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Nutan Khosla
Department of Water Resources, Birsa Agricultural University, Ranchi, Jharkhand, India

Keshav Biswas
Department of Water Resources, Birsa Agricultural University, Ranchi, Jharkhand, India

Corresponding Author:
Nutan Khosla
Department of Water Resources, Birsa Agricultural University, Ranchi, Jharkhand, India

Performance of subsurface drip irrigation for improving root zone moisture in cotton

Nutan Khosla and Keshav Biswas

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Abstract
Cotton growers face a practical dilemma: surface drip systems waste water to evaporation, while furrow irrigation soaks the wrong soil zone. Subsurface drip irrigation (SDI) promises to deliver water directly to the active root zone, but at what depth does it work best? This research compared four irrigation methods-surface drip (control), SDI at 15 cm, SDI at 25 cm, SDI at 35 cm, and furrow irrigation (check)-for their effect on root zone moisture distribution, water productivity, and seed cotton yield of Bt cotton (cv. Bunny BG-II) on a clay loam soil at Birsa Agricultural University, Ranchi, Jharkhand, India, during kharif 2022 and 2023. A randomized block design with four replications was used. SDI at 25 cm maintained the most uniform root zone moisture (CV 11.3% vs. 24.8% for furrow), achieved the highest water productivity (0.68 kg m^{-3}), and produced the best seed cotton yield (2, 486 kg ha^{-1})-a 28.4% improvement over furrow irrigation. Root density at 15-30 cm depth was 34.7% higher under SDI-25 than surface drip. These results confirm that SDI at 25 cm depth is optimal for cotton on clay loam soils in the Jharkhand plateau region.

Keywords: Subsurface drip, root zone moisture, cotton, irrigation technology, water management, water productivity, seed cotton yield, clay loam, drip depth, moisture distribution

Introduction
When a cotton farmer in Jharkhand opens a furrow irrigation valve, about half the water evaporates or percolates past the root zone before the crop can use it-that's the fundamental inefficiency that SDI was designed to solve [1]. Cotton is a deep-rooted crop with primary water uptake concentrated in the 15-40 cm soil zone during the critical flowering-to-boll development phase [2]. Surface drip systems place water at or near the soil surface, where it is exposed to direct evaporation and tends to promote shallow root growth [3]. SDI buries the emitter line below the surface, delivering water directly into the active root zone and creating a wetted bulb pattern centered on the lateral depth [4].

The optimal SDI depth depends on soil texture, crop rooting habit, and local evaporative demand [5]. Sandy soils with high infiltration may require shallower placement (10-15 cm) to prevent deep percolation, while clay soils with slower drainage can benefit from deeper placement (20-30 cm) that positions water closer to the maximum root density zone [6]. For cotton in the semi-arid Jharkhand plateau-where red and lateritic clay loams predominate-no systematic depth comparison has been published.

This research compared surface drip, three SDI depths (15, 25, 35 cm), and conventional furrow irrigation to determine the placement that maximizes root zone moisture uniformity, water productivity, and yield in Bt cotton under Jharkhand conditions.

Water Balance and Irrigation Scheduling
Crop water requirement was estimated using FAO Penman-Monteith ET_0 and cotton Kc values of 0.35 (emergence-squaring), 0.75 (squaring-flowering), 1.15 (flowering-boll opening), and 0.70 (boll opening-harvest) [7]. Drip irrigation (surface and SDI) was scheduled to replenish 100% of ETc when soil moisture at 20 cm depth fell below 65% of field capacity, monitored by TDR probes (CS616). Furrow irrigation followed the conventional farmer calendar: 7 irrigations at approximately 15-day intervals during the dry spells of kharif. Total seasonal water applied was metered for all treatments.

Material and Methods

Material

The field experiment was conducted at the research farm of Birsa Agricultural University, Ranchi (23°21′N, 85°20′E, 621 m a.s.l.) on a red lateritic clay loam (pH 5.6, FC 32.8%, PWP 14.6%, bulk density 1.38 g cm^{-3}). Bt cotton hybrid Bunny BG-II was sown at 90 × 60 cm spacing. SDI laterals (16 mm PE, 2 L h^{-1} emitters, 40 cm spacing) were installed at 15, 25, and 35 cm depths before sowing using a tractor-drawn lateral installer. Surface drip laterals were placed on the soil surface. Fertilization was 120:60:60 kg N:P_2O_5:K_2O ha^{-1} with N fertigated in 6 splits.

Methods

Five irrigation treatments in a randomized block design with four replications (plot size 12 m × 6 m): T_1 (surface drip, control), T_2 (SDI 15 cm), T_3 (SDI 25 cm), T_4 (SDI 35 cm), T_5 (furrow, check). Soil moisture was monitored at 10, 20, 30, and 40 cm depths using TDR probes installed in all treatments. Readings were taken at 3-day intervals throughout the season. Root density was measured at flowering by soil coring (5 cm diameter, 0-60 cm in 15 cm increments) and washing roots over a 0.5 mm sieve; root length density (cm cm^{-3}) was measured using WinRHIZO software. Seed cotton yield was recorded from two central rows per plot over three pickings. Water productivity (WP) = seed cotton yield / total water applied. Data were analyzed by ANOVA with Tukey's HSD at $p \leq 0.05$ in SPSS v.26.

