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# Interactive effects of pre-planting soil moisture and early-stage deficit irrigation on rainfed sugarcane establishment in contrasting soil types

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## Abstract

Uneven rainfall and early-season drought threaten sugarcane productivity in rainfed systems. Improving pre-planting soil moisture and early-stage irrigation can enhance water productivity and resilience. This study examined the effects of pre-planting soil moisture and deficit irrigation on sugarcane establishment, growth, and yield in contrasting soil types. A factorial field experiment (3 × 3 RCBD) was conducted in clay and sandy loam soils to evaluate the effects of soil moisture and deficit irrigation. Measurements included germination and emergence percentage, plant height, leaf area index (LAI), chlorophyll content (SPAD), and yield components. Two-budded setts (stem cuttings) of sugarcane cultivar "Khon Kaen 3 (KK3)" were planted in each plot to ensure uniform germination and vigor. In clay soil, 80% FC with full irrigation (DI0) accelerated emergence (6-7 days) and achieved >85% germination, whereas 30% FC × DI60 delayed emergence by six days and reduced germination of buds from planted setts to ~64%, decreasing cane and sugar yields by ≈20%. Moderate deficits (DI30) improved water efficiency without yield loss. Maintaining high residual soil moisture with full or moderate irrigation during establishment enhances water productivity and resilience in water-limited sugarcane systems.

**Keywords:** deficit irrigation, pre-planting soil moisture, rainfed agriculture, sugarcane establishment, water productivity

## Introduction

Sugarcane (Saccharum officinarum L.) produces sugar, ethanol, molasses, and other value-added products, boosting Thailand's economy. Thailand is a leading sugar exporter with 1.76 million hectares of vertically integrated production for milling, bioenergy, and bioplastics. Sugarcane's long growth cycle (10-12 months) and biomass accumulation in rainfed regions make it sensitive to water availability (Santos et al., 2019; De Jesus Antunes Júnior et al., 2021; Sajid et al., 2023). As sugarcane is vegetatively propagated using stem cuttings (setts) rather than seeds, the term "germination" in this study specifically refers to the sprouting of buds from planted setts. Germination and tillering are especially vulnerable to water stress because they determine plant population, canopy development, root establishment, and nutrient uptake (Zhao, 2010; Sajid et al., 2023). Stress during this stage can delay emergence, reduce tiller initiation, lower root-to-shoot ratios, and lower yields (Bahmani and Eghbalian, 2018; Khonghintaisong et al., 2021). In this context, "emergence" describes the appearance of young shoots above the soil surface following bud sprouting.

Post-rainy-season planting (October-November) in lower-northern, northeastern, and western regions of Thailand relies on residual monsoon soil moisture to sprout buds (Jintrawet et al., 1999). Climate variability, delayed harvesting, and labor constraints push planting to December-January, when soils are drier and rainfall is unpredictable (Moroizumi et al., 2008; Wonprasaid et al., 2023). The remaining soil moisture is essential for sugarcane establishment, and insufficient moisture can cause prolonged dormancy, weak seedlings, and poor stand establishment (Wijma et al., 2021; Leanasawat al., 2022). Clay soils retain water longer than sandy soils, which dry quickly and expose germinating buds to short moisture pulses and higher mortality (Da Luz et al., 2020; Amorim et al., 2022).

Deficit irrigation, supplying water below crop evapotranspiration (ETc), has been studied to optimize water use during critical growth stages (Fereres and Soriano, 2007; Dingre and Gorantiwar, 2020). Its use in mid- and late season is well-documented (Dingre et al., 2021), but rainfed or semi-arid systems have few studies on its germination and establishment effects. Semi-arid India and Thailand show that targeted irrigation at planting or shortly after can boost bud sprouting and early growth without overwatering, especially in sandy soils (Dingre and Gorantiwar, 2020; Wonprasaid et al., 2023). Genotypic variation also affects water-limited establishment, with some cultivars, like KK3, germinating and growing faster in light-textured soils (Khonghintaisong et al., 2021; Leanasawat al., 2022).

Due to climate change-induced droughts and unpredictable rainfall, knowledge of pre-planting soil moisture, early-stage deficit irrigation, soil type, and cultivar traits are essential for sugarcane establishment in rainfed systems. These factors have been studied separately in most studies, leaving gaps in their field interactions. We believe that soil type-specific pre-planting soil moisture and targeted early-stage irrigation can boost emergence, stand establishment, and water use efficiency. This study examines the interactive effects of pre-planting soil moisture and early-stage deficit irrigation on sugarcane emergence and establishment across different soil textures in rainfed Thailand. These findings will offer evidence-based sugarcane-based agroecosystem resilience and water productivity recommendations.

## Results

### *Soil moisture constants*

Water stress was better buffered by clay than sandy soil in early dry season (Table S2). Clay soil FC ranged from 30.1 ± 1.6% in October 2023 to 11.3 ± 0.5% in February 2024, while sandy soil FC ranged from 14.0 ± 0.7% to 5.2 ± 0.3%. Stable permanent wilting point (PWP) was observed in clay soil (22.2 ± 0.0-0.2%) and sandy soil (7.1 ± 0.0-0.1%). Dry weather reduced both soils' AW. Clay soil's AW (7.9 ± 1.6% in October) decreased to -10.9 ± 0.2% by February, indicating low moisture. AW values in sandy soil decreased from 6.9 ± 0.7% to -1.9 ± 0.1%, despite a similar trend. Clay soil had a higher allowable deficit during October (4.75 ± 0.7%) than sandy soil (4.10 ± 0.4%), but this became negligible during dry months (December-February). Under rainfed conditions, sandy soils lose moisture, while clay soils retain water and buffer early-season water stress. Sugarcane irrigation management is guided by early dry season FC and AW decreases, indicating water stress.

