



Productivity of auxin-treated sugarcane bud chip under field conditions

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Abstract

Background and Objective: Sugarcane (*Saccharum officinarum*) is a key crop for sugar and bioethanol. Traditional propagation uses much seed cane, raising costs. The bud chip technique reduces seed use efficiently. Auxins enhance growth and yield. This study evaluated auxin-treated bud chips under field conditions, focusing on growth, yield, and economic efficiency.

Methodology: This study evaluated the performance of auxin-treated sugarcane bud chips under field conditions. The experiment utilized a randomized complete block design (RCBD) with 11 treatment combinations, including a control treatment using untreated seed cane. The remaining treatments involved bud chip soaked in various auxin soaking durations and concentrations (10, 20, and 30 minutes soaking at 150, 200, and 250 ppm) prior to planting. Data were collected on survival counts, plant height, internodal length, number of tillers, biomass yield, amount of juice, cane yield per plot at harvest, and return on investment (ROI).

Main Results: Sugarcane propagated through the bud chip method and treated with auxin at 200 ppm consistently outperformed non-treated and seed cane methods in terms of growth and yield parameters. Soaking durations of 10, 20, and 30 minutes at 200 ppm auxin significantly enhanced plant height, internodal length, number of tillers, biomass yield, juice extract, and cane yield per hectare. Among all treatments, 30 minutes of soaking at 200 ppm auxin produced the best results,

achieving the highest ROI of $223.09 \pm 38.90\%$. These auxin-treated bud chip propagations are more effective than seed cane and non-auxin treatments, and 30 minutes of soaking at 200 ppm is the most advantageous in growth, yield, and profitability.

Conclusions: These findings confirm that auxin-treated sugarcane bud chips significantly enhance growth, yield, and profitability, offering a cost-effective and sustainable alternative to conventional sugarcane propagation. It provides technological options for farmers, researchers, and industry stakeholders aiming to optimize sugarcane.

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INTRODUCTION

The cultivation of sugarcane (*Saccharum officinarum*) is essential for the global sugar industry and plays a significant role in providing economic stability for farmers (Singh *et al.*, 2019; Magarey, 2020). According to data from the Philippine Statistics Authority (PSA, 2023), Cagayan Valley ranked as the fifth-largest producer of sugarcane from April to June 2023, contributing 129,80.08 metric tons to national production. Traditionally, sugarcane is propagated using cane stalk cuttings known as setts. This conventional method involves using sugarcane stems with 2–3 buds, each measuring 25–30 cm in length. The bud chip technique, which uses single-node tissue segments with root primordia, has gained attention for its efficiency in reducing planting material requirements (Liang *et al.*, 2019; Mohanty and Nayak, 2021). However, field-level survival and vigor remain issues, with reported mortality rates of 35–40% due to desiccation, pathogens, and suboptimal rooting (Singh *et al.*, 2021). To address these limitations, plant growth regulators (PGRs), particularly auxins, have been applied to improve rooting and early growth. Auxins enhance cell elongation and stimulate adventitious root formation, promoting robust seedling establishment (Guan *et al.*, 2019; Adem *et al.*, 2024). Among them, naphthaleneacetic

acid (NAA) is widely used for its stability, low cost, and proven effectiveness in sugarcane and other crops (Wu and Birch, 2007). The required seed cane per hectare is approximately more than 10% of total production. However, this technique presents logistical challenges, particularly in transportation, handling, and storage (Mohanty and Nayak, 2021). The large volume of planting material required increases susceptibility to deterioration, reducing bud viability and affecting sprouting rates (Li, 2023; Dean *et al.*, 2024). Tissue culture was once considered an alternative to conventional planting but has declined in popularity due to its complexity and physical limitations (Nayak and Yadav, 2021). Farmers remain skeptical about its practicality and prefer to use traditional sugarcane cuttings, reinforcing their reliance on familiar propagation methods (Sanghera and Sharma, 2024).

Previous studies have primarily utilized auxins such as NAA, indole-3-butyric acid (IBA), and 2,4-dichlorophenoxyacetic acid (2,4-D) under nursery or controlled conditions, with limited emphasis on their effects under direct field planting using bud chips (Wani *et al.*, 2022; Musacchi, 2023). While IBA and 2,4-D are effective in promoting rooting, they have been reported to cause phytotoxic effects on non-target plant species, including symptoms such as leaf curling,

necrosis, and stunted growth, particularly when misapplied (Magnoli *et al.*, 2020; Garcia *et al.*, 2025).

In contrast, NAA was selected for this study due to its lower phytotoxic risk at recommended concentrations. Although excessive application of NAA may result in tissue necrosis or abnormal root formation, it is generally considered safer and more suitable for field application in most crops (Ashraf *et al.*, 2018; Khan *et al.*, 2023). Furthermore, its consistent performance in promoting root initiation and shoot development under tropical field conditions makes NAA a practical and reliable choice for farmers utilizing the bud chip technique. This study, therefore, focused on NAA to establish a practical baseline for improving sugarcane propagation, with future research encouraged to explore comparative or synergistic effects with other auxins or plant growth regulators.

Furthermore, to enhance sugarcane production while minimizing seed cane requirements and associated costs, the bud chip technique emerges as a promising alternative (Soomro, 2024). Factors such as soil-borne diseases, bud desiccation, temperature fluctuations, and poor soil conditions contribute to high mortality rates. One effective strategy to improve survival is the application of plant hormones, particularly auxins like NAA. Bud chips treated with plant hormones exhibit higher concentrations of reducing sugars, leading to improved water and nutrient use efficiency as well as greater resistance to pests (Wu and Birch, 2007). Given the rising global demand for sugarcane-based products, optimizing production practices is essential. The bud chip technique, when integrated with auxin application in nursery or greenhouse settings, enhances root and shoot development, ultimately improving growth and yield in field conditions (Begum *et al.*, 2024).

