

SUBSURFACE DRIP IRRIGATION IMPROVES WATER PRODUCTIVITY AND YIELD OF SUGARCANE UNDER SEMI-ARID CONDITIONS

L'IRRIGATION GOUTTE À GOUTTE SOUTERRAINE AMÉLIORE LA PRODUCTIVITÉ DE L'EAU ET LE RENDEMENT DE LA CANNE À SUCRE EN CONDITIONS SEMI-ARIDES

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ABSTRACT

Climate change-driven water scarcity poses a major constraint to irrigated sugarcane production in semi-arid regions where crop growth depends almost entirely on irrigation. This study evaluated subsurface drip irrigation (SDI) as a climate-resilient alternative to conventional furrow irrigation in the South-Eastern Lowveld of Zimbabwe. A split-block field experiment comparing SDI and furrow irrigation was conducted at the Zimbabwe Sugar Association Experiment Station using three commercial sugarcane varieties (N14, ZN15 and ZN9). Data collected during the 2024/25 season included irrigation water applied, cane yield, estimated recoverable crystal (ERC), sugar yield, and crop structural parameters.

SDI outperformed furrow irrigation in both water use and yield. It reduced seasonal irrigation water from 13.50 to 9.46 ML ha⁻¹, achieving a 30% saving. Mean cane yield increased from 150.0 t ha⁻¹ under furrow to 188.4 t ha⁻¹ under SDI. Sugar yield also improved from 19.67 to 25.31 t ha⁻¹. Variety-specific responses confirmed this advantage. Cane yield gains under SDI ranged from 19% to 28%. Sugar yield increased by 26% to 43% relative to furrow irrigation. These gains were mainly due to longer stalks and higher biomass. Estimated recoverable crystal values were higher under SDI, indicating better physiological performance. However, lodging remained high under both systems. It exceeded 90% and was slightly higher under SDI. This has implications for mechanised green-cane harvesting.

These results demonstrate that SDI improves water productivity and crop performance under semi-arid conditions, providing a promising climate-resilient irrigation strategy. Continued multi-year evaluation is required to confirm long-term performance and scalability.

Keywords: Subsurface drip irrigation; Water-use efficiency; Climate-resilient agriculture; Sugarcane productivity; Semi-arid environments; Irrigation innovation.

RÉSUMÉ

La pénurie d'eau due au changement climatique constitue une contrainte majeure pour la production irriguée de canne à sucre dans les régions semi-arides, où la croissance des cultures dépend presque entièrement de l'irrigation. Cette étude a évalué l'irrigation goutte à goutte souterraine (SDI) comme solution de remplacement résiliente au climat par rapport à l'irrigation conventionnelle à la raie dans le Lowveld du sud-est du Zimbabwe. Une expérience de terrain en blocs divisés comparant la SDI à l'irrigation à la raie a été menée à la station expérimentale de la Zimbabwe Sugar Association sur trois variétés commerciales de canne à sucre (N14, ZN15 et ZN9). Les données recueillies au cours de la

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campagne 2024/25 comprenaient le volume d'eau d'irrigation appliqué, le rendement en canne, la teneur estimée en cristaux récupérables (ERC), le rendement en sucre et les paramètres structuraux de la culture.

La SDI a surpassé l'irrigation à la raie tant sur le plan de l'utilisation de l'eau que du rendement. Elle a réduit le volume saisonnier d'eau d'irrigation de 13,50 à 9,46 ML ha⁻¹, soit une économie de 30 %. Le rendement moyen en canne est passé de 150,0 t ha⁻¹ sous irrigation à la raie à 188,4 t ha⁻¹ sous SDI. Le rendement en sucre est également passé de 19,67 à 25,31 t ha⁻¹. Les réponses propres aux différentes variétés ont confirmé cet avantage. Sous SDI, les gains de rendement en canne variaient de 19 % à 28 %. Le rendement en sucre a augmenté de 26 % à 43 % par rapport à l'irrigation à la raie. Ces gains s'expliquaient principalement par des tiges plus longues et une biomasse plus importante. Les valeurs estimées de cristaux récupérables étaient supérieures sous SDI, indiquant de meilleures performances physiologiques. Toutefois, la verse est restée élevée sous les deux systèmes. Elle dépassait 90 % et était légèrement plus importante sous SDI, ce qui a des conséquences pour la récolte mécanisée de la canne verte.