### *Germination and growth parameters*

Initial soil moisture (P), deficit irrigation (D), and soil type (S) strongly influenced sugarcane shoot emergence from sprouted buds, early growth, and leaf physiology. Table 4 shows how these factors affect rainfed sugarcane in clay and sandy soils. Higher pre-planting soil moisture (FC80) and full irrigation (DI0) consistently produced the fastest emergence (6.0-6.3 days) and highest germination rates (89.0-92.3%) across all soil types. Under low initial moisture (FC30) with severe deficit (DI60), emergence was delayed to 11.0-12.3 days and germination fell to 64.0-64.7%. Similar patterns were observed in shoot dry weight, LAI, SPAD, and leaf number per plant. FC80 DI0 had the highest values in both soil types and FC30 DI60 the lowest. Most clay soil had slightly higher growth parameters than sandy soil. Soil type, pre-planting moisture, and deficit irrigation significantly impact most parameters ($P < 0.05$ to $P < 0.001$), with significant two-way and three-way interactions (S × P, S × D, P × D, and S × P × D) for selected growth and physiological traits These results quantify how early water management affects sugarcane establishment and inform the discussion.

**Table 4.** Effects of initial soil moisture and deficit irrigation on sugarcane emergence, germination, early growth, and leaf physiology in clay and sandy soils under rainfed conditions.

| Factor | Days to emergence (days) | Days to emergence (days) | Germination (%) | Germination (%) | Leaves plant-1 | Leaves plant-1 | Dry shoot weights | Dry shoot weights | LAI | LAI | SPAD | SPAD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Factor** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** |
| FC80 DI0 | 6.3 f | 6.0 f | 92.3 a | 89.0 a | 11.3 a | 10.7 a | 103.4 a | 92.4 a | 3.2 a | 2.9 a | 43.5 a | 40.4 a |
| FC80 DI30 | 8.3 de | 8.0 d | 85.0 c | 79.7 d | 9.7 bc | 8.7 abc | 82.7 d | 76.0 c | 2.8 d | 2.3 d | 39.3 d | 36.3 d |
| FC80 DI60 | 10.3 c | 10.0 b | 73.7 f | 70.0 f | 8.7 de | 8.3 bc | 66.3 f | 58.4 e | 2.2 g | 1.8 f | 35.4 g | 30.3 g |
| FC50 DI0 | 7.0 f | 7.3 e | 89.0 b | 87.0 b | 11.3 a | 10.0 ab | 99.4 b | 89.9 b | 3.1 b | 2.8 b | 42.4 b | 39.5 b |
| FC50 DI30 | 9.3 d | 9.0 c | 80.3 d | 78.0 d | 10.3 b | 9.7 ab | 79.6 e | 74.5 cd | 2.7 e | 2.2 e | 38.3 e | 34.4 f |
| FC50 DI60 | 11.3 b | 11.0 a | 70.0 g | 67.0 g | 9.3 cd | 8.7 abc | 62.8 g | 57.4 e | 2.1 h | 1.7 g | 33.3 h | 29.4 h |
| FC30 DI0 | 8.0 e | 8.0 d | 85.7 c | 84.0 c | 11.3 a | 9.3 abc | 95.6 c | 88.3 b | 2.9 c | 2.7 c | 41.4 c | 38.5 c |
| FC30 DI30 | 10.3 c | 9.3 c | 77.0 e | 74.7 e | 10.3 b | 8.3 bc | 78.5 e | 73.1 d | 2.5 f | 2.2 e | 37.1 f | 35.5 e |
| FC30 DI60 | 12.3 a | 11.0 a | 64.7 h | 64.0 h | 8.3 e | 7.3 c | 59.7 h | 54.7 f | 1.9 i | 1.7 g | 32.4 i | 28.4 i |
| ANOVA | | | | | | | | | | | | |
| Soil type (S) | * | * | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| Pre-planting soil moisture (P) | *** | *** | *** | *** | ** | ** | *** | *** | *** | *** | *** | *** |
| Deficit irrigation (D) | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| S x P | * | * | ** | ** | ns | ns | ** | ** | *** | *** | *** | *** |
| S x D | ns | ns | ns | ns | ns | ns | *** | *** | *** | *** | ** | ** |
| P x D | ns | ns | ns | ns | ns | ns | ns | ns | *** | *** | ** | ** |
| S x P x D | ns | ns | ns | ns | ns | ns | ns | ns | ** | ** | *** | *** |

For each treatment, the mean was calculated from four replicates. Means within a column followed by different letters are significantly different at $P < 0.05$ according to the least significant difference (LSD) test. ns: not significant, *: significant at $P < 0.05$, **: significant at $P < 0.01$, and ***: significant at $P < 0.001$

The first 90 days after planting, soil moisture, irrigation deficit, and type affected sugarcane biomass accumulation. Clay soil with high pre-planting moisture (FC80) and full irrigation (DI0) had the highest biomass (Fig. 1). With medium moisture (FC50) and no irrigation deficit, biomass was moderate, but severe deficit irrigation (DI60) reduced biomass at all moisture levels. The FC30/DI60 combination produced the least biomass. Sandy soil had similar trends but less biomass than clay soil due to lower water-holding capacity and faster moisture depletion under deficit irrigation. Biomass accumulation was significantly affected by soil type, initial moisture, irrigation regime, and interactions ($P < 0.001$).