Although sugarcane typically requires 10–12 months to reach harvest maturity, recent innovations in planting materials, such as bud chips, offer promising avenues for improving productivity and resource

efficiency. Bud chips, being a cost-effective and sustainable alternative to traditional seed cane planting, allow for easier handling, reduced planting material requirements, and enhanced multiplication rates. This study emphasizes the need to evaluate the productivity of bud chips treated with plant hormones, specifically NAA, under field conditions. The incorporation of NAA, a synthetic auxin, may enhance root initiation and early growth, potentially leading to improved crop stand and yield. Therefore, the objective of this study was to evaluate the performance of auxin-treated sugarcane bud chips under field conditions, specifically focusing on growth parameters, yield components, and economic efficiency.

MATERIALS AND METHODS

Experimental Design and Treatments

The experiment was conducted at the Sugarcane Nursery Greenhouse and Sugarcane Production Area of Isabela State University (ISU), Cabagan Campus, located at 17.4144° N latitude and 121.7670° E longitude in Cabagan, Isabela, Philippines. The study was conducted from June to November 2024. The soil in the area is classified as clay loam, with good moisture-retaining capacity and moderate fertility. Climatic conditions during the experiment featured a tropical monsoon climate, with relative humidity typically ranging from 71% to 85% during the wet season (PAGASA, 2024), an average temperature of 24–30°C, and consistent rainfall during the wet season.

A randomized complete block design (RCBD) was employed with three replications. Each block represented a replication and was composed of all the treatment combinations randomly assigned within that block. The total experimental area measured 2,079.00 m² and was divided into three blocks (replications), each containing a complete set of treatments to control for variability across the experimental field. Each replication consisted of eleven (11) treatment plots, totaling thirty-three (33) plots across the study. Each

plot measured 5.0 m in width and 5.0 m in length and contained 4 planting rows, with a row-to-row spacing of 0.8 m and a hill-to-hill distance of 0.5 m within the rows. There was a 2.0 m buffer zone between plots within a replication to avoid edge effects and an additional 2.0 m spacing between replications. This layout ensured uniform exposure to environmental conditions and minimized experimental error due to plot interference.

The treatments consisted of sugarcane bud chips treated with varying concentrations of NAA, including a control (non-bud chip), no auxin bud chip and nine bud chip with NAA concentrations (in ppm), as detailed in the treatment matrix showed in Table 1, furthermore, selection of NAA concentrations and soaking durations in this study was based on the need to improve the sprouting and early growth of sugarcane bud chips. NAA is a type of plant hormone (auxin)

known to promote root and shoot development. Different concentrations were used to find the most effective level that encourages growth without harming the buds. Lower concentrations (like 150 ppm) were expected to gently stimulate growth, while moderate levels (200 ppm) were chosen because they are often reported as ideal in previous studies. Higher concentrations (250 ppm) were included to see if more hormone would give better results or if it would slow down or damage the buds. Soaking times were also varied (10, 20, and 30 minutes) to determine how long the buds should be exposed to the hormone for best results. Shorter times test quick absorption, while longer times check if more hormone uptake improves the effect or causes harm. Including different concentrations and soaking durations helps identify the best treatment that supports strong, uniform sprouting in sugarcane bud chips.

Table 1 Description of treatments and experimental design used in the evaluation of different concentrations of naphthaleneacetic acid (NAA) and soaking durations on sugarcane bud chip performance under field conditions

Treatment	Description
T1	Non-bud chip/seed cane (control)
T2	Bud chip, no auxin applied
T3	10 minutes soaking at 150 ppm
T4	10 minutes soaking at 200 ppm
T5	10 minutes soaking at 250 ppm
T6	20 minutes soaking at 150 ppm
T7	20 minutes soaking at 200 ppm
T8	20 minutes soaking at 250 ppm
T9	30 minutes soaking at 150 ppm
T10	30 minutes soaking at 200 ppm
T11	30 minutes soaking at 250 ppm

Note: The treatments include two controls: T1, which serves as the absolute control, consisted of conventionally planted seed cane (whole setts) without any auxin treatment; and T2, which served as the comparative control, consisted of bud chip planting material without auxin application.

Plant Material Preparation

The soil was collected from the sugarcane field using a wheelbarrow as the initial step in preparing

the growing medium for nursery propagation. This collection provides a suitable substrate for transplanting the sugarcane bud chips. Following collection, the

soil was sieved to remove large particles, including stubbles, compacted clumps, and other debris, to ensure a uniform and fine texture promoting good aeration, drainage, and root development during the early growth stage in polyethylene bags. By preparing clean and well-structured soil, the procedure aimed to create optimal nursery conditions that would support the successful establishment of the auxin-treated sugarcane bud chips before their transfer to the main field. Sugarcane cuttings were obtained from the production site of Isabela State University (ISU), Cagayan, with careful selection to ensure only healthy and disease-free cuttings were used.

The sugarcane variety used was PHIL 2006–1899, an erect to recumbent cultivar with moderate growth and a yield potential of 148.29 t/ha. It is resistant to smut, leaf scorch, and downy mildew (SRA, 2024). Planting materials aged 8–10 months were collected from the ISU Cagayan sugarcane production site. Healthy, disease-free stalks were selected and processed using a manually fabricated sugarcane bud chipper, producing individual bud chips. These were transplanted into 4" × 4" × 6" polyethylene bags filled with sieved field soil. The seedlings were maintained in the nursery for 60 days under partially shaded conditions, and regular watering was done to ensure proper root development. Only vigorous and uniformly growing seedlings were selected for field transplanting. To apply NAA, a stock solution was prepared using the wettable powder form of NAA, assumed to be 100% pure. The powder was dissolved in 10 mL of ethyl alcohol and then diluted with distilled water to create a 1,000 mL stock solution. Concentrations in parts per million (ppm) were prepared using the formula $C_1V_1 = C_2V_2$, with 1.0 mg/L equivalent to 1 ppm. Bud chips were soaked in the NAA solutions before planting.