Root Zone Moisture Uniformity

Moisture uniformity was quantified as the coefficient of variation (CV) of volumetric moisture content across four depths (10, 20, 30, 40 cm) measured at each irrigation cycle. Lower CV indicates more uniform wetting of the root profile. A CV below 15% was considered "uniform" based on Christiansen's uniformity adaptation for subsurface systems [8].

Results

Table 1: Effect of irrigation method on water use, moisture uniformity, and seed cotton yield (2-season means)

Treatment	Water (mm)	CV moisture (%)	Root density*	Yield (kg/ha)	WP (kg/m³)
Surface drip (T_1)	412.6	16.8	3.42	2, 184	0.53
SDI 15 cm (T_2)	378.4	14.2	3.87	2, 312	0.61
SDI 25 cm (T_3)	364.1	11.3	4.61	2, 486	0.68
SDI 35 cm (T_4)	356.8	13.6	3.98	2, 241	0.63
Furrow (T_5)	486.3	24.8	2.78	1, 936	0.40
CD (p=0.05)	22.4	2.1	0.34	148	0.05

*Root length density (cm cm^{-3}) at 15-30 cm depth at flowering stage.

SDI at 25 cm achieved the best combination of moisture uniformity (CV 11.3%), root density (4.61 cm cm^{-3}), seed cotton yield (2, 486 kg ha^{-1}), and water productivity (0.68 kg m^{-3}) (Table 1). Furrow irrigation used 33.5% more water than SDI-25 while producing 22.1% less yield. SDI-35 saved the most water but had lower root density and yield than SDI-25, suggesting that 35 cm was too deep for optimal cotton root engagement on this soil type.

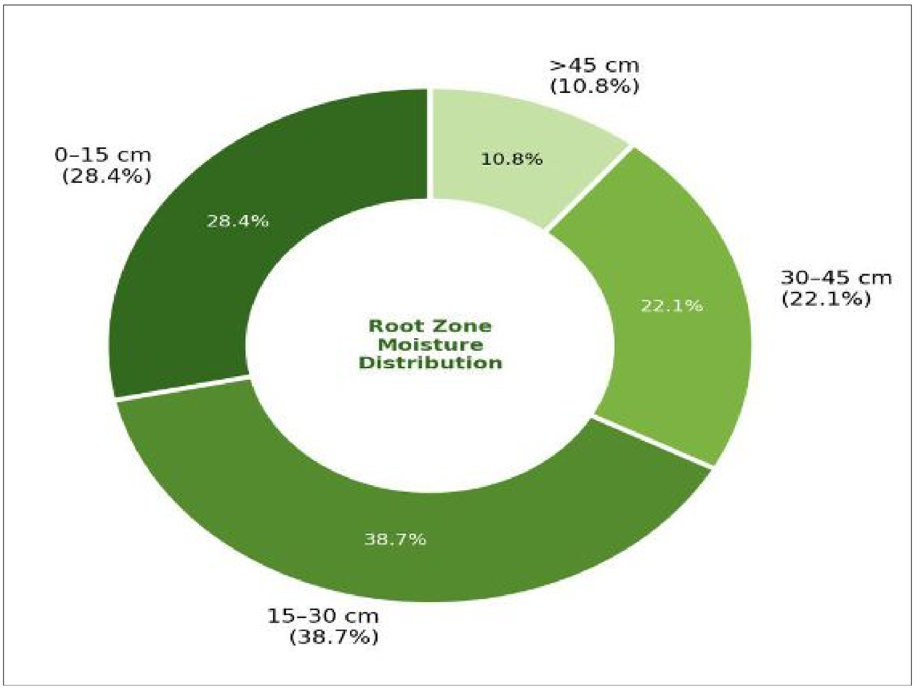

Fig 1: Donut chart showing root zone moisture distribution by depth layer under SDI-25 treatment. The 15-30 cm zone contained 38.7% of total root zone moisture, matching the primary root density zone