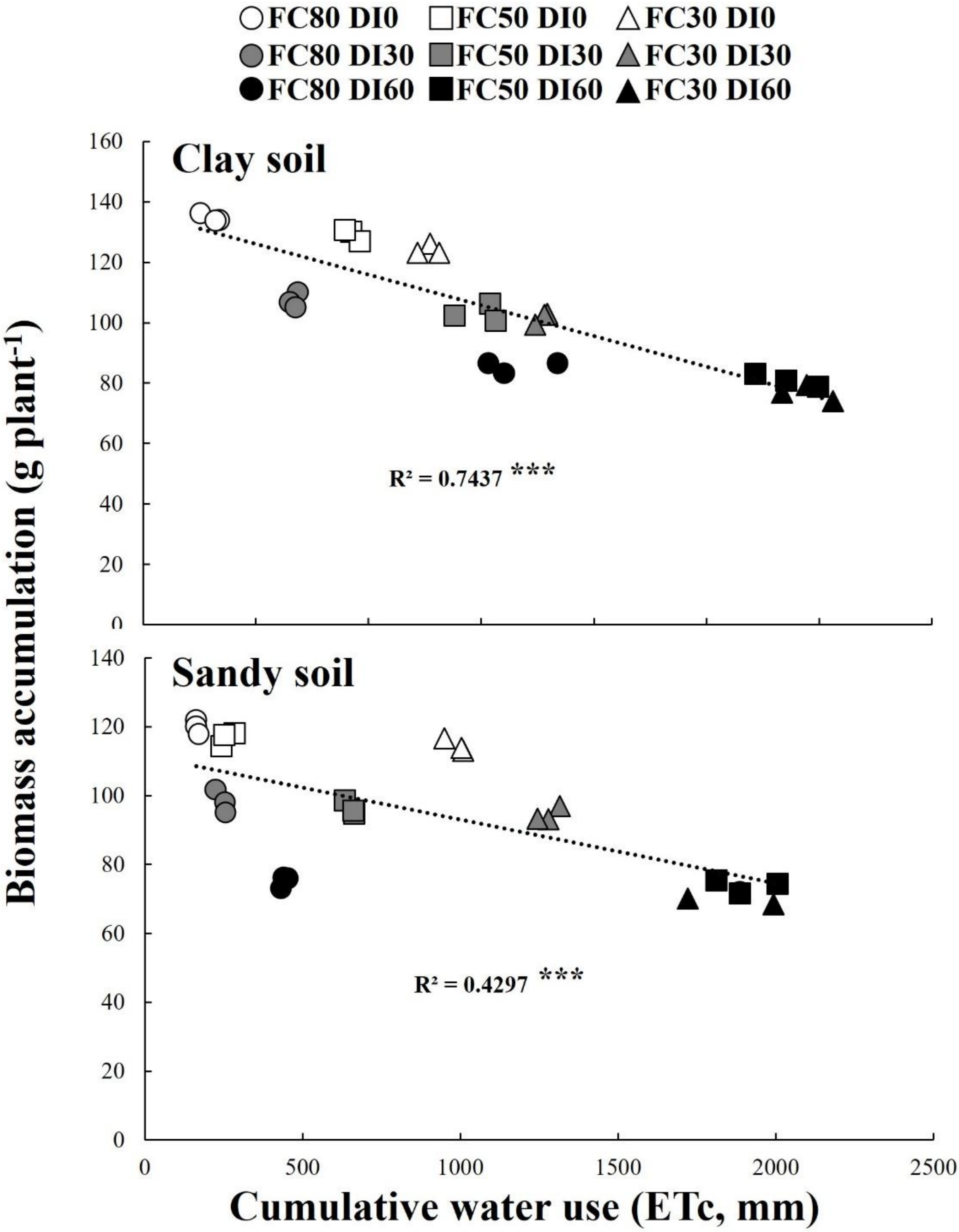

**Fig. 1.** Sugarcane biomass accumulation (g $plant^{-1}$) under different initial soil moisture levels and deficit irrigation regimes in rainfed clay (top) and sandy (bottom) soils. Asterisks (***) indicate statistical significance at P < 0.001.

Based on soil type, pre-planting moisture, and irrigation, plant height increased gradually from 30 to 90 days after planting (DAP) (Fig. 2). Clay soil plants grew taller than sandy soil plants under full irrigation (DI0) and high (FC80) and medium (FC50) pre-planting moisture. Low initial moisture (FC30) and severe deficit irrigation (DI60) reduced plant height, with the greatest difference at 60 DAP (90 cm in clay FC80 DI0 vs. 60 cm in clay FC30 DI60 Sugarcane establishment requires early-season water for rapid stem elongation.