Ces résultats montrent que la SDI améliore la productivité de l'eau et les performances des cultures dans des conditions semi-arides, offrant ainsi une stratégie d'irrigation résiliente au climat prometteuse. La poursuite de l'évaluation sur plusieurs années est nécessaire pour confirmer les performances à long terme et la possibilité d'un déploiement à grande échelle.

Mots clés : Irrigation goutte à goutte souterraine; Efficacité de l'utilisation de l'eau; Agriculture résiliente au climat; Productivity de canne à sucre; Environments semi-aride; Innovation en irrigation.

INTRODUCTION

Sugarcane production in semi-arid environments is increasingly constrained by climate change-induced water scarcity, rising temperatures, and increasing evaporative demand. These challenges are particularly pronounced in the South-Eastern Lowveld of Zimbabwe, where annual rainfall averages below 500 mm, maximum temperatures frequently exceed 35 °C, and annual reference evapotranspiration approaches 2000 mm (Chirindo, 2018). Under such conditions, sugarcane production depends entirely on irrigation, making water-use efficiency the most critical determinant of productivity and sustainability. Climate projections for semi-arid regions indicate increasing irrigation demand, declining water availability, and greater variability in rainfall, all of which threaten the sustainability of irrigated sugarcane systems unless water productivity improves substantially (FAO, 2020). Consequently, improving irrigation efficiency while maintaining high cane and sugar yields has become central to climate-resilient sugarcane production in water-limited environments.

Despite operating in a water-scarce environment, approximately 80% of Zimbabwe's 50,000 ha sugarcane area is still irrigated using conventional furrow irrigation (Mabaya et al. 2025). This method is inherently inefficient, typically requiring between 15 and 18 ML ha⁻¹ per season (Nzima et al., 2022), with widespread over-irrigation frequently observed in upstream fields and inadequate water delivery to downstream users (Mabaya and Hama, 2025). These inefficiencies contribute to increasing water conflicts, uneven crop performance, and declining overall system productivity. Excessive irrigation has also resulted in rising waterlogging, poor drainage, and irrigation-induced soil degradation (Mabaya et al., 2025). Irrigation-induced salinity is widely recognised as a major constraint in poorly drained irrigated agriculture, particularly under surface irrigation systems with high application depths (Ayars et al., 2015). Secondary salinity and sodicity are expanding in the South-Eastern Lowveld region currently affecting approximately 2200 ha and 2100 ha respectively (Mabaya et al., 2025).

These constraints contribute to declining productivity, with average cane yields of approximately 65 t ha⁻¹ in outgrower schemes and 90–100 t ha⁻¹ in estates (Ndeketea et al., 2014). These yields are substantially below the potential of approximately 200 t ha⁻¹ achievable under optimized irrigation and agronomic management (Mabaya and Hama, 2025). The current production system is further constrained by harvesting practices dominated by manual pre-burning of sugarcane. Pre-harvest

burning removes crop residues that would otherwise contribute to soil organic matter, moisture conservation, and improved soil structure.

The absence of trash blanketing increases soil evaporation, reduces infiltration, and accelerates soil degradation. In addition, pre-burning contributes to greenhouse gas emissions particularly carbon dioxide (Capaz et al., 2013), while waterlogged conditions associated with excessive irrigation may be increasing methane emissions (Liu et al., 2011). These practices reduce both environmental sustainability and long-term soil productivity, highlighting the need for irrigation technologies that support green-cane harvesting and residue retention (Thorburn et al., 2017).

Subsurface drip irrigation (SDI) has emerged as a promising climate-adaptive irrigation technology for high-water-demand crops grown under semi-arid conditions. By applying water directly to the root zone at low flow rates and high frequency, SDI reduces evaporation losses, minimizes deep percolation, and improves uniformity of water distribution (Llovet and Peper, 2026). These characteristics improve crop water productivity, reduce waterlogging, and limit salinity development. In addition, SDI enables precise fertigation, improves crop physiological performance, and enhances biomass accumulation, thereby increasing yield per unit of water applied. Previous studies have reported substantial improvements in water-use efficiency and productivity of row crops under subsurface drip irrigation compared with conventional surface drip irrigation methods (Ayars et al., 1999). Furthermore, SDI field layouts can facilitate much needed transition toward green-cane harvesting systems, enabling trash blanketing, improved soil moisture retention, and enhanced carbon sequestration. When combined with solar-powered pumping systems, SDI also offers opportunities to address energy supply constraints common in irrigated agriculture in Zimbabwe.