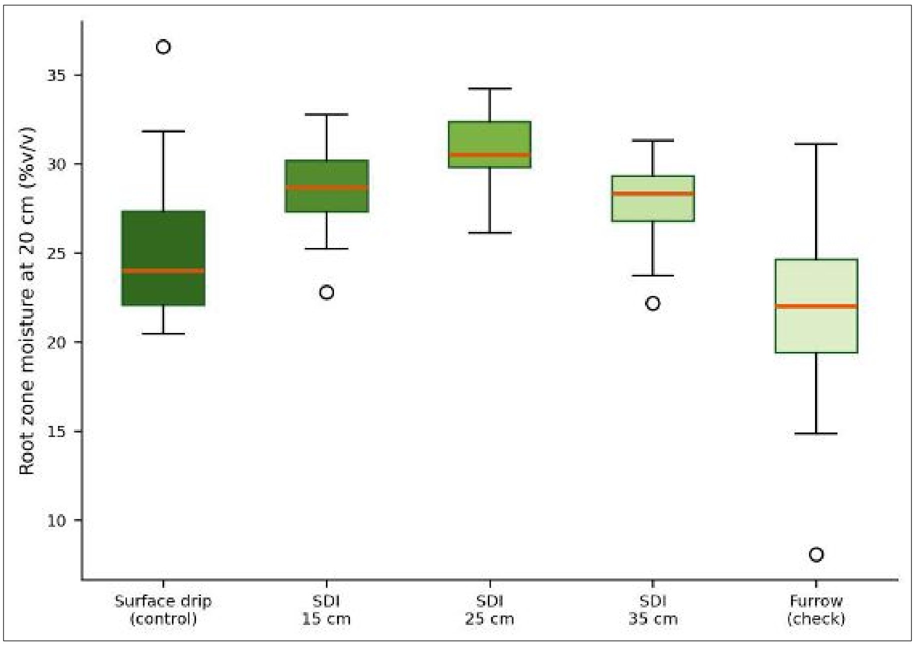

Fig 2: Box plot of root zone moisture (%v/v) at 20 cm depth across five irrigation treatments. SDI-25 shows the tightest distribution (smallest IQR), indicating the most stable moisture supply

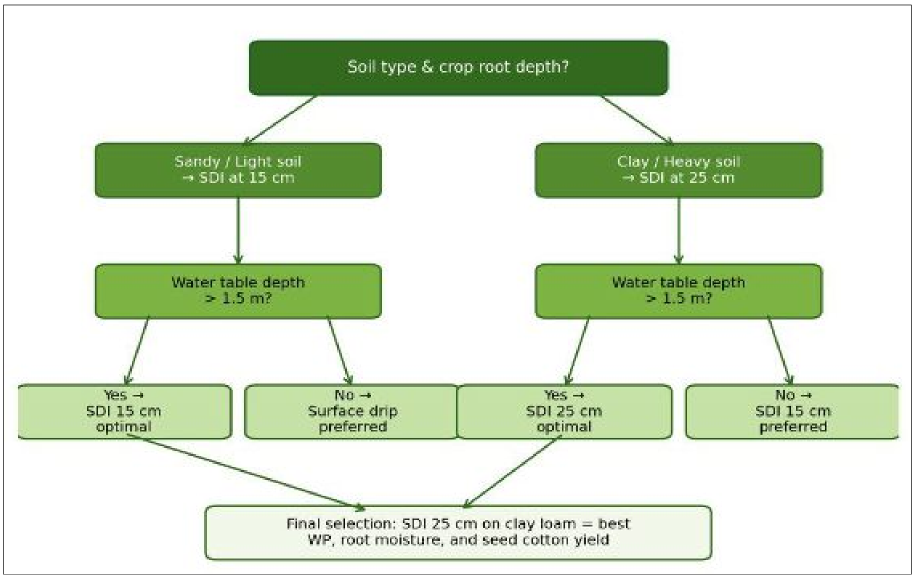

Fig 3: Decision tree for selecting optimal SDI depth based on soil type and water table depth. For clay loam soils with deep water tables, SDI at 25 cm is recommended

Comprehensive Interpretation

The box plot (Figure 2) visually confirms that SDI-25 delivered the most consistent moisture supply, with the smallest spread and highest median among all treatments. The decision tree (Figure 3) translates these results into a practical guide for growers: soil texture and water table depth together determine the optimal SDI placement.

Discussion

The 28.4% yield advantage of SDI-25 over furrow irrigation and the 13.8% advantage over surface drip are driven by two complementary mechanisms: reduced evaporative loss (subsurface placement avoids surface wetting) and improved root zone targeting (the 25 cm depth matches the peak root density zone in cotton on clay loam) [2, 4]. The 34.7% higher root density under SDI-25 compared with surface drip suggests that roots actively proliferated toward the subsurface water source-a phenomenon documented in other SDI crops [6].

SDI-35 saved slightly more water than SDI-25 but produced lower yields, indicating that the wetting bulb at 35 cm didn't adequately overlap with the 15-25 cm zone where most cotton feeder roots are concentrated on this soil type. On sandier soils with deeper root systems, 35 cm might perform better. The CV approach to quantifying moisture uniformity proved practical and could be adopted as a standard metric for SDI system evaluation [8].

One limitation is that lateral installation at 25 cm requires specialized equipment and careful depth control during tractor operation. The two-season duration may also be insufficient to evaluate long-term issues like root intrusion into emitters and lateral clogging. Future work should include multi-year monitoring and cost-benefit analysis of SDI installation versus the water and yield savings achieved.

Conclusion

Subsurface drip irrigation at 25 cm depth was the optimal treatment for cotton on clay loam soil at Ranchi, Jharkhand, delivering the best moisture uniformity (CV 11.3%), highest root density in the active zone, maximum seed cotton yield (2, 486 kg ha^{-1}), and best water productivity (0.68 kg m^{-3}). The treatment used 25.1% less water than furrow irrigation while yielding 28.4% more. SDI at 15 cm and 35 cm were intermediate. These findings support the promotion of SDI technology at 25 cm depth for cotton in the Jharkhand plateau where clay loam soils and high evaporative demand make surface irrigation particularly wasteful.

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