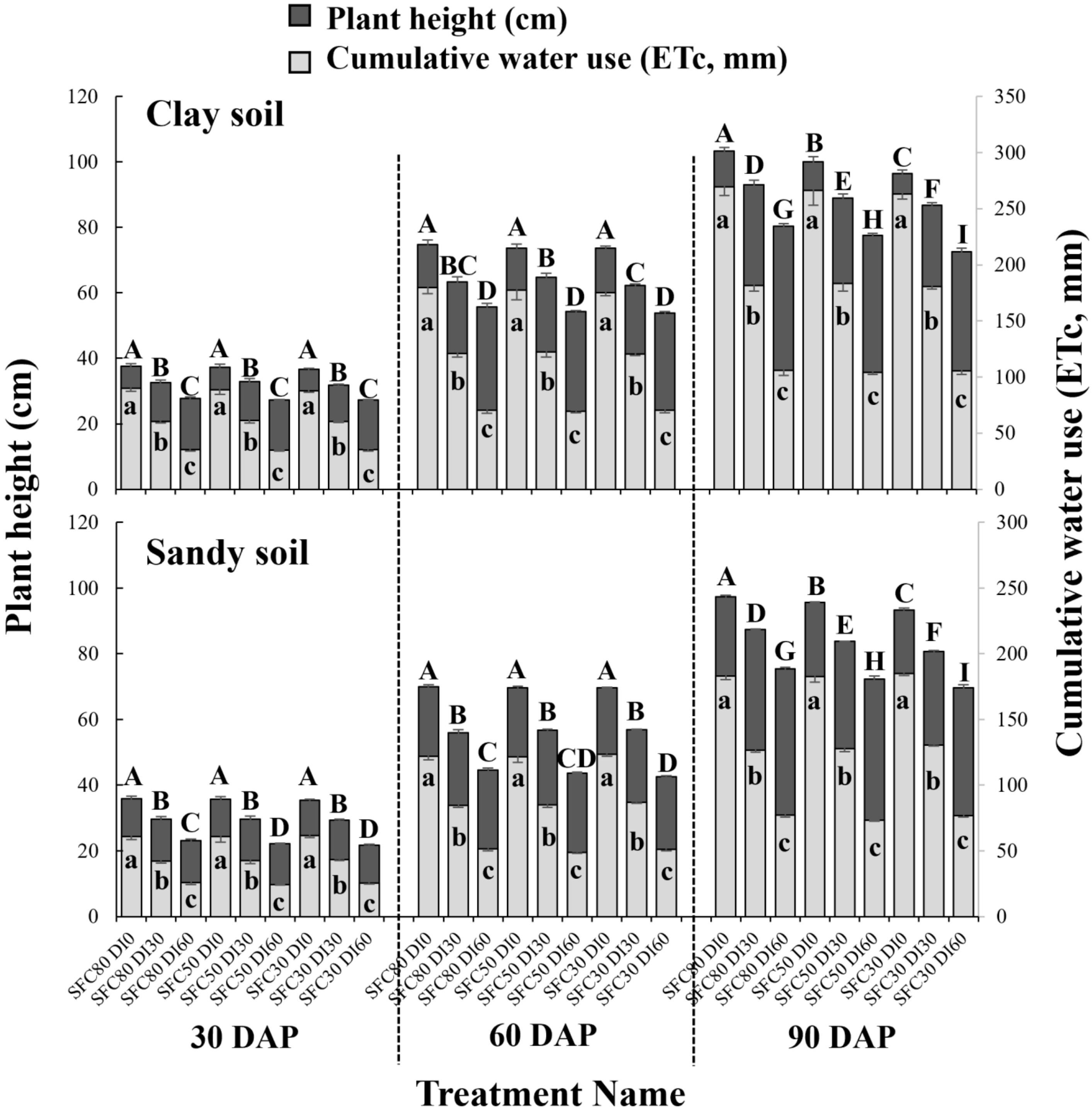

**Fig. 2.** Sugarcane plant height at 30, 60, and 90 DAP under varying initial soil moisture and deficit irrigation in rainfed clay (top) and sandy (bottom) soils. Data are mean ± SD (n = 4). Uppercase letters indicate plant height differences; lowercase letters indicate cumulative water use differences ($P < 0.05$).

Per-clump tillering increased from 30 to 90 DAP, depending on treatment and soil type (Fig. 3). Clay soil produced more tillers than sandy soil under full irrigation and high and medium pre-planting moisture (FC80 and FC50). Low initial moisture (FC30) and severe irrigation deficit (DI60) stunted tiller growth. Tiller counts were highest in clay soil with FC80 DI0 and FC50 DI0 at 90 DAP and lowest in sandy soil with FC30 DI60. Early soil moisture and irrigation affected tiller formation and sugarcane yield.