Planting Procedure

To ensure efficient and thorough soil cultivation, the experimental site underwent plowing, harrowing,

and levelling using a riding-type tractor. Proper pulverization of the soil was ensured before planting to create an optimal growing environment. Comprehensive soil sampling was carried out before land preparation, collecting samples from 0–20 cm soil depth in a zigzag pattern across the field. The composite samples were submitted to the Soil Laboratory of the Department of Agriculture for fertility analysis. Based on the results, a recommended fertilizer formulation of 120 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹ was adopted. The phosphorus (as complete fertilizer 14-14-14) and potassium (as muriate of potash 0-0-60) were applied basally before planting. Nitrogen was applied in split doses: 50% at 30 days after transplanting (DAT), 25% at 45 DAT, and the remaining 25% at 60 DAT using urea (46-0-0).

The hardened bud chip sugarcane seedlings were transplanted to the prepared experimental plots. It was done manually during the early morning hours to minimize transplanting shock and moisture loss following the recommended spacing of 1.2 m between rows and 0.5 m between hills. Proper watering schedules were applied at critical growth phases, including germination, tillering, and maturation, to support optimal crop development. Weed management was performed manually through hand weeding to eliminate potential competition for nutrients, sunlight, space, and moisture. Pest and disease control followed an integrated pest management (IPM) strategy. Preventive measures when pest thresholds were reached, Mancozeb (80 WP) at 2.5 g/L was used for managing fungal diseases such as red rot. Applications were done using a knapsack sprayer during the early morning or late afternoon to avoid phytotoxicity and improve efficacy. Routine monitoring of sugarcane crops was conducted to promptly identify and address any pest or disease infestations. Harvesting was manually done using a bolo once the sugarcane had reached full maturity, which was at 160 DAT. Each stalk was carefully cut at the base to minimize

damage and ensure complete collection of the mature plant parts.

Data Collection

The data collected in this study were systematically categorized into growth characteristics, yield characteristics, and statistical analysis procedures to comprehensively evaluate the performance of auxin-treated sugarcane bud chips under field conditions.

Growth characteristics

The survival number of sugarcane bud chip seedlings that survived was gathered at 30 DAT. The plant height of 5 samples was measured from the base of the stalk to the dewlap using a meter stick, while the number of tillers per plant and number of leaves were manually counted at 30, 60, and 160 DAT. Internodal length was also recorded by measuring the middle portion of the stalk using a meter stick. These observations were aimed at assessing the early establishment, vegetative growth, and development trends of sugarcane under different concentrations of NAA.

Yield characteristics

The biomass yield was obtained by weighing the matured sugarcane using a digital scale, while juice extract yield per stalk was measured using a sugarcane juice extractor, with the extracted juice volume quantified using a graduated cylinder. For each treatment, a 10 m² harvest area was designated within the central rows of the plot to avoid border effects. This area was carefully measured and marked using measuring tapes and stakes before harvest. The total plot size was larger than 10 m² to accommodate proper spacing and buffer rows. Computed yield per hectare (t/ha) estimation was based solely on the sugarcane stalks harvested from this demarcated 10 m² area, with all leaves and roots removed before weighing. The computed cane yield in tons per hectare

(t/ha) was calculated using the following formula: Yield per hectare (t/ha) = (Yield from 10 m² in kg/10) × 10,000/1,000.

Cost and return analysis were conducted to determine the return on investment (ROI) for each treatment. This analysis involved computing the total production cost, including expenses for material inputs (such as fertilizers, pesticides, etc.), labor cost, and other operational costs. A significant distinction in cost arises between the use of seed cane and bud chips as planting materials. Seed cane, which involves planting entire stalks or portions thereof, typically requires about 6–10 t/ha, that incurs high costs due to the volume of material needed, increased transportation requirements, and associated labor. In contrast, bud chip technology uses single-eye buds, requiring only about 500–600 kg of cane per ha. Although the bud chip method demands initial investments in nursery management, trays, and additional labor for transplanting, it offers greater uniformity, higher multiplication rates, and overall lower cost per hectare compared to seed cane. The application of NAA introduces another cost component that varies depending on the concentration used. NAA is used to enhance rooting and early growth of bud chips, and the cost includes the chemical itself, materials used for solution preparation, labor for soaking or treatment, and equipment. While seed cane is typically planted without NAA, its use is essential for the successful establishment of bud chips, and therefore must be factored into total production expenses for those treatments. Gross income was determined based on the computed yield per hectare and the prevailing market price of sugarcane. The net income was obtained by subtracting the total production cost from the gross income. ROI was then calculated using the formula: ROI (%) = (Net income / Total cost) × 100% (Sugiyanto and Kustiawan, 2020). This analysis demonstrated that bud chip-treated sugarcane, particularly when applied with an optimal concentration of NAA, could yield higher returns on

investment due to reduced input costs and improved crop establishment. Thus, the use of bud chips, in combination with growth-promoting substances like NAA, offers a potentially more profitable alternative to traditional seed cane planting.

Statistical Analysis

The quantitative data were analyzed using analysis of variance (ANOVA) to determine whether significant differences existed among treatments. Prior to conducting ANOVA, assumptions of normality and homogeneity of variances were verified using the Shapiro-Wilk test and Levene's test, respectively, to ensure the validity of the analysis. When significant treatment effects were observed, mean comparisons were conducted using Duncan's multiple range test (DMRT) at a 5% level of significance to identify specific differences between treatment means. The standard deviation (SD) was also calculated to assess the

variability within each treatment group. All statistical procedures were performed using SPSS (Statistical Package for the Social Sciences) software, ensuring accurate and efficient data analysis.