The first key question, however, is whether SDI can simultaneously reduce irrigation water use, improve crop physiology, increase productivity, and enhance sugarcane crop water productivity under semi-arid Zimbabwean conditions. Specifically, there is a need to quantify water savings relative to traditional furrow irrigation, evaluate changes in crop growth characteristics such as stalk length, diameter, and population, and determine impacts on cane yield, sugar yield, and estimated recoverable crystal. In addition, understanding broader system-level benefits of SDI, including reduced drainage problems, mitigation of salinity risks, improved suitability for green-cane harvesting, and potential expansion of irrigated area using saved water, is critical for assessing its role as a climate-resilient irrigation strategy.

This study therefore evaluates the performance of subsurface drip irrigation compared with conventional furrow irrigation for sugarcane production in the semi-arid South-Eastern Lowveld of Zimbabwe. The objective is to determine whether SDI can improve irrigation water-use efficiency, enhance crop productivity, and support transition toward climate-smart sugarcane production systems in water-scarce environments.

MATERIALS AND METHODS

Study Area

The study was conducted at the Zimbabwe Sugar Association Experiment Station (ZSAES) located in the South-Eastern Lowveld of Zimbabwe (21°02'13"S; 31°36'53"E) as shown in Figure 1. The region falls within a semi-arid climatic zone receiving approximately 500 mm of annual rainfall, with sugarcane production entirely dependent on irrigation. The experimental field (Field M1) is characterised by sandy clay loam soils classified under the Lithosol group, with a slightly acidic pH of 6.77 and total available moisture (TAM) of approximately 100 mm. The estimated exchangeable sodium percentage (ESP) of 4.6% indicates soils suitable for sugarcane under well-managed irrigation conditions. These climatic and soil characteristics make the site representative of irrigated sugarcane production systems in Zimbabwe's Lowveld.



Figure 1. Study area

Experimental Design

The experiment was established using a split-plot design comparing two irrigation systems, namely subsurface drip irrigation (SDI) and conventional furrow irrigation (Furrow). Irrigation method constituted the main plot factor, while sugarcane varieties formed the subplot treatments. Three widely cultivated commercial varieties (ZN9, ZN15 and N14) were randomly assigned within each irrigation treatment. Each subplot measured 6 m in length and consisted of three sugarcane rows. A total of 192 subplots were established, with 96 subplots allocated to each irrigation system as shown in Figure 2 to ensure reliable comparisons under variable field conditions.



Figure 2. Experimental setup for the trial

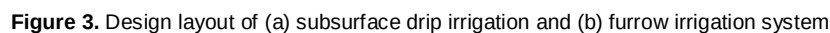
Irrigation System Configuration

Subsurface Drip Irrigation System Layout

SDI laterals were installed at a depth of 0.20 m below the soil surface to deliver water directly to the root zone. Emitters were spaced at 0.5 m intervals along the drip line, each with a discharge of approximately 1.35 L h⁻¹. Dripper lines were spaced at 1.9 m to align with the tramline planting configuration. The sketch for setup is shown in Figure 3 (a)

Furrow Irrigation system layout

Furrow irrigation followed Zimbabwe standard sugarcane estate practice (Mabveni et al., 2024). Rows were spaced at 1.5 m, with furrows opened to a depth of approximately 0.5 m. Water was supplied using gravity-fed siphon pipes, with 2 x 40 mm diameter siphons per furrow. The sketch for setup is shown in Figure 3 (b)



Planting was conducted in November 2024 after land preparation and irrigation system installation using unburnt certified seed cane. Setts were treated with fungicides prior to planting, and cutting tools were disinfected to prevent disease transmission. Uniform crop management practices were applied across treatments, including fertilisation, pest and disease control, and general field maintenance. Single super phosphate was applied before planting at uniform rates across all plots to ensure consistent nutrient availability. Nitrogen Fertiliser was applied in splits to both subplots.

