stronger seedlings derived from tissue culture before transplanting [14] and more tillering [15]. At physiological maturity, PBZ increased the total biomass due to increased leaf dry weight when compared with the PBZ-free treatment. Based on PBZ response to biomass, increasing sugarcane yield with PBZ may be consistent with a previous report in sesame crop [13].

A strategy for improving early drought resistance in sugarcane might be achieved by reducing water loss in the transpiration process during the water deficit period together with maintaining yield productivity at the harvesting stage. This approach corresponds to a small canopy size and abscisic acid function (ABA) for closing stomata, and good growth performance in recovery. The characteristics against drought in the formative phase of sugarcane were determined as 1) providing a smaller canopy and reducing stomatal conductance, 2) maintaining chlorophyll content and efficiency, and 3) contributing assimilates to the roots to find water in drought conditions [9]. Additionally, sugarcane that experiences water stress at the early growth stage, and the rapid increase in stalk and leaf dry weights during the elongation phase, could maintain biomass productivity at physiological maturity in sugarcane [8]. In our results, even though this research was conducted without a water deficit situation, 100 mg/L PBZ might possibly be appropriate to respond to the drought problem in the early season of sugarcane. It retarded the plant height of sugarcane from 30-135 DAP, whereas it promoted tiller number, SCMR, biomass, and root weight, significantly improving the final biomass of sugarcane. However, 50 mg/L PBZ did not increase root dry weight allocation; this would not contribute to the drought resistance. Despite the fact that 150, 200, and 250 mg/L PBZ provided the same final biomass level as 100 mg/L PBZ, they had a shorter stalk than 100 mg/L PBZ, while the tiller number was the opposite. Furthermore, the production cost in the sugarcane production system will increase with a higher dose of PBZ use. This information will be beneficial for understanding the role of PBZ in sugarcane and recommending a dose to use in elite sugarcane genotypes that are drought susceptible. However, this research is an initial stage of PBZ technology application, and more knowledge and information, such as the responses of various genotypes and applying different approaches and with different soil types, should be gathered before its adoption by farmers. Furthermore, it would be better to clearly determine the effect of PBZ under drought conditions; the growth and physiology under PBZ treatment in early drought resistance experiments need to be established first.

5. Conclusion

In the formative sugarcane developmental stage, PBZ inhibited plant height, whereas tiller number, chlorophyll content, root dry weight, and biomass increased. A PBZ concentration of 100 mg/L was defined as a suitable concentration in the early developmental stage of sugarcane, inhibiting the plant height until 135 DAP, whereas it encouraged drought resistance traits, namely SCMR and root dry weight, and increased final biomass and tiller number. This research is an initial stage of PBZ technology application, and it provides useful information for further investigating PBZ application to resist drought in sugarcane.

6. Acknowledgements

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7. References

[1] FAO. Production [Internet]. 2020 [cited 2021 Nov 14]. Available from: http://www.fao.org/faostat/en/#data / QC.