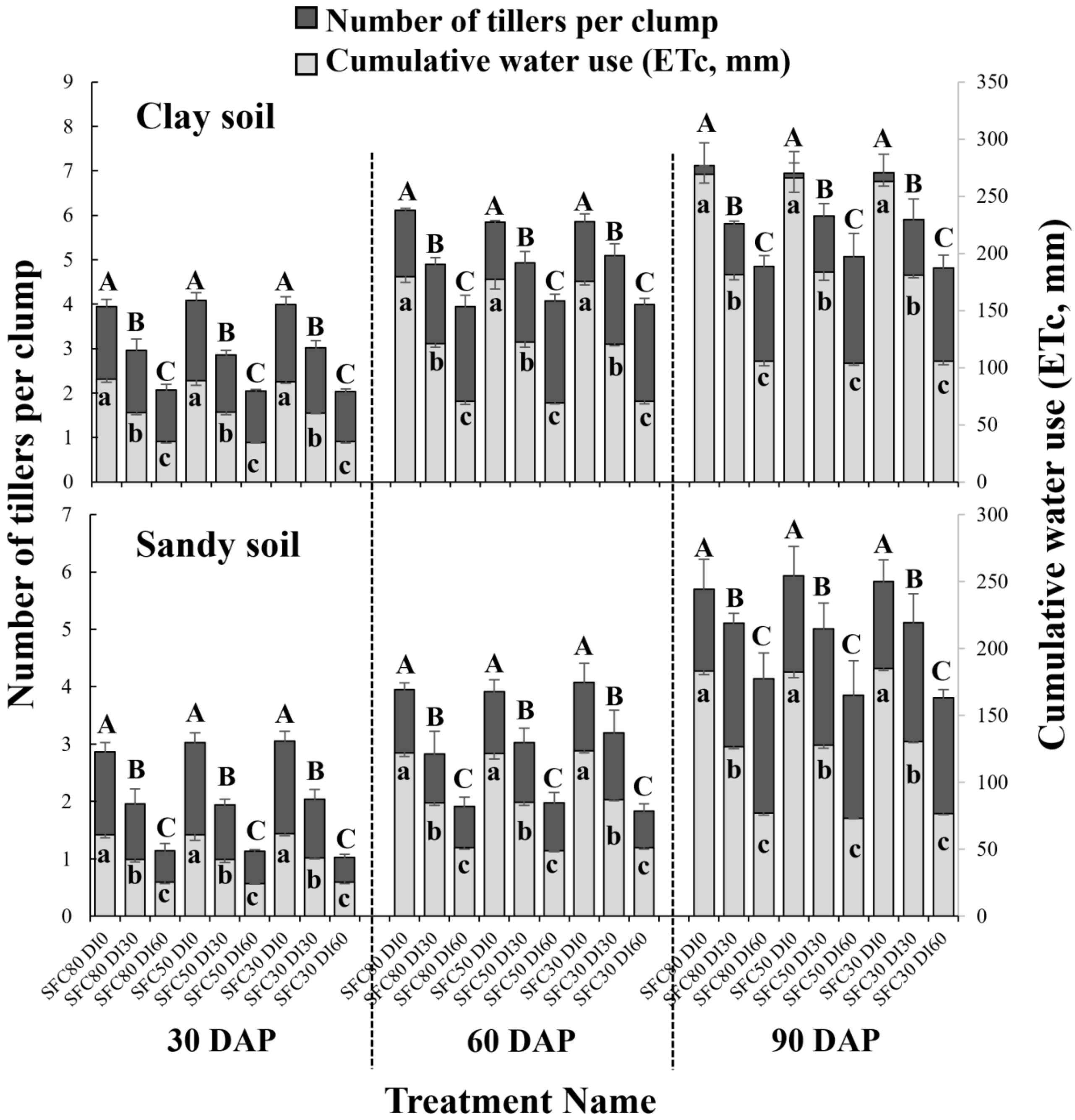

**Fig. 3.** Number of tillers per clump at 30, 60, and 90 DAP under varying initial soil moisture and deficit irrigation in rainfed clay (top) and sandy (bottom) soils. Data are mean ± SD (n = 4). Uppercase letters indicate differences in tiller number; lowercase letters indicate differences in cumulative water use ($P < 0.05$).

Soil type and deficit irrigation significantly affected cumulative water use, plant height, and tiller number at 30, 60, and 90 DAP (Table 5). Pre-planting soil moisture significantly affected plant height ($P < 0.05$-$0.001$), but not water usage or tillering. The S × D interaction affected ETc and plant height early on, while P × D had a minor impact at 60 DAP. Other interactions were insignificant. The results show that soil type and early-season irrigation affect sugarcane growth and tiller development.

**Table 5.** Two-way ANOVA for the effects of soil type (S), pre-planting soil moisture (P), and deficit irrigation (D) on cumulative water use (ETc, mm), plant height (cm), and tiller number per clump at 30, 60, and 90 DAP under flooding and waterlogging stress.

| ANOVA | Cumulative water use (ETc, mm) | Cumulative water use (ETc, mm) | Cumulative water use (ETc, mm) | Plant height (cm) | Plant height (cm) | Plant height (cm) | Tillers clump-1 | Tillers clump-1 | Tillers clump-1 |
|---|---|---|---|---|---|---|---|---|---|
| **ANOVA** | **30 DAP** | **60 DAP** | **90 DAP** | **30 DAP** | **60 DAP** | **90 DAP** | **30 DAP** | **60 DAP** | **90 DAP** |
| Soil type (S) | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| Pre-planting soil moisture (P) | ns | ns | ns | *** | * | *** | ns | ns | ns |
| Deficit irrigation (D) | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| S x P | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| S x D | *** | *** | *** | *** | *** | ns | ns | ns | ns |
| P x D | ns | ns | ns | ns | * | ns | ns | ns | ns |
| S x P x D | ns | ns | ns | ns | ns | ns | ns | ns | ns |

For each treatment, the mean was calculated from four replicates. ns: not significant, *: significant at $P < 0.05$, and ***: significant at $P < 0.001$

### *Yield components, yield, and sugar yield*

Pre-planting soil moisture, deficit irrigation, and soil type heavily influenced sugarcane yield and components. Table 8• shows how these factors affect stalk number, length, diameter, fresh stalk weight, total cane yield, and sugar yield in rainfed clay and sandy soils. Higher pre-planting soil moisture and moderate deficit irrigation increased stalk number, length, diameter, and weight. Low initial moisture (FC30) with no deficit (DI0) in sandy soil produced the highest cane yield (133.4 t ha$^{-1}$) and sugar yield (24.60 t CCS ha$^{-1}$), while high initial moisture (FC80) with full irrigation (DI0) in clay soil produced the lowest (32.8 t ha$^{-1}$) and sugar yield (4.02 t CCS ha$^{-1}$ ANOVA revealed that pre-planting soil moisture and irrigation deficits significantly affected yield and components ($P < 0.001$), while soil type significantly affected stalk length ($P < 0.001$). Several significant interactions (S × P, P × D, S × P × D) showed a combined impact on sugarcane productivity. These findings provide a quantitative foundation for discussing irrigation management strategies to increase sugarcane yield under different soil moisture conditions.

**Table 6.** Sugarcane yield and yield components (stalk number, length, diameter, fresh weight, total yield, and sugar yield) under varying initial soil moisture and deficit irrigation in rainfed clay and sandy soils.