Routine maintenance of the SDI system included inspection of pumps, filters, pressure valves, and drip lines, with weekly flushing to remove sediment and biofilm. Hydrogen peroxide treatments were applied mid-season and at the end of the season to control organic buildup, while hydrochloric acid was used once per season to remove mineral scaling. Root intrusion was controlled using Trellan herbicide application through the irrigation system. Furrow irrigation maintenance involved regular desilting of feeder canals to maintain the command.

Irrigation water use and crop performance data were collected throughout the growing season. Irrigation records included date, duration, evapotranspiration, discharge, and rainfall for each irrigation event. Growth measurements were taken at approximately 30-day intervals beginning 62 days after planting. Parameters measured included plant height, tiller population, and stalk counts. Harvesting was done in November 2025. At harvest, additional measurements included cane yield (t ha^{-1}), estimated recoverable crystal (ERC, % cane), sugar yield (t ha^{-1}), lodging percentage, and biomass weight. These measurements enabled comparison of water use, crop growth, and productivity between SDI and furrow irrigation systems. The most suitable varieties for SDI and furrow irrigation are also being identified based on ratooning ability over five years.

Rainfall-Evapotranspiration Deficit

Figure 4 shows monthly rainfall and reference evapotranspiration during the 2024/25 season, revealing a pronounced climatic water deficit typical of semi-arid environments. While seasonal rainfall was above normal totalling 658.4 mm, evapotranspiration reached 1813.5 mm, indicating that atmospheric demand exceeded rainfall by more than 1100 mm. This imbalance represents the primary external climatic constraint influencing irrigation decisions in the South-Eastern Lowveld region. From May to October, rainfall was negligible while evapotranspiration remained high ($\approx 98\text{--}213$ mm), confirming that crop water requirements during this period must be met through irrigation. Even during

the rainy months (January–March), evapotranspiration was comparable to rainfall, indicating limited effective rainfall contribution. These results align with established findings that sugarcane production in semi-arid environments operates under continuous water deficit conditions (Rockström and Falkenmark, 2000). Such sustained deficits increase irrigation demand and magnify inefficiencies associated with surface irrigation systems. Under these conditions, irrigation technologies capable of delivering water directly to the root zone are expected to reduce seasonal water use. The rainfall–evapotranspiration deficit therefore provides the climatic basis for evaluating irrigation performance and comparing SDI with furrow irrigation under water-limited conditions (FAO, 2020; Pereira et al., 2025).