RESULTS AND DISCUSSION

Effect of Auxin-Treated Sugarcane Bud Chip on Growth Traits

The survival counts of sugarcane bud chip seedlings treated with auxin were evaluated during their transition from screenhouse to field conditions. Each treatment consisted of an equal number of 10 transplanted seedlings. The variation in the number of recovered seedlings across treatments is presented in Table 2, with recovery rates ranging from 7.33 to 10 seedlings after transplanting. Among the auxin-treated seedlings, T5, T6, and T11 achieved the highest recovery rates, with a mean of 8.67 out of 10 seedlings. T3, T8, T9, and T10 recorded a slightly lower mean

Table 2 Effect of varying concentrations of naphthaleneacetic acid (NAA) and soaking durations on survival count of sugarcane seedlings propagated through the bud chip method under field conditions

Treatment	Survival counts
T1	10.00 ± 0.00
T2	9.00 ± 0.00
T3	8.00 ± 0.00
T4	7.33 ± 0.47
T5	8.67 ± 0.94
T6	8.67 ± 1.89
T7	8.33 ± 0.47
T8	8.00 ± 1.63
T9	8.00 ± 0.00
T10	8.00 ± 0.82
T11	8.67 ± 0.47

Note: Values are expressed as mean ± standard deviation from three replications per treatment. The treatment codes used in this study are as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

recovery of 8 seedlings. Conversely, the lowest recovery rate was observed in T4, with a mean of 7.33 seedlings. Interestingly, non-auxin-treated seedlings showed superior recovery rates. T1 (non-bud chip/seed cane-control), representing farmers' practice and control, recorded the highest mean recovery with 10 seedlings, followed by T2 (no auxin bud chip) with a mean of 9 seedlings. These results suggest that auxin treatments did not significantly enhance the adaptability of sugarcane bud chip seedlings under the tested conditions. One possible reason is that the field environment already provides sufficient natural stimuli (e.g., moisture, temperature, and soil nutrients) for root initiation and growth, making the exogenous application of auxin unnecessary or even inhibitory. In some cases, excess or poorly timed application of auxin can disrupt the natural hormonal balance, potentially leading to abnormal growth responses or reduced root development. Additionally, environmental stressors such as high temperature, intense sunlight, or water stress may have interfered with auxin uptake or activity, limiting its effectiveness. These findings suggest that under practical field conditions, the use of auxin may not always translate to improved transplant recovery and should be evaluated case-by-case depending on the specific crop, environment, and timing.

The response of sugarcane bud chip seedlings treated with NAA in terms of plant height under field conditions is presented in Table 3. The ANOVA results revealed highly significant differences in plant height at 30 DAT, 60 DAT, and at maturity. At 30 DAT, T4 recorded the tallest plants (4.35 ± 0.25 cm), significantly surpassing all other treatments. Treatments T7, T10, T9, T11, T6, T5, and T2 formed a statistically similar group with plant heights ranging from 4.08 ± 0.12 cm to 4.20 ± 0.16 cm. However, T3, T8, and T1 exhibited the shortest plant heights, ranging from 3.57 ± 0.17 cm to 3.90 ± 0.37 cm, demonstrating a highly significant difference from the other treatments. The early stimulation

of plant height observed in NAA-treated bud chips aligns with the findings of Jahan *et al.* (2019), who reported that auxin enhances cell elongation and division, thereby accelerating initial growth.

At 60 DAT, T7 attained the greatest height (36.22 ± 0.57 cm), followed closely by T4 (35.93 ± 0.82 cm), both of which significantly outperformed the control (19.03 ± 1.35 cm). This sustained growth improvement suggests that 200 ppm NAA enhances vegetative development over time. At maturity, the tallest plants were observed in T4 (162.53 ± 5.06 cm), T7 (162.33 ± 2.05 cm), and T10 (161.29 ± 6.65 cm), significantly exceeding the control treatment (90.75 ± 8.18 cm). These results indicate that applying 200 ppm NAA, irrespective of soaking duration, improves sugarcane growth performance. Similar studies (Hussain *et al.*, 2021) have demonstrated that the appropriate concentration and application of NAA promote cell elongation and division, ultimately influencing plant height. This study provides practical insights into sugarcane cultivation by demonstrating how auxin treatment can improve bud chip establishment, leading to better crop performance. Bud chip technology already reduces planting material requirements, and the addition of auxin treatment further enhances early growth and overall plant height, making sugarcane production more efficient. These findings can benefit sugarcane farmers by promoting better seedling development, potentially increasing overall yield and economic returns.

On the other hand, Table 4 demonstrates the significant effects of NAA treatments on tiller production in sugarcane at different growth stages under field conditions. ANOVA revealed highly significant differences in the number of tillers at 30 and 60 DAT and significant differences at the elongation stage (160 DAT). Among the treatments, T8 recorded the highest mean tiller count of 3.00 at 30 DAT, closely followed by T4 (2.96 ± 0.22), both of which were statistically similar but significantly higher than T5 (2.00 ± 0.16), T3 (1.92 ± 0.12),

Table 3 Effect of varying concentrations of naphthaleneacetic acid (NAA) and soaking durations on plant height of sugarcane propagated through bud chip method under field conditions

Treatment	Plant height (cm)		
	30 DAT	60 DAT	Maturity
T1	3.57 ± 0.17 ^d	19.03 ± 1.35 ^d	90.75 ± 8.18 ^c
T2	4.08 ± 0.12 ^{ab}	27.29 ± 3.04 ^c	136.27 ± 19.80 ^{ab}
T3	3.90 ± 0.37 ^{bc}	25.56 ± 0.79 ^c	118.30 ± 10.25 ^{bc}
T4	4.35 ± 0.25 ^a	35.93 ± 0.82 ^a	162.53 ± 5.06 ^a
T5	4.08 ± 0.12 ^{ab}	29.17 ± 1.01 ^{bc}	122.67 ± 26.82 ^b
T6	4.13 ± 0.09 ^{ab}	25.73 ± 0.88 ^c	137.80 ± 15.46 ^{ab}
T7	4.20 ± 0.16 ^{ab}	36.22 ± 0.57 ^a	162.33 ± 2.05 ^a
T8	3.77 ± 0.21 ^{bc}	30.55 ± 4.23 ^{abc}	142.53 ± 17.82 ^{ab}
T9	4.17 ± 0.06 ^{ab}	29.27 ± 4.10 ^{bc}	118.73 ± 21.58 ^{bc}
T10	4.20 ± 0.16 ^{ab}	34.37 ± 0.95 ^{ab}	161.29 ± 6.65 ^a
T11	4.13 ± 0.19 ^{ab}	30.64 ± 0.51 ^{abc}	140.27 ± 9.48 ^{ab}