[2] Aquino GS, Medina CC, Costa DC, Shahab M, Santigo AD. Sugarcane straw management and its impact on production and development of ratoons. Ind Crops Prod. 2017;102:58-64.
[3] Pipitpukdee S, Attavanich W, Bejranonda S. Climate change impacts on sugarcane production in Thailand. Atmosphere 2020;11(4):408-424.
[4] Set-Tow S, Songsri P, Jongrungklang N. Variations in root distribution patterns and cane yield of 16 elite sugarcane clones grown under varied soil conditions. Sugar Tech 2020;22(6):1018-1031.
[5] Robertson MJ, Inman-Bamberb NG, Muchowa RC, Wood AW. Physiology and productivity of sugarcane with early and mid-season water deficit. Field Crops Res. 1999;64(3):211-227.
[6] Ferreira THS, Tsunada MS, Bassi D, Araújo P, Mattiello L, Guidelli GV, et al. Sugarcane water stress tolerance mechanisms and its implications on developing biotechnology solutions. Front Plant Sci. 2017;8:1107-1125.
[7] Khumla N, Sakuanrungsirikul S, Punpee P, Hamarn T, Chaisan T, Soulard L, Songsri P. Sugarcane breeding, germplasm development and supporting genetics research in Thailand. Sugar Tech 2022;24(1):193-209.
[8] Chapae C, Songsri P, Gonkhamdee S, Jongrungklang N. Understanding drought responses of sugarcane cultivars controlled under low water potential conditions. Chil J Agric Res. 2020;80(3):370-380.
[9] Khonghintaisong J, Songsri P, Toomsan B, Jongrungklang N. Rooting and physiological trait responses to early drought stress of sugarcane cultivars. Sugar Tech 2018;20(4):396-406.
[10] Soumya PR, Kumar P, Pal M. Paclobutrazol: a novel plant growth regulator and multi-stress ameliorant. Indian J Plant Physiol. 2017;22(3):267-278.
[11] Pan S, Rasul F, Li W, Tian H, Mo Z, Duan M, et al. Roles of plant growth regulators on yield, grain qualities and antioxidant enzyme activities in super hybrid rice (*Oryza sativa* L.). Rice. 2013;6(9):9-19.
[12] Guoping Z. Gibberellic acid3 modifies some growth and physiologic effects of paclobutrazol (PP333) on wheat. J Plant Growth Regul. 1997;16:21-25.
[13] Mehmood MZ, Afzal GQO, Din AMU, Raza MA, Khan I, Hassan MJ, et al. Paclobutrazol improves sesame yield by increasing dry matter accumulation and reducing seed shattering under rainfed conditions. Int J Plant Prod. 2021;15(3):337-349.
[14] Valdes TD, Leopoldo PR, Felipe AT, Carlos AO, Teresa JA. Dose of paclobutrazol in the growth of sugarcane seedlings in vitro in the acclimatization stage. J Agric Sci. 2017;8(8):751-758.
[15] Liu J, Song L, Fang T, Xin L, Yibo H, Kaichao W, et al. Effects of seed soaking with paclobutrazol on tillering and physiological characteristics of sugarcane seedlings. Asian J Agric Res. 2017;9(1):65-69.
[16] Jangpromma N, Thammasirirak S, Jaisil P, Songsri P. Effects of drought and recovery from drought stress on above ground and root growth, and water use efficiency in sugarcane (*Saccharum officinarum* L.). Aust J Crop Sci. 2012;6(8):1298-1304.
[17] Khonghintaisong J, Songsri P, Jongrungklang N. Root characteristics of individual tillers and the relationships with above-ground growth and dry matter accumulation in sugarcane. Pak J Bot. 2020;52(1):101-109.
[18] Taratima W, Ritmaha T, Jongrungklang N, Maneerattanarungroj P, Kunpratum, N. Effect of stress on the leaf anatomy of sugarcane cultivars with different drought tolerance (*Saccharum officinarum*, Poaceae). Rev Biol Trop. 2020;68(4):1159-1170.
[19] Songsri P, Jogloy S, Holbrook CC, Kesmala T, Vorasoot N, Akkasaeng C, et al. Association of root, specific leaf area and SPAD chlorophyll meter reading to water use efficiency of peanut under different available soil water. Agric. Water Manag. 2009;96(5):790-798.
[20] Gomez KA, Gomez AA. Statistical procedures for agricultural research, 2nd ed. New York: John Wiley & Sons. 1984.
[21] Pirahmadi L, Shekari F, Javanmard A, Noori K. Improvement of wheat (*Triticum aestivum* L.) yield by application of paclobutrazol. IIOABJ. 2016;7(5):314-325.
[22] Kamran M, Ahmad S, Ahmad I, Hussain I, Meng X, Zhang X, et al. Paclobutrazol application favors yield improvement of maize under semiarid regions by delaying leaf senescence and regulating photosynthetic capacity and antioxidant system during grain-filling stage. Agronomy 2020;10(2):187-211.
[23] Rady MM, Gaballah MS. Improving barley yield grown under water stress conditions. Res J Recent Sci. 2012;1(6):1-6.
[24] Desta B, Amare G. Paclobutrazol as a plant growth regulator. Chem Biol Technol Agric. 2021;8(1):1-15.
[25] Detpitthayanan S, Romyanon K, Songnuan W, Metam M, Pichakum A. Paclobutrazol application improves grain 2AP content of Thai jasmine rice KDML105 under low-salinity conditions. J Crop Sci Biotech. 2019; 22(3):275-282.
[26] Tesfahun W. A review on: Response of crops to paclobutrazol application. Cogent food agric. 2018;4(1):169-178.
[27] Xia X, Tang Y, Wei M, Zhao D. Effect of paclobutrazol application on plant photosynthetic performance and leaf greenness of herbaceous peony. Horticulturae. 2018;4(1):5-17.

[28] Assueroa SG, Lorenzob M, Pe´ez Ramı´reza NM, Vela´zqueza LM, Tognetti JA. Tillering promotion by paclobutrazol in wheat and its relationship with plant carbohydrate status. New Zealand J Agric Res. 2012; 55(4):347-358.
[29] Xing P, Duan M, Liu Y, Mo Z, Lai R, Tang X. Enhancement of yield, grain quality characters, 2 acetyl 1 pyrroline content, and photosynthesis of fragrant rice cultivars by foliar application of paclobutrazol. J Plant Growth Regul. 2022;42:748-758.
[30] Yim KO, Kwon YW, Bayer DE. Growth responses and allocation of assimilates of rice seedlings by paclobutrazol and gibberellin treatment. J Plant Growth Regul. 1996;16(1):35-41.
[31] Silva MA, Silva JAG, Enciso J, Sharma V, Jifon J. Yield components as indicators of drought tolerance of sugarcane. Sci Agric. 2008;65(6):620-627.
[32] Silva MA, Jifon JL, Silva AG, Santos MD, Sharma V. Relationships between physiological traits and productivity of sugarcane in response to water deficit. J Agric Sci. 2014;152(1):104-118.
[33] Liu C, Liu Y, Lu Y, Liao Y, Nie J, Yuan X, et al. Use of a leaf chlorophyll content index to improve the prediction of above-ground biomass and productivity. Peer J. 2019;6(1):6240-6255.
[34] Khonghintaisong J, Songsri P, Jongrungklang N. Understanding growth rate patterns among different drought resistant sugarcane cultivars during plant and ratoon crops encountered water deficit at early growth stage under natural field conditions. Agronomy 2021;11(3):2083-2103.