| **Factor** | **Stalks plot-1** | **Stalks plot-1** | **Stalk length (cm)** | **Stalk length (cm)** | **Stalk diameter (cm)** | **Stalk diameter (cm)** | **Fresh stalk weight (kg plot-1)** | **Fresh stalk weight (kg plot-1)** | **Total cane yield (t ha-1)** | **Total cane yield (t ha-1)** | **Sugar yield (t CCS ha-1)** | **Sugar yield (t CCS ha-1)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Factor** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** | **Clay** | **Sandy** |
| FC80 DI0 | 258 d | 284 e | 81.7 f | 88.6 f | 4.58 f | 4.61 f | 188.4 g | 173.7 f | 32.8 g | 30.2 f | 4.02 g | 3.62 f |
| FC80 DI30 | 321 c | 284 e | 102.3 e | 92.0 ef | 4.95 e | 4.71 ef | 280.1 f | 178.4 f | 48.8 f | 31.1 f | 6.17 f | 3.87 f |
| FC80 DI60 | 404 b | 305 de | 117.5 d | 94.4 e | 5.40 d | 4.78 e | 401.8 e | 195.7 f | 70.0 e | 34.1 f | 9.06 e | 4.37 ef |
| FC50 DI0 | 456 a | 345 d | 125.4 c | 103.3 d | 5.77 c | 5.04 d | 566.4 d | 272.2 e | 98.7 d | 47.4 e | 12.82 d | 5.93 e |
| FC50 DI30 | 490 a | 437 c | 130.3 b | 129.9 c | 5.83 bc | 5.80 c | 630.5 cd | 478.8 d | 109.8 cd | 83.4 d | 14.00 cd | 10.92 d |
| FC50 DI60 | 479 a | 538 b | 135.4 a | 153.4 b | 5.95 abc | 6.28 b | 683.2 bc | 798.3 c | 118.9 bc | 139.1 c | 15.67 bc | 18.50 c |
| FC30 DI0 | 500 a | 580 a | 138.3 a | 167.8 a | 6.09 a | 6.70 a | 766.1 a | 1049.3 a | 133.4 a | 182.6 a | 17.79 a | 24.60 a |
| FC30 DI30 | 494 a | 560 ab | 137.6 a | 163.3 a | 6.03 ab | 6.58 a | 735.4 ab | 959.8 b | 128.1 ab | 167.0 b | 16.78 ab | 22.06 b |
| FC30 DI60 | 498 a | 538 ab | 136.2 a | 155.3 b | 6.04 ab | 6.35 b | 713.8 ab | 824 c | 124.3 ab | 143.3 c | 16.61 ab | 18.33 c |
| ANOVA | | | | | | | | | | | | |
| Soil type (S) | ns | ns | *** | *** | ns | ns | ns | ns | ns | ns | ns | ns |
| Pre-planting soil moisture (P) | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| Deficit irrigation (D) | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| S x P | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| S x D | ns | ns | ns | ns | * | * | ns | ns | ns | ns | ns | ns |
| P x D | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| S x P x D | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |

For each treatment, the mean was calculated from four replicates. Means within a column followed by different letters are significantly different at P < 0.05 according to the least significant difference (LSD) test. ns: not significant, *: significant at P < 0.05, and ***: significant at P < 0.001

### *Correlation coefficients*

Sugarcane's cumulative water use, water use efficiency, days to emergence, germination percentage, growth, and yield were strongly correlated under different initial soil moisture and deficit irrigation regimes (Table S3). Water use was positively correlated with germination percentage, plant height, tillers, leaves, dry shoot weight, biomass accumulation, leaf area index, and SPAD values ($r = 0.883$, $P < 0.001$). Day-to-emergence correlation was negative with cumulative water use ($r = -0.771$, $P < 0.001$) and other growth parameters. Stalk number, length, diameter, fresh stalk weight, total cane yield, and sugar yield exhibited strong positive correlations ($r > 0.97$, $P < 0.001$), while cumulative water use and efficiency showed moderate to weak negative correlations. These relationships show how early-season water availability, vegetative growth, and final yield in rainfed sugarcane interact.

## Discussion

Under rainfed conditions, pre-planting soil moisture and early-stage deficit irrigation affected sugarcane establishment most, with soil texture moderating these effects. Low initial moisture (FC30) delayed emergence by up to six days and reduced germination to 64%, especially in sandy soils with rapid drainage and low water retention (Alghamdi et al., 2023; Viana et al., 2023). While moisture below PWP restricts xylem flow and metabolic activity, adequate soil moisture maintains root turgor, hydraulic conductivity, and cellular activity, promoting bud break, shoot initiation, and early root proliferation (Hou et al., 2022). Early-season soil moisture and irrigation also affected vegetative growth. High pre-planting moisture and full irrigation produced taller plants, more tillers, and higher biomass in clay soils due to superior water-holding capacity and stomatal conductance. Limited water availability led to physiological changes like decreased tillering, stomatal closure, $CO_2$ assimilation, and carbohydrate availability for growth (Zhou et al., 2018; He et al., 2022; Shamuyarira et al., 2022). Stress-induced LAI and SPAD losses reduced photosynthetic capacity, likely via hormones (Kim et al., 2022; Wu et al., 2022; Bouremani, 2023). Soil moisture and irrigation affected yield components differently. Resource allocation theory states that stalk density and quality trade-offs occur when low initial moisture increases stalk number, especially in sandy soils, but stalks are thinner and lighter (De Almeida Silva et al., 2008). Mild early water deficits (FC30 DI0 and DI30) improve water use efficiency and sucrose partitioning, while severe deficits (DI60) reduce yields by ~20% (Santos et al., 2019; Li et al., 2022; Niu et al., 2024; Wang et al.• Early-season vigor, biomass, and yield are strongly correlated, indicating that irrigation and moisture determine productivity. Due to better water retention, slower moisture depletion, and higher nutrient availability, clay soils had more biomass, taller plants, and tillering than sandy soils. Sandy soil reached PWP faster and produced less during deficit irrigation due to rapid drainage and lower field capacity (Ismail and Ozawa, 2007; Alghamdi et al., 2023). This study may not capture natural rainfall, soil heterogeneity, pest and disease pressures, or multi-season ratoon performance due to the controlled field setup. Study cultivar diversity, root hydraulic and hormonal responses to water stress, and precision irrigation. Practical applications include timing planting to coincide with higher residual soil moisture, mulching or organic amendments, and soil texture-specific irrigation schedules: deeper, less frequent irrigation in clay soils, more frequent in sandy soils. Physiological monitoring, modeling, and precision irrigation are needed for water-efficient sugarcane production.