Note: Means within the same column followed by different superscript letters (a, b, c, d) are significantly different ($P < 0.05$), as determined by Duncan's multiple range test. Values are expressed as mean ± standard deviation. DAT = days after transplanting. The treatment codes used in this study are as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

and T1 (1.47 ± 0.19). This early stimulation of tiller growth can be attributed to the role of NAA in enhancing cell division and elongation, which promotes shoot proliferation. Interestingly, NAA-treated plants in T2 to T11 maintained a high number of active tillers, ranging from 7.93 ± 0.90 to 9.80 ± 0.16 at 160 DAT, significantly surpassing the control (T1) with only 3.33 ± 0.47 tillers. The control treatment (farmer's practice) did not show an increase in tiller count beyond 60 DAT, likely due to the closer planting distance, which favored stem elongation at the expense of tillering. Additionally, the denser planting increased susceptibility to insect pests such as fall armyworm (*Spodoptera frugiperda*) and stem borer (*Chilo terrenellus*), as well as diseases like red rot (*Glomerella tucumanensis*), further limiting tiller production. These findings highlight the benefits of NAA treatment in enhancing sugarcane tillering, which directly contributes to yield potential.

The increased tiller production observed between 30 and 60 DAT indicates that auxin application during early growth stages can promote the development of multiple shoots, leading to higher biomass accumulation. This is consistent with the findings of Jahan *et al.* (2019), who reported that NAA enhances growth and yield in cereals and legumes. From a practical standpoint, the application of NAA in sugarcane bud chip seedlings can be recommended to optimize tiller formation, particularly when combined with appropriate planting distances. By promoting a balanced plant structure, NAA-treated sugarcane stands are likely to achieve greater stalk density, improved resistance to lodging, and ultimately higher productivity. However, factors such as soil fertility, moisture availability, and pest management should be carefully considered to maximize the benefits of this treatment in diverse field conditions. Future research should explore the long-term effects

of NAA application on ratoon crop performance and its interaction with other agronomic practices for sustainable sugarcane production.

Moreover, Table 5 demonstrates the significant influence of NAA treatments on the internodal length of sugarcane bud chip seedlings under field conditions. ANOVA revealed highly significant differences among treatments, indicating that auxin application plays a crucial role in regulating stem elongation. Among the treatments, T4 exhibited the longest mean internodal length (11.19 ± 0.30 cm), followed by T7 (10.83 ± 0.47 cm), T10 (10.40 ± 0.28 cm), and T8 (10.39 ± 0.86 cm). These treatments formed a statistically similar group but displayed highly significant differences when compared to T9 (8.81 ± 0.02 cm), T3 (8.68 ± 1.03 cm), and T1 (7.43 ± 0.60 cm), which recorded the shortest internodal lengths. The observed increase

in internodal length with NAA application, particularly in T4, suggests that this growth regulator effectively enhances stem elongation. Auxins like NAA promote cell elongation by modulating cell wall plasticity, allowing for increased expansion and elongation of internodes (Majda and Robert, 2018; Pantoja-Guerra *et al.*, 2023).

This response highlights the potential of NAA treatment in optimizing sugarcane morphology, particularly for improved light interception and better resource allocation. Interestingly, while NAA significantly influenced internodal elongation, its effect on node formation appeared to be less pronounced. This differential response may be attributed to the specific regulatory role of auxins in plant growth. While NAA primarily enhances cell elongation, processes such as node formation are likely governed by a more complex

Table 4 Effect of varying concentrations of naphthaleneacetic acid (NAA) and soaking durations on the number of tillers at 30 and 60 days after transplanting (DAT), and active tillers at 160 DAT (elongation stage) in bud chip-propagated sugarcane under field conditions

Treatment	Number of tillers per hill		Number of active tillers per hill (160 DAT)
	30 DAT	60 DAT	
T1	1.47 ± 0.19^d	3.04 ± 0.15^d	3.33 ± 0.47^b
T2	2.40 ± 0.43^{abc}	6.16 ± 1.35^{abc}	8.67 ± 1.64^a
T3	1.92 ± 0.12^{cd}	4.95 ± 0.91^{bc}	9.00 ± 0.91^a
T4	2.96 ± 0.22^a	8.00 ± 0.72^a	9.80 ± 0.16^a
T5	2.00 ± 0.16^{bcd}	4.48 ± 0.55^{cd}	7.93 ± 0.90^a
T6	2.20 ± 0.00^{bc}	4.92 ± 0.82^{bc}	8.07 ± 0.34^a
T7	2.65 ± 0.49^{ab}	6.73 ± 1.47^{ab}	9.40 ± 2.37^a
T8	3.00 ± 0.00^a	5.22 ± 1.04^{bc}	7.93 ± 1.57^a
T9	2.34 ± 0.19^{abc}	5.03 ± 0.45^{bc}	8.13 ± 2.08^a
T10	2.60 ± 0.28^{ab}	6.32 ± 0.48^{abc}	9.07 ± 1.09^a
T11	2.53 ± 0.50^{abc}	5.73 ± 0.34^{bc}	8.13 ± 1.65^a

Note: Means within the same column followed by different superscript letters (a, b, c, d) are significantly different ($P < 0.05$), as determined by Duncan's multiple range test. Values are expressed as mean $\pm$ standard deviation. The treatment codes used in this study are as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

interplay of hormonal and environmental factors. These findings suggest that targeted application of growth regulators can be strategically utilized to modify sugarcane growth patterns, improving plant architecture and potentially increasing biomass accumulation. From a practical perspective, the application of 200 ppm NAA could be recommended to farmers seeking to optimize sugarcane internodal elongation, particularly in bud chip seedlings. Longer

internodes may contribute to improved stalk quality and ease of harvesting, enhancing both productivity and economic returns. However, environmental factors such as soil fertility, water availability, and varietal differences may influence the effectiveness of NAA applications. Future studies should explore the interaction of these factors with auxin treatments to develop site-specific recommendations for sustainable sugarcane production.

