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Deficit irrigation strategies for maximizing economic returns in water-limited wheat production

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Abstract
Deficit irrigation is to water management what a household budget is to personal finance: it accepts that resources are limited and allocates them where the return per unit is highest. This research tested four irrigation levels—full irrigation (100% crop evapotranspiration, ETc), 75% ETc, 50% ETc, and rainfed control—on winter wheat (*Triticum aestivum* L., cv. AKAW-4627) at Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra, over two rabi seasons (2021–22 and 2022–23). The 75% ETc strategy reduced water applied by 23.7% relative to full irrigation while lowering grain yield by only 8.5% (4.31 vs. 4.71 t ha^{-1}). Water productivity peaked at 1.83 kg m^{-3} under 75% ETc compared with 1.42 kg m^{-3} for full irrigation. Net returns were highest at 75% ETc (42,380 INR ha^{-1}, BCR 2.47). The 50% ETc level saved 47% of water but cut yield by 27.6%, making it economically inferior. These results position the 75% ETc strategy as the optimal trade-off between water saving and economic return for wheat in semi-arid Maharashtra.

Keywords: Deficit irrigation, economic returns, wheat production, water limitation, water productivity, ETc scheduling, semi-arid agriculture, benefit-cost ratio, crop water stress, Maharashtra

Introduction
Think of a farm's water supply the way a family thinks about a fixed salary: spending it all on one category might feel safe, but spreading it wisely across needs gives a better overall outcome [1]. That analogy captures the logic behind deficit irrigation (DI), which deliberately applies less water than the crop's full evapotranspiration demand and reallocates the saved volume to additional area or to critical growth stages [2, 3].
In Maharashtra's Vidarbha region, canal water for rabi wheat is allocated at 500–600 mm per hectare, but actual crop ETc reaches 400–450 mm under normal conditions [4]. Farmers tend to over-irrigate during early growth and under-irrigate during grain fill, precisely the wrong sequence for wheat, where the crown-root initiation and anthesis stages are most sensitive to water stress [5, 6].
Published DI trials from north-western India and the Mediterranean have shown that applying 70–80% ETc reduces yield by 5–15% but raises water productivity by 20–50%, a trade-off that is almost always economically positive [7, 8]. But site-specific data from Vidarbha's black cotton soils—which have high water-holding capacity and crack during drying—are scarce [9]. This research aimed to: (a) compare four irrigation levels on wheat yield and water productivity, (b) identify the strategy that maximises net economic return per hectare, and (c) determine whether grain protein content changes under mild deficit.

Cost Analysis
Irrigation costs were calculated from pump diesel consumption (3.2 L per 50 mm application on 1 ha), diesel price (89.7 INR L^{-1}), and labour (150 INR per irrigation event). Full irrigation required eight irrigations of ~60 mm each; 75% ETc required six; 50% ETc required four; rainfed received zero supplemental water. Total variable costs (seed, fertiliser, pesticide, labour, diesel) were 17,140 INR ha^{-1} for full irrigation and 15,920 INR ha^{-1} for 75% ETc. Gross returns at the minimum support price of 2,125 INR q^{-1} were 100,082 and 91,583 INR ha^{-1}, respectively. Net return peaked at 42,380 INR ha^{-1} under 75% ETc (BCR 2.47), exceeding full irrigation's 40,710 INR ha^{-1} (BCR 2.37), because the lower water cost more than offset the modest yield reduction.

Material and Methods
Material
The trial was at Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola (20.70° N, 77.02° E; 282 m a.s.l.), on a deep black cotton soil (Vertisol; clay 52%, pH 8.3, OC 0.48%). Wheat cv. AKAW-4627 was sown at 100 kg ha^{-1} in the third week of November each year. Reference ET_0 was computed daily from an on-site automatic weather station using the FAO Penman–Monteith equation; crop ETc was derived by multiplying ET_0 by the stage-specific crop coefficient (Kc) from FAO-56 [10]. Irrigations were applied through gated pipes with measured discharge.

Methods
Four treatments—100% ETc (T_1), 75% ETc (T_2), 50% ETc (T_3), and rainfed (T_4)—were arranged in a randomised complete block design with four replications on 6 × 5 m plots. Irrigation scheduling followed a soil-water-balance approach, replenishing the deficit to the prescribed ETc fraction when cumulative depletion reached 50% of available soil moisture (ASM). Soil moisture was tracked at 15 and 30 cm by gravimetric sampling twice weekly. Grain yield, straw yield, harvest index, 1000-grain weight, and grain protein (Kjeldahl N × 5.7) were recorded at maturity. Water productivity (WP) = grain yield / total water input (irrigation + effective rainfall). Data were analysed by two-way ANOVA (treatment × year) with Tukey's HSD at $p \leq 0.05$.

Results

Table 1: Water use, grain yield, protein content, and economic returns under four irrigation levels (pooled 2021–22 and 2022–23).