## Materials and Methods

### *Site description*

There were two field experiment sites in Phitsanulok Province, Thailand: Bo Thong Subdistrict (16°38′27″N, 100°09′03″E; 48 m a.s.l.) and Plak Raet Subdistrict (16°40′33″N, 100°06′06″E; 52 m a.s.l.) with clay and sandy soil, These sites can assess early sugarcane responses to pre-planting soil moisture and deficit irrigation with different water-holding capacities. Phitsanulok Meteorological Station (15-20 km from study sites) recorded air temperature, relative humidity, rainfall, wind speed, and pan evaporation daily. The FAO Penman-Monteith method was used to calculate reference evapotranspiration ($ET_0$) according to Allen et al. (1998) The experiment had temperatures from 12.5 to 39.3°C, relative humidity from 67 to 85%, and daily $ET_0$ from 4.1 to 6.4 mm (Table 1).

**Table 1.** Meteorological variables of the experimental periods between 2023 and 2025 at Bang Rakam District, Phitsanulok Province, Thailand, approximately 15-20 km from the study sites.

| No. | Month-Year | Range of Temperature (°C) | Relative Humidity (%) | Rainfall (mm) | Wind Speed ($m\ s^{-1}$) | Pan evaporation (mm) | Reference ETr (mm) |
|---|---|---|---|---|---|---|---|
| **1** | **Oct-23** | **22.0-36.2** | **76.5** | **115.6** | **2.3** | **7.2** | **5.3** |
| 2 | Nov-23 | 19.4-35.6 | 78.0 | 0 | 2.6 | 6.5 | 4.9 |
| 3 | Dec-23 | 20.8-34.9 | 71.5 | 0 | 2.4 | 6.3 | 4.6 |
| 4 | Jan-24 | 12.5-34.5 | 74.0 | 27.5 | 2.3 | 5.4 | 4.1 |
| 5 | Feb-24 | 17.5-34.9 | 69.5 | 0 | 2.5 | 6.8 | 5.0 |
| 6 | Mar-24 | 20.5-36.6 | 71.0 | 13.4 | 1.8 | 7.0 | 5.4 |
| 7 | Apr-24 | 20.6-39.3 | 68.5 | 128.8 | 1.6 | 8.0 | 6.2 |
| 8 | May-24 | 22.3-38.4 | 76.0 | 132.7 | 1.9 | 8.4 | 6.4 |
| 9 | Jun-24 | 23.0-36.3 | 77.5 | 147.4 | 2.3 | 7.9 | 5.8 |
| 10 | Jul-24 | 23.6-35.2 | 81.5 | 122.4 | 2.6 | 6.2 | 5.1 |
| 11 | Aug-24 | 23.8-35.0 | 85.0 | 348.9 | 2.8 | 6.0 | 4.8 |
| 12 | Sep-24 | 23.5-34.9 | 84.5 | 372.6 | 2.9 | 5.8 | 4.7 |
| 13 | Oct-24 | 24.0-36.5 | 80.5 | 296.7 | 2.4 | 7.3 | 5.4 |
| 14 | Nov-24 | 19.4-36.2 | 77.0 | 50.6 | 2.5 | 6.4 | 5.0 |
| 15 | Dec-24 | 20.8-34.9 | 77.5 | 0 | 2.3 | 6.5 | 4.9 |
| 16 | Jan-25 | 16.6-34.7 | 72.5 | 5.4 | 2.3 | 5.8 | 4.3 |
| 17 | Feb-25 | 17.5-35.5 | 70.0 | 98.4 | 2.4 | 7.4 | 5.6 |
| 18 | Mar-25 | 20.7-37.0 | 67.0 | 3.1 | 1.7 | 7.1 | 5.3 |

### *Sugarcane germination*

The commercial variety Khon Kaen 3 (KK3) was chosen for its drought resistance, high yield, and widespread cultivation in Thailand (Khumla et al., 2021). Two-budded setts (20-25 cm in length) were cut from the middle third (approximately the 5th - 10th nodes) of eight-month-old mother stalks to ensure uniform bud vigor and maturity. Ratoon stunting disease (RSD) and leaf scald were controlled by hot-water treatment (50 °C for 1 h) without affecting germination or shoot vigor (Carvalho et al., 2016). During the establishment phase, germination and emergence were monitored to assess the success of bud sprouting and early shoot development. Germination percentage was calculated as the proportion of setts that produced visible sprouts, while emergence time was recorded as the number of days until shoots appeared above the soil surface. These observations helped quantify the effects of soil moisture and irrigation on early plant establishment.

### *Soil properties*

The physical and chemical properties of 0-60 cm soil samples were analyzed using standard methods (Table 2). The soil, with 55.46% clay content, had 15.84 cmol $kg^{-1}$ cation exchange capacity (CEC), 2.01% OM, and 87 mg $kg^{-1}$ exchangeable K. Sandy soil had 8.02% clay, 0.92% OM, 5.3 cmol $kg^{-1}$ CEC, and 24.5 mg $kg^{-1}$ exchangeable K. Soil pH between 4.7 and 5.65 and bulk density between 2.72 and 0.96 mg $m^{-3}$ were observed for clay and sandy soils. Available water (AW) was calculated by subtracting field capacity (FC) from permanent wilting point (PWP). Clay had 37.45% field capacity and 15.27% available water across the 0-60 cm profile (Table 3). The sandy soil's FC and AW dropped 17.27% and 10.17%. Allen et al. (1998) cap AW depletion at 60%. Table 3 shows that sandy soil could deplete water by 5.8% to 6.5% and clay soil by 8.6% to 9.8%. Gravimetric soil moisture measurements (PR2 profile probe, Delta-T Devices Ltd., UK) determined irrigation treatments later in the experiment. We converted moisture values to volumetric using each soil's bulk density. These steps were essential because texture affects water retention.