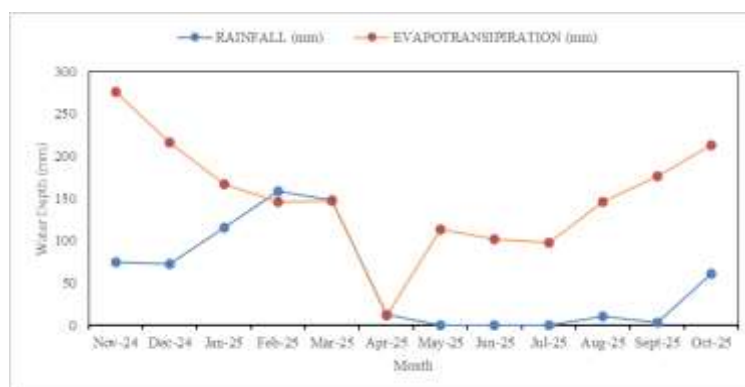


Figure 4. Monthly rainfall vs evapotranspiration (2024/25 season) at ZSAES

Seasonal Irrigation Water Use and Water Savings

Figure 5 compares monthly irrigation water applied under SDI and conventional furrow during the 2024/25 season. Furrow irrigation required higher water application throughout the season, ranging from 0.8 to 1.8 ML ha⁻¹ per month, whereas SDI ranged between 0.32 and 1.35 ML ha⁻¹. The reduced irrigation demand under SDI was particularly evident during periods of high atmospheric demand, indicating improved matching of irrigation supply with crop water requirements. Cumulatively, seasonal irrigation water applied under furrow irrigation totalled 13.54 ML ha⁻¹ compared with 9.45 ML ha⁻¹ under SDI, representing a water saving of approximately 4.09 ML ha⁻¹ or 30.2%. Under semi-arid conditions characterised by persistent evapotranspiration deficits, such reductions directly address water scarcity constraints by lowering seasonal irrigation demand (Llovet and Peper, 2026). The saved water can be reallocated to expand irrigated area or improve supply reliability without additional water resources (Hamdy et al., 2003). These results therefore demonstrate that SDI provides a more efficient irrigation strategy capable of improving water productivity and supporting climate-resilient irrigation management under limited water availability (Ayars et al., 2015).

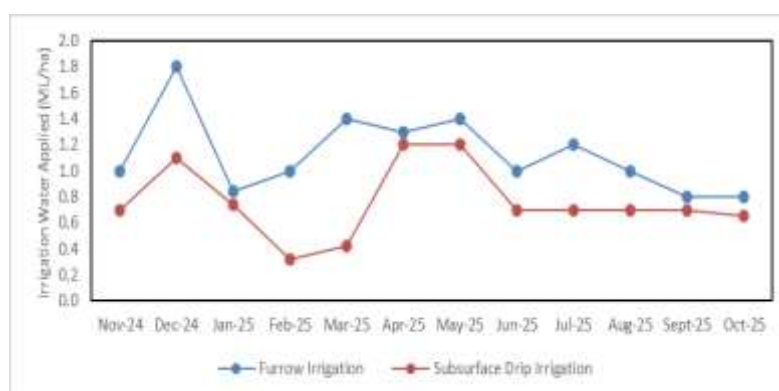


Figure 5. Monthly irrigation water applied under subsurface drip and furrow irrigation (2024/25 season)

Cane and Sugar Yield Response to Irrigation Method

Figure 6 compares cane and sugar yield of varieties ZN15, ZN9 and N14 under SDI and furrow. SDI consistently produced higher cane yields compared to furrow across all varieties, with mean yields increasing from 165 to 200.6 t ha⁻¹ for ZN15, from 133.5 to 169 t ha⁻¹ for ZN9, and from 168 to 200 t ha⁻¹ for N14. This represents yield improvements ranging from approximately 19% to 27% under SDI. Correspondingly, sugar yields also increased, with ZN15 rising from 20.7 to 26.6 t ha⁻¹, ZN9 from 17.1 to 24.3 t ha⁻¹, and N14 from 20.05 to 25.9 t ha⁻¹. The consistent increase in sugar yield indicates that higher biomass production under SDI did not dilute sucrose content, but rather improved crop physiological performance. Enhanced yields under SDI are likely associated with improved soil moisture availability, reduced water stress, and sustained canopy development (Inman-Bamber and Smith, 2005). These results demonstrate that SDI improves both cane productivity and sucrose recovery, confirming that precision irrigation enhances productive efficiency rather than biomass alone, which is critical for evaluating irrigation technologies under water-limited conditions (Raheja et al., 2025).

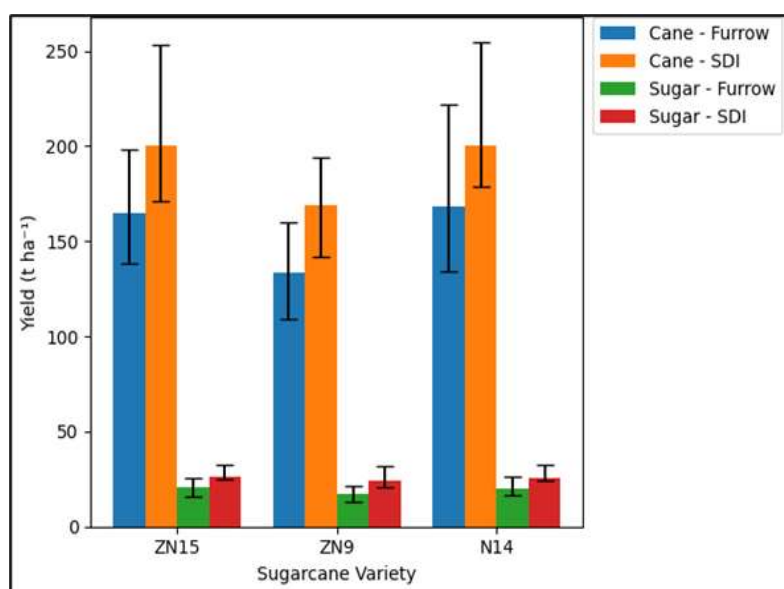


Figure 6. Cane yield and sugar yield response of three sugarcane varieties under subsurface drip irrigation (SDI) and conventional furrow irrigation (furrow)

