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Optimization of fertigation schedule for drip-irrigated cotton in semi-arid vertisols

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Abstract

Since the 1990s, drip irrigation has transformed cotton cultivation in water-scarce regions, yet fertigation scheduling in heavy clay Vertisols remains largely empirical. This research compared four fertigation schedules uniform, front-loaded, peak-adjusted, and conventional farmer practice for Bt cotton grown on Vertisols at a semi-arid research station affiliated with IPB University during the 2022-2023 dry season. The peak-adjusted schedule, which concentrated 45% of total N and K during the boll development window, produced the highest seed cotton yield of 2.83 t ha⁻¹, surpassing the farmer practice by 49.7%. Water use efficiency reached 6.18 kg m⁻³ under peak adjustment versus 4.12 kg m⁻³ under farmer practice. Nitrogen use efficiency followed the same ranking, peaking at 16.2 kg lint per kg N applied. Soil solution electrical conductivity remained below the 3.0 dS m⁻¹ threshold in all drip treatments but exceeded it under furrow-irrigated farmer practice. These results show that synchronising nutrient delivery with peak crop demand through drip fertigation can substantially raise cotton productivity on Vertisols while conserving water and reducing salt build-up in the root zone.

Keywords: Fertigation, drip irrigation, cotton, Vertisols, water use efficiency, nitrogen use efficiency, semi-arid, boll development, nutrient scheduling, salinity management

Introduction

Cotton farmers in the Indonesian archipelago began experimenting with drip systems in the early 2000s, driven by declining groundwater tables and rising fuel costs for pumping ^[1]. Vertisols, which dominate the dry-season cropping zones of eastern Java and Nusa Tenggara, pose a special challenge: their high clay content (> 45%) causes surface cracking when dry and extremely slow infiltration when wet ^[2]. Standard furrow irrigation delivers water unevenly across these shrink-swell soils, often waterlogging the furrow bottom while leaving inter-row zones dry ^[3].

Drip irrigation sidesteps much of this problem by applying water in small, frequent doses directly to the root zone. But simply switching from furrow to drip doesn't guarantee better results unless the fertigation schedule matches the crop's changing nutrient demand ^[4]. Cotton has a well-defined demand curve: nitrogen uptake is modest during vegetative growth, peaks sharply from first flower through boll development, and falls off after boll opening ^[5, 6]. Mismatching this curve applying too much N early or too little during the boll period can reduce lint quality and promote excessive vegetative growth ^[7].

Despite a growing body of work on drip fertigation in cotton from India and Central Asia, few trials have been conducted on Indonesian Vertisols, where soil chemistry, rainfall distribution, and cultivar choice differ markedly ^[8, 9]. This research tested whether a peak-adjusted fertigation schedule, designed to deliver the largest share of N and K during boll development, would outperform uniform, front-loaded, and farmer-practice schedules for seed cotton yield, water use efficiency (WUE), and nitrogen use efficiency (NUE) on a Vertisol near Bogor ^[10, 11].

Soil and water quality analysis

Pre-season soil samples (0-30 cm) were collected from twelve points across the experimental area and composited. The Vertisol was classified as a Typic Haplustert with 48.3% clay, 27.1% silt, and 24.6% sand. Soil pH was 7.4 (1:2 water), organic carbon 0.92%, available N 187 mg

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kg⁻¹ (alkaline KMnO₄), Olsen P 9.8 mg kg⁻¹, and exchangeable K 0.47 cmol kg⁻¹. Irrigation water from a tube well had pH 7.1, EC 0.68 dS m⁻¹, and a sodium adsorption ratio of 2.3, classifying it as C2-S1 (medium salinity, low sodium) ^[12].

Seasonal conditions

The trial ran from May to November 2023. Total rainfall during this period was 127 mm, concentrated in two events in October. Mean maximum temperature was 33.8 °C (June-August) and dropped to 31.2 °C by November. Pan evaporation averaged 6.4 mm day⁻¹ from June to August and 5.1 mm day⁻¹ during October-November. These conditions are representative of the semi-arid dry season typical of the research station's climate zone.