Treatment	Water applied (mm)	Yield (t ha^{-1})	HI	WP (kg m^{-3})	Protein (%)	Net return (INR ha^{-1})	BCR
T_1 (100% ETc)	471	4.71	0.42	1.42	11.3	40,710	2.37
T_2 (75% ETc)	359	4.31	0.43	1.83	12.1	42,380	2.47
T_3 (50% ETc)	249	3.41	0.41	2.08	12.8	28,940	2.01
T_4 (Rainfed)	87*	2.18	0.38	1.67	13.4	14,620	1.54
CD (p=0.05)	—	0.28	0.02	0.14	0.6	—	—

* Effective rainfall only. HI = harvest index; WP = water productivity; BCR = benefit-cost ratio. Net returns at MSP of 2,125 INR q^{-1}.

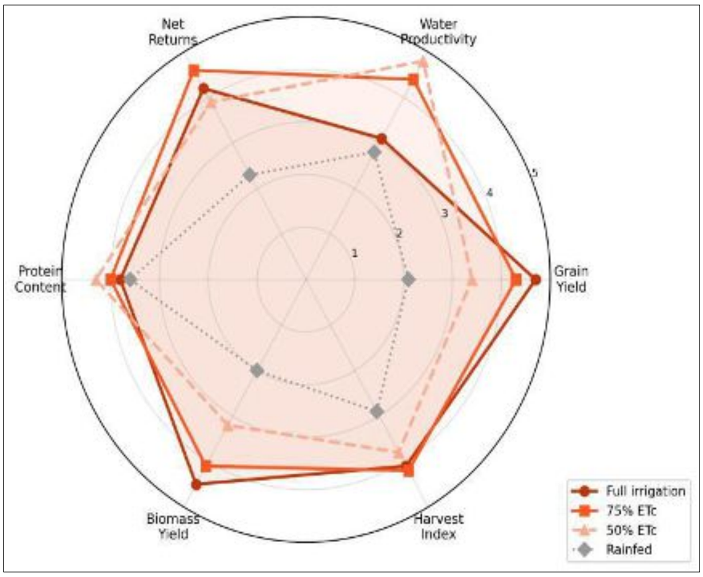

Fig 1: Radar comparison of yield, water productivity, net returns, protein content, biomass, and harvest index across four irrigation levels.

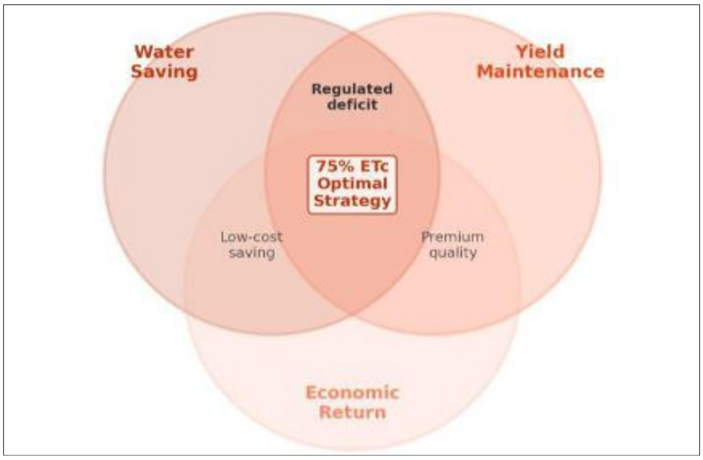

Fig 2: Venn diagram showing the intersection of water saving, yield maintenance, and economic return, with 75% ETc occupying the optimal overlap zone.

Comprehensive Interpretation

The 75% ETc treatment sat at the intersection of three objectives: it saved 23.7% of water, lost only 8.5% of yield, and produced the highest net return (42,380 INR ha^{-1}). Water productivity rose from 1.42 to 1.83 kg m^{-3}—a 29% gain. An unexpected bonus was a 0.8 percentage-point increase in grain protein (12.1% vs. 11.3%), consistent with the well-known concentration effect under mild water deficit [11]. The 50% ETc level maximised WP (2.08 kg m^{-3}) but the 27.6% yield loss made it economically unattractive. Rainfed wheat was the least profitable despite zero irrigation cost, because yield fell below 2.2 t ha^{-1}.

Discussion

The 8.5% yield penalty at 75% ETc matches the 5–12% range from Mediterranean wheat DI trials [7, 12]. On Akola's deep Vertisol, the stored moisture in the 30–60 cm zone buffered early-season deficit, allowing roots to access water that lighter soils would not hold [9]. This buffering effect likely explains why the yield loss here was at the lower end of published ranges.

The protein increase under deficit has direct market implications. Wheat with >12% protein commands a premium in the Indian milling sector, and shifting from 11.3 to 12.1% could add 50–80 INR q^{-1} above MSP [13]. If that premium were included, the BCR advantage of 75% ETc would widen further.

Limitations include the two-season, single-site scope and the absence of a phenological-staging DI treatment (e.g., full irrigation at anthesis only). Such stage-targeted strategies have shown promise in Punjab [14] and would be worth testing on Vidarbha's Vertisols, where the soil's self-mulching property may interact differently with growth-stage timing.

Conclusion

Irrigating wheat at 75% ETc saved 23.7% of water, reduced yield by only 8.5%, and delivered the highest net return and BCR among all treatments. Water productivity rose 29% and grain protein increased by 0.8 percentage points. For semi-arid Vidarbha, the 75% ETc strategy is the most economically rational deficit irrigation option. Stage-specific deficit scheduling and multi-location testing should be explored next.

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