Crop Structural Response to Irrigation Technology

Figure 7 illustrates the structural crop response of sugarcane varieties ZN15, ZN9 and N14 under SDI and furrow irrigation. SDI increased stalk length across all varieties, with mean values rising from 2.61 to 2.93 m for ZN15, 2.38 to 2.67 m for ZN9, and 2.75 to 3.02 m for N14, indicating improved vegetative growth and reduced moisture stress. Stalk population also increased under SDI, particularly for ZN15 (97 to 110 ×10³ ha⁻¹) and ZN9 (83 to 90 ×10³ ha⁻¹), contributing to greater biomass accumulation. In contrast, stalk diameter showed minimal or slightly lower values under SDI, suggesting that yield gains were driven primarily by taller stalks and improved stand density rather than thicker canes. Estimated recoverable crystal (ERC) also increased under SDI for all varieties, confirming that enhanced biomass production did not dilute sucrose concentration. These results indicate that SDI improved crop physiological performance through sustained soil moisture availability, promoting elongation growth and canopy development (Llovet and Peper, 2026). Such structural improvements explain the higher cane and sugar yields observed under SDI and demonstrate the mechanism by which precision irrigation enhances productive efficiency under water-limited conditions (de Menezes et al., 2024).

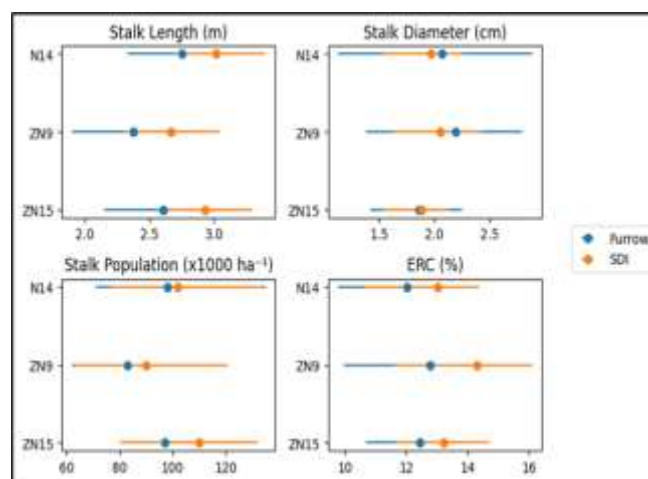


Figure 7. Structural response of sugarcane varieties under subsurface drip irrigation (SDI) and conventional furrow irrigation showing (a) stalk length, (b) stalk diameter, (c) stalk population and (d) estimated recoverable crystal (ERC)

Sugarcane Crop Water Productivity (CWP) under SDI and Furrow Irrigation

Table 1 shows that SDI substantially improved both cane and sugar water productivity relative to conventional furrow irrigation across all varieties. Cane water productivity under furrow irrigation ranged from 9.9 to 12.4 t ML⁻¹, whereas SDI increased this to 17.9–21.2 t ML⁻¹. Similarly, sugar water productivity increased from 1.26–1.53 t ML⁻¹ under furrow irrigation to 2.57–2.81 t ML⁻¹ under SDI. Overall, SDI improved cane water productivity from 12.3 to 21.0 t ML⁻¹ and sugar water productivity from 1.50 to 2.77 t ML⁻¹. This indicates that SDI produced substantially more cane and sugar per unit of irrigation water applied (Singh, 2021), directly confirming the irrigation principle of “more crop per drop” (Seenappa2015).