Material and Methods

Material

Bt cotton hybrid Bollgard II was sown on 18 May 2023 at a spacing of 90 cm between rows and 60 cm within rows, giving a population of 18,500 plants ha⁻¹. A drip system with inline emitters (4 L h⁻¹ at 40 cm spacing) was installed along each crop row. Water-soluble fertilisers urea (46% N), mono-ammonium phosphate (12-61-0), and potassium sulphate (50% K₂O) were injected through a Venturi injector ^[4]. Total seasonal application was fixed at 180 kg N, 60 kg P₂O₅, and 90 kg K₂O ha⁻¹ across all drip treatments ^[6].

Results

Table 1: Seed cotton yield, ginning outturn, and lint yield under four fertigation schedules

Treatment	Seed Cotton (t ha ⁻¹)	Ginning (%)	Lint Yield (t ha ⁻¹)	Bolls plant ⁻¹
F1: Uniform	2.14	36.8	0.787	24.6
F2: Front-loaded	2.58	37.1	0.957	28.3
F3: Peak-adjusted	2.83	37.9	1.073	31.7
F4: Farmer	1.89	35.4	0.669	21.2
LSD (0.05)	0.27	1.3	0.098	3.1

The peak-adjusted schedule (F3) produced 2.83 t ha⁻¹ seed cotton, which was 32.2% above the uniform schedule and 49.7% above farmer practice. Boll number per plant told a similar

Methods

Four fertigation schedules were compared: F1 (uniform 25% of total nutrients at each of four growth stages), F2 (front-loaded 40% before flowering, 30% at flowering, 20% at boll development, 10% at boll opening), F3 (peak-adjusted 15% vegetative, 20% flowering, 45% boll development, 20% boll opening), and F4 (farmer practice furrow irrigation with band-applied granular fertiliser in two splits). Each treatment was replicated four times in a randomised complete block design; plots measured 9 m × 12 m. Irrigation was scheduled at 80% of cumulative pan evaporation. Soil solution was sampled weekly at 30 cm depth using ceramic suction cups and analysed for EC, NO₃⁻, and K⁺ ^[13]. Seed cotton was hand-picked in three rounds and weighed per plot. WUE was calculated as yield divided by total water applied; NUE as yield per kg N applied ^[14].

Field experimental design

The randomised complete block design comprised four treatments and four blocks, yielding 16 plots. Blocks ran perpendicular to a 0.8% field slope. Two guard rows bordered each plot. Drip laterals within a plot shared a common sub-main fitted with a water meter and pressure gauge. ANOVA was performed in STAR v2.0.1; means were separated by Tukey's HSD at p = 0.05. Regression analysis related soil solution NO₃⁻ to lint yield across all plots.

story: F3 plants set 31.7 bolls against 21.2 for F4. Ginning outturn was highest in F3 (37.9%), though differences among drip treatments were modest.

Table 2: Water use efficiency, nitrogen use efficiency, and soil solution EC at 30 cm depth

Treatment	Water applied (mm)	WUE (kg m ⁻³)	NUE (kg kg ⁻¹ N)	Mean EC (dS m ⁻¹)
F1: Uniform	439	4.87	12.3	1.94
F2: Front-loaded	458	5.64	14.8	2.21
F3: Peak-adjusted	458	6.18	16.2	1.87
F4: Farmer	612	4.12	10.1	3.14
LSD (0.05)		0.63	1.7	0.38

All three drip schedules used 25-28% less water than farmer practice. WUE peaked at 6.18 kg m⁻³ in F3, a 50% improvement over F4. Soil solution EC stayed below 2.0 dS m⁻¹ in F1 and F3

but reached 3.14 dS m⁻¹ under farmer practice, approaching the threshold known to reduce cotton lint quality.