Table 5 Effect of varying concentrations of naphthaleneacetic acid (NAA) and soaking durations on internodal length of bud chip-propagated sugarcane under field conditions

Treatment	Internodal length (cm)
T1	7.43 ± 0.60 ^d
T2	9.78 ± 0.47 ^{abc}
T3	8.68 ± 1.03 ^{cd}
T4	11.19 ± 0.30 ^a
T5	9.03 ± 0.12 ^{bc}
T6	9.79 ± 0.63 ^{abc}
T7	10.83 ± 0.47 ^a
T8	10.39 ± 0.86 ^{ab}
T9	8.81 ± 0.02 ^{bcd}
T10	10.40 ± 0.28 ^a
T11	10.09 ± 1.09 ^{abc}

Note: Means within the same column followed by different superscript letters (a, b, c, d) are significantly different ($P < 0.05$), as determined by Duncan's multiple range test. Values are expressed as mean ± standard deviation. The treatment codes used in this study are as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

Effect of Auxin-Treated Sugarcane Bud Chip on Sugarcane Yield

Table 6 highlights the significant effects of NAA treatments on biomass yield per plant in sugarcane under field conditions. Among the treatments, T4 exhibited the highest biomass yield, with a mean of $1,060.00 \pm 22.73$ g, followed closely by T7 ($1,031.67 \pm 8.50$ g). Similarly, T8 ($1,016.67 \pm 59.70$ g) and T10 ($1,013.67 \pm 9.84$ g) produced statistically comparable

biomass yields. These treatments significantly outperformed T5 (626.67 ± 174.77 g), T9 (576.00 ± 33.98 g), T3 (566.33 ± 71.60 g), and the control (T1) with the lowest yield of 525.33 ± 68.63 g. The increased biomass accumulation in T4 and T7 can be attributed to the physiological role of NAA in enhancing cell elongation, division, and efficient nutrient translocation. These findings align with Tolera (2016), who reported the positive influence of plant growth regulators like

NAA on sugarcane productivity. Furthermore, research by Xie *et al.* (2023) demonstrated that optimal auxin concentrations, such as those provided by NAA, stimulate root and shoot development, ultimately leading to greater biomass accumulation. These results underscore the importance of integrating NAA application into sugarcane cultivation practices to maximize biomass production. The findings suggest that applying 200 ppm NAA can effectively promote plant growth, potentially leading to improved stalk yield and sugar content. From a practical perspective, farmers can utilize NAA treatments to enhance overall plant vigor, particularly in conditions where early vegetative growth is critical for achieving higher productivity. However, factors such as soil fertility, planting density, and environmental conditions should be optimized to maximize the benefits of this treatment. Future studies should explore the long-term effects of NAA on ratoon cropping and its interaction with other agronomic practices to ensure sustainable sugarcane production.

Table 6 presents the volume of juice extract per stalk (mL) in sugarcane treated with NAA in bud chip under field conditions. The highest mean juice extract was recorded in T4 (231.67 ± 12.47 mL), followed closely by T7 (230.33 ± 3.86 mL), T10 (224.67 ± 9.39 mL), and T8 (216.67 ± 1.25 mL). While these treatments were not significantly different from each other, they showed a statistically significant increase in juice extract compared to T11 (209.33 ± 11.81 mL), T6 (195.33 ± 2.49 mL), and T2 (185.00 ± 0.82 mL). The lowest juice volume was observed in T1 (80.00 ± 11.43 mL), which was highly significant compared to all other treatments. The reduced juice output in T1 is attributed to its shorter stalk height and reduced internodal length, which limit juice accumulation. These findings emphasize the strong correlation between stalk elongation and juice production, as taller stalks with longer internodes provide greater storage capacity for juice. This aligns with the research of Sujatha *et al.* (2018), who highlighted the role of

NAA in enhancing internodal elongation, consequently increasing juice content. Similarly, a study by Arain *et al.* (2024) on the effects of NAA and 2,4-dichlorophenoxy acetic acid in sugarcane cultivation found that NAA application significantly increased internode length, which directly influenced juice yield by improving stalk development. These results suggest that the application of NAA can be an effective strategy for increasing juice yield in sugarcane by promoting morphological traits that enhance juice accumulation. Integrating NAA treatment into sugarcane cultivation may improve overall productivity, especially in varieties where stalk height and internodal elongation are key determinants of juice extraction efficiency.

Figure 1 presents the cane yield (tons of cane per hectare or t/ha) in sugarcane treated with varying concentrations of NAA using the bud chip method under field conditions. Results showed that T10 achieved the highest mean yield of 164.71 ± 4.65 t/ha. ANOVA revealed no significant differences between T10 and T11 (148.99 ± 7.78 t/ha), T8 (141.61 ± 4.62 t/ha), T4 (139.59 ± 5.25 t/ha), and T7 (135.77 ± 4.06 t/ha). However, these treatments exhibited significantly higher yields compared to T5 (92.06 ± 29.28 t/ha), T3 (82.82 ± 5.71 t/ha), T9 (76.18 ± 0.30 t/ha), and T1 (28.35 ± 4.65 t/ha), which recorded the lowest yield. A clear distinction was observed among treatments, with those receiving 200 ppm of auxin (NAA) exhibiting superior yield performance. This highlights both the economic and agronomic advantages of the bud chip method when enhanced with auxin application. The improved yield in auxin-treated bud chips can be attributed to enhanced physiological and morphological traits. A strong positive correlation was observed between cane yield and key growth parameters such as internodal length, plant height, biomass yield, and juice extract volume. These results underscore the efficacy of NAA in promoting sugarcane growth and development, ultimately leading to significantly higher yields. This aligns with the findings of Khan *et al.*

Table 6 Effect of varying concentrations of naphthaleneacetic acid (NAA) and soaking durations on the biomass yield and amount of juice extract yield per stalk in sugarcane treated of NAA in bud chip under field condition