Under persistent evapotranspiration deficits and constrained water availability, these results provide strong quantitative evidence that irrigation performance should be evaluated not only by total yield, but by yield per unit water applied. The superior performance of SDI reflects reduced non-productive water losses and more precise root-zone water delivery, making it a more efficient and data-driven irrigation option under semi-arid conditions (Llovet and Peper, 2026).

Table 1. Crop water productivity under subsurface drip irrigation (SDI) and furrow irrigation (furrow)

Sugarcane variety	Cane productivity [t ML ⁻¹]		Sugar productivity [t ML ⁻¹]	
	Furrow	SDI	Furrow	SDI
N14	12.4	21.1	1.48	2.74
ZN9	9.9	17.9	1.26	2.57
ZN15	12.2	21.2	1.53	2.81
Overall	12.3	21.0	1.50	2.77

Lodging Response and Harvesting Implications

The SDI configuration incorporates defined drip-bed dimensions that enhance inter-row uniformity and improve equipment trafficability (see Figure 3a). This provides a structured platform suitable for mechanised green-cane harvesting and supports the transition from burnt cane systems to green-cane harvesting with trash blanketing. Green-cane harvest systems when in place will contribute to reduced carbon dioxide emissions, improved soil moisture retention, enhanced carbon sequestration, and increased soil fertility (Gomathi et al., 2024). However, lodging remains a significant agronomic concern. Lodging exceeded 90% under both irrigation systems and was slightly higher under SDI than

under furrow. This increase is associated with greater stalk elongation and higher biomass accumulation, which elevate the centre of gravity and increase susceptibility to bending. Although this structural response contributes to higher cane yield, excessive lodging can reduce harvesting efficiency and increase cane harvest losses, particularly under mechanised systems (Norris et al., 2016). Effective management through appropriate varietal selection is essential to fully realise the benefits of SDI.

System-Level Implications for Climate-Resilient Irrigation Strategy

The results indicate that subsurface drip irrigation (SDI) has implications beyond plot-level yield improvement and should be interpreted as a system-level climate-resilient irrigation strategy. By reducing seasonal irrigation demand from 13.54 to 9.45 ML ha⁻¹, SDI saved 4.09 ML ha⁻¹, equivalent to about 30.2% less water per hectare. At scale, this means the water used to irrigate 1 ha under furrow irrigation could irrigate approximately 1.43 ha under SDI, offering substantial scope for area expansion or improved supply reliability under fixed water allocations. In addition, lower and more targeted water application reduces the likelihood of deep percolation, prolonged saturation, and poor field drainage, thereby lowering risks of waterlogging and secondary salinity that commonly accompany surface irrigation in semi-arid schemes (Mabaya et al., 2025). These hydrological benefits are especially important in the Lowveld, where irrigation inefficiency increasingly threatens long-term soil productivity. Furthermore, the structured SDI layout supports equipment trafficability and provides a practical pathway toward green cane harvesting, enabling trash blanketing, moisture conservation, soil carbon build-up, and reduced carbon dioxide emissions from pre-harvest burning. SDI therefore represents not only a water-saving technology, but a scalable foundation for more resilient, resource-efficient, and climate-smart sugarcane production systems (Ayars et al., 2015).

CONCLUSIONS

This study evaluated subsurface drip irrigation (SDI) relative to conventional furrow irrigation using field-based measurements to inform irrigation decision-making under external climatic constraints. The first-year results show that SDI reduced seasonal irrigation demand from 13.54 to 9.45 ML ha⁻¹ (30.2% saving) while increasing mean cane yield from 166.4 to 199.0 t ha⁻¹ and sugar yield from 20.35 to 26.2 t ha⁻¹. Consequently, crop water productivity improved from 12.3 to 21.0 t cane ML⁻¹ and from 1.50 to 2.77 t sugar ML⁻¹, demonstrating substantially greater production per unit water applied. Structural crop responses, including increased stalk length (2.67 to 2.97 m) and higher stalk population (93 to 103 ×10³ ha⁻¹), explain the yield gains observed under SDI. At system level, the water savings suggest potential expansion of irrigated area, reduced risks of waterlogging and salinity, and support for mechanised green cane harvesting through trafficable drip-bed configurations. These findings represent first-year results; continued monitoring over the planned five-year period is required to confirm long-term performance and scalability.

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