**Table 2.** Average physical and chemical properties of two soil types (clay soil and sandy soil) used for sugarcane cultivation at depths of 0-60 cm from the soil surface.

| Soil Property | Clay Soil | Sandy Soil | T-test (0.05) |
|---|---|---|---|
| **% Sand** | **9.66 b** | **77.81 a** | *** |
| % Silt | 34.88 a | 9.52 b | *** |
| % Clay | 55.46 a | 12.68 b | *** |
| Texture Class | Clay Loam | Sandy Loam | - |
| pH | 5.65 a | 4.70 b | *** |
| EC (dS m-1) | 0.06 a | 0.02 b | ** |
| CEC (cmol kg-1) | 15.84 a | 5.30 b | *** |
| OM (%) | 2.01 a | 0.92 b | *** |
| Total N (%) | 0.046 b | 0.051 a | ** |
| Available P (mg kg-1) | 1.27 b | 1.70 a | ** |
| Exc. K (mg kg-1) | 87.00 a | 24.50 b | *** |
| Soil Bulk Density (mg $m^{-3}$) | 2.72 a | 0.96 b | *** |

For each soil type, the mean was calculated from four replicates. Means within a row followed by different letters are significantly different at $P < 0.05$ according to the least significant difference T-test. ** = significant at $P < 0.01$. *** = significant at $P < 0.001$.

**Table 3.** Soil moisture constants (cm cm$^{-1}$) at 100% Field Capacity (FC) for different soil layers from different soil types of the experimental fields.

| Soil type | Depth (cm) | FC (%) | PWP (%) | AW (%) | AD (%) |
|---|---|---|---|---|---|
| **Clay soil** | **0-15** | **39.5** | **23.2** | **16.3** | **9.8** |
| | 15-30 | 38.1 | 22.7 | 15.4 | 9.2 |
| | 30-45 | 36.8 | 21.8 | 15.0 | 9.0 |
| | 45-60 | 35.4 | 21.0 | 14.4 | 8.6 |
| Sandy soil | 0-15 | 18.6 | 7.8 | 10.8 | 6.5 |
| | 15-30 | 17.5 | 7.2 | 10.3 | 6.2 |
| | 30-45 | 16.8 | 6.9 | 9.9 | 5.9 |
| | 45-60 | 16.2 | 6.5 | 9.7 | 5.8 |

FC: Field Capacity (%), PWP: Permanent Wilting Point (%), AW: Available Water (%), and AD: Allowable Deficit (%).

### *Experimental design*

A 3 × 3 factorial experiment was conducted using a randomized complete block design (RCBD) with four replications per site (clay and sandy soils, Table S1). High pre-planting soil moisture (80% FC, October 2023), medium (50% FC, December 2023), and low (30% FC, February 2024) were factors A. Factor B was deficit irrigation with three levels: DI0 (100% ETc), DI30 (70% ETc), and DI60 (40% ETc) (Table S1). Soil probes measured 0-60 cm soil moisture. Each plot measured 6.0 × 9.6 m (57.6 m$^2$) and consisted of six rows. To prevent lateral water movement, buffer plots separated treatments. Early development (0-90 days after planting, DAP) was observed. After 90 DAP, all plots were rainfed for 12-month crop growth and yield assessment.

### *Irrigation scheduling*

Scheduled irrigation from 0 to 90 DAP using crop ETc = ET$_0$ × Kc (Kc = 0.4-0.7 for emergence to early vegetative stages; Allen et al., 1998). In DI0, DI30, and DI60 regimes, surface drip irrigation with pressure-regulated lateral lines (1.6 m apart, emitters 0.4 m) delivered precise volumes (Keller and Karmeli, 1974). At five depths (10/20/30/40 and 60 cm), we monitored soil moisture weekly to ensure accurate deficit application (Whalley et al., 2008). Total irrigation depended on soil moisture, texture, and deficit (Table S1).

### *Data collection*

Environmental parameters (air temperature, relative humidity, rainfall, wind speed, pan evaporation, and ET$_0$) were monitored daily (Pereira et al., 1995; Allen et al., 1998; Lord and Ayars, 2007 Early growth parameters (1-12 weeks after planting) included days to emergence, germination percentage, plant height, leaf number, tiller number, and shoot biomass; late-stage (3-12 months) included plant height, stem diameter, and tiller number to assess growth and maturation. At 12 months post-planting (MAP), yield components include stalk number, length, diameter, fresh weight, total cane yield (t ha$^{-1}$), and sugar yield (based on CCS).

### *Statistical analysis*

Two-way ANOVA examined pre-planting soil moisture, deficit irrigation, and interactions on emergence, early growth, water use, and yield. LSD ($P < 0.05$) showed significant differences. After analyzing clay and sandy soils separately, a combined dataset was analyzed. Pearson correlation was used to study sugarcane water use, WUE, plant emergence, growth, yield, and yield components. Using Excel graphs and Statistix 9.0 analyses.

## Conclusions

This study found that pre-planting soil moisture and early-stage deficit irrigation affect sugarcane establishment, growth, and yield under rainfed conditions, with soil texture modulating these effects. In clay soils, 80% FC and full irrigation produced the fastest emergence, highest germination, and highest biomass. At low moisture (30% FC), severe deficits (DI60) reduced yield, while moderate deficits (DI30) increased water efficiency without lowering yield. Rapid emergence and biomass accumulation increased yield, emphasizing the importance of early soil moisture and irrigation in maximizing productivity across soil types.

## Statement of contributions

Conceptualization: AW, SI; Methodology: AW; Investigation: AW, SC; Data curation: AW, SC; Formal analysis: AW; Visualization: AW; Writing - original draft: AW; Writing - review and editing: SI, SC; Supervision: SI; Funding acquisition: AW; Project administration: AW. All authors read and approved the final manuscript.

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## Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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