Treatment	Biomass yield per plant (g)	Amount of juice extract yield per stalk (mL)
T1	525.33 ± 68.63 ^d	80.00 ± 11.43 ^d
T2	720.67 ± 21.31 ^{bc}	185.00 ± 0.82 ^b
T3	566.33 ± 71.60 ^{cd}	175.67 ± 3.40 ^c
T4	1,060.00 ± 22.73 ^a	231.67 ± 12.47 ^a
T5	626.67 ± 174.77 ^{cd}	166.33 ± 5.44 ^c
T6	812.33 ± 23.04 ^b	195.33 ± 2.49 ^b
T7	1,031.67 ± 8.50 ^a	230.33 ± 3.86 ^a
T8	1,016.67 ± 59.70 ^a	216.67 ± 1.25 ^a
T9	576.00 ± 33.98 ^{cd}	166.67 ± 1.25 ^c
T10	1,013.67 ± 9.84 ^a	224.67 ± 9.39 ^a
T11	957.33 ± 27.44 ^a	209.33 ± 11.81 ^b

Note: Means within the same column followed by different superscript letters (a, b, c, d) are significantly different ($P < 0.05$), as determined by Duncan's multiple range test. Values are expressed as mean ± standard deviation. The treatment codes used in this study are as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

(2023), who reported that auxin application enhances biomass production and sucrose accumulation in sugarcane, leading to increased overall yield. Furthermore, Sreelatha *et al.* (2019) demonstrated that soaking sugarcane bud chips in NAA improved tiller production, which plays a crucial role in maximizing cane yield. The superior performance of T10, T4, and T7 may also be attributed to the optimal NAA concentrations applied. Mehdi *et al.* (2024) noted that inappropriate auxin levels could disrupt hormonal balance, leading to inhibited growth. These results are consistent with those of Manzoor *et al.* (2023), who found that plant growth regulators such as NAA significantly enhance sugarcane height and yield by promoting structural and physiological traits essential for cane productivity.

The significant improvement in growth and yield components observed in NAA-treated sugarcane

bud chips can be attributed to the physiological role of auxins in stimulating early root and shoot development. Soaking the nodes in NAA before planting initiates a cascade of cellular responses, including increased cell division and elongation, particularly in the meristematic regions (Fahad *et al.*, 2015; Gouraj, 2023). This early hormonal priming enhances root initiation and proliferation, resulting in better anchorage and more efficient uptake of water and nutrients throughout the plant's life cycle (Kumar *et al.*, 2024). Although NAA was applied only once before planting, its effects persisted because early developmental advantages strongly influence subsequent vegetative growth and biomass accumulation (Hussain *et al.*, 2021). The well-established root systems likely supported better tillering, cane girth, and internode elongation, which are critical components of sugarcane yield (Kumar *et al.*, 2023). Moreover, the early stimulation of physiological processes may have set a favorable

trajectory for hormonal balance and metabolic activity, leading to improved source-sink relationships during the crop's development (Bhattacharya, 2021). These findings suggest that even a single exposure to synthetic auxins like NAA can induce long-term

developmental benefits by optimizing the initial growth conditions, supporting the hypothesis that pre-sowing hormonal treatment can be a cost-effective and practical strategy for increasing field productivity.

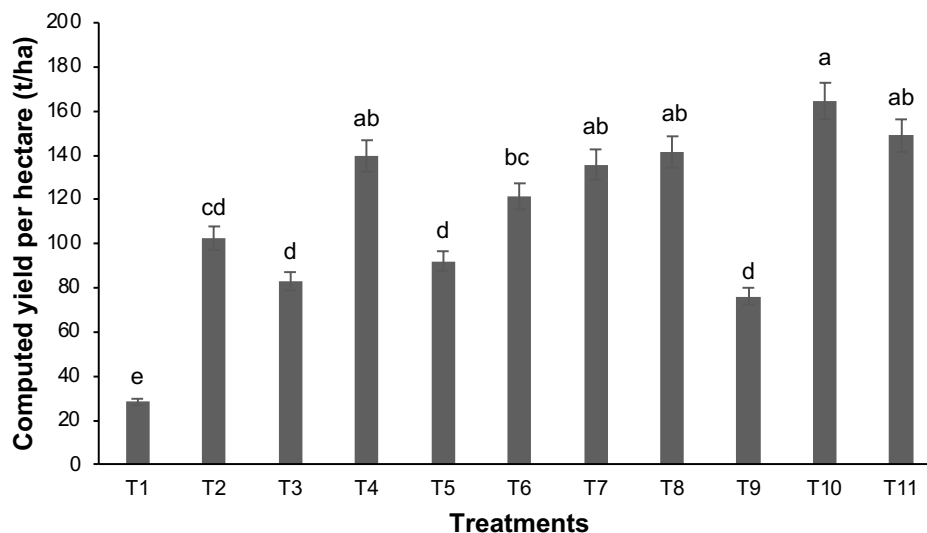


Figure 1 Tons cane per hectare (t/ha) of sugarcane produced from bud chips as affected by varying concentrations and soaking durations of naphthaleneacetic acid (NAA) under field conditions. Different superscript letters (a, b, c, d, e) on the bars indicate significant differences among treatment means ($P < 0.05$), according to Duncan's multiple range test. Data are presented as mean $\pm$ standard deviation. Treatments were as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

The Return on Investment (ROI)

Figure 2 presents the ROI for sugarcane treated with NAA using the bud chip method under field conditions. T10 recorded the highest ROI at $223.09 \pm 38.90\%$, followed by T11 ($193.16 \pm 25.38\%$), T8 ($182.78 \pm 28.49\%$), and T4 ($177.72 \pm 22.70\%$). Although ANOVA revealed no significant differences among these top-performing treatments, the differences were significant when compared to T7 ($172.09 \pm 23.86\%$) and T6 ($145.41 \pm 20.30\%$), and highly significant when compared to T3 ($80.43 \pm 12.13\%$), T9 ($67.98 \pm 6.10\%$), and T1 ($36.72 \pm 21.54\%$), which recorded the lowest ROI values. These findings reinforce the earlier yield

data, demonstrating that bud chip-based propagation, especially with optimal NAA application, significantly enhances both biological yield and economic returns. The markedly lower ROI in T1 (seed cane) confirms that this traditional method is not only less productive but also less economically viable than the innovative bud chip system enhanced with plant growth regulators. The strong alignment between high cane yield and high ROI in T10 suggests that bud chip propagation with 200 ppm NAA not only maximizes agronomic performance but also delivers the highest financial return per unit cost, making it the most effective and economically sustainable treatment.

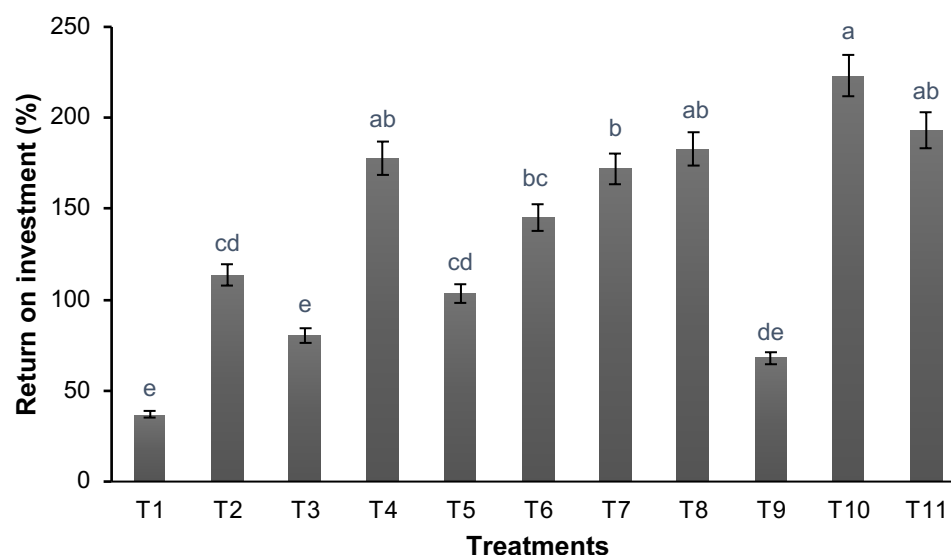


Figure 2 Percentage (%) of return on investment of sugarcane as influenced by varying concentrations of naphthaleneacetic acid (NAA) and soaking durations using the bud chip method under field conditions. Different superscript letters (a, b, c, d, e) on the bars indicate significant differences among treatment means ($P < 0.05$), according to Duncan's multiple range test. Data are presented as mean $\pm$ standard deviation. Treatments were as follows: T1 corresponds to seed cane (control), T2 refers to bud chip without auxin application, T3 to T5 represent bud chips soaked for 10 minutes in 150, 200, and 250 ppm NAA, respectively, T6 to T8 correspond to bud chips soaked for 20 minutes in 150, 200, and 250 ppm NAA, respectively, and T9 to T11 refer to bud chips soaked for 30 minutes in 150, 200, and 250 ppm NAA, respectively.

This study is consistent with the findings of Mohanty and Nayak (2021), who reported that the bud chip method results in significantly higher profits and is three times more cost-effective than conventional planting. Similarly, Begum *et al.* (2022) and Parajuli *et al.* (2019) found that net returns under the Sustainable Sugarcane Initiative (SSI) improved with bud chip technology. Hussain *et al.* (2021) noted that NAA application enhances yield and the benefit-cost ratio, while Mishra (2019) documented higher gross and net returns using this method. Despite higher input costs, Sugeerthi *et al.* (2018) observed that chip-budded sugarcane generated the highest net income of ₹124,159/ha and a benefit-cost ratio of 2.63. Kumar *et al.* (2024) also reported an increase in net profit with bud chip planting compared to conventional

approaches. These findings collectively affirm that the bud chip method is a viable and economically advantageous alternative to traditional sugarcane planting techniques, particularly when paired with plant growth regulators like NAA. Finally, while the results provide valuable insights into the performance of the sugarcane variety under specific site conditions, it is important to acknowledge that outcomes may vary with different varieties or agro-climatic conditions. Since the study focused on a single variety and location, the generalizability of the results is limited. Future studies should investigate a broader range of varieties and environments to better understand the interactions between genotype, input responsiveness, and local growing conditions. This limitation should be considered when extrapolating the findings to others.

CONCLUSIONS

This study demonstrated that auxin-treated sugarcane bud chips significantly improved growth parameters, yield components, and economic returns under field conditions. Treatments, particularly those involving 200 ppm auxin, enhanced plant height, internodal length, number of tillers, biomass accumulation, bagasse yield, juice extract yield, and computed cane yield per hectare. These outcomes highlight auxin's positive role in promoting vegetative growth, stimulating lateral shoot production, and supporting uniform crop development, which are essential for achieving high productivity. However, while the 200 ppm treatment consistently delivered superior performance, other auxin concentrations and soaking durations produced variable effects, with some offering only marginal improvements over the control. This variability suggests that the efficacy of auxin application is highly dependent on the precise dosage and exposure time, presenting a potential trade-off between treatment efficiency and practical field application, particularly in resource-limited settings. The economic analysis reinforced the agronomic findings, demonstrating that auxin application, especially at 200 ppm, provided a favorable return on investment, supporting its potential as a cost-effective strategy for improving farm profitability. Additionally, the observed increase in bagasse yield may contribute to bioenergy production or industrial uses, adding value to the sugarcane production chain.

Nevertheless, this study was conducted using a single sugarcane variety under specific agro-climatic conditions, which may limit the

generalizability of the results. It is important to note that varietal responses to auxin application can vary considerably due to inherent genetic differences among cultivars. Therefore, to fully validate the broader applicability of these findings, future research should explore genotype $\times$ environment $\times$ treatment ($G \times E \times T$) interactions through multi-location trials involving diverse sugarcane varieties and contrasting environmental conditions. This approach will provide a more comprehensive understanding of how different cultivars respond to auxin treatments across varying agro-ecological contexts, and further studies on its application in ratoon management and assessment of its long-term agronomic and economic impacts are essential to fully unlock the potential of this technology for diverse sugarcane-growing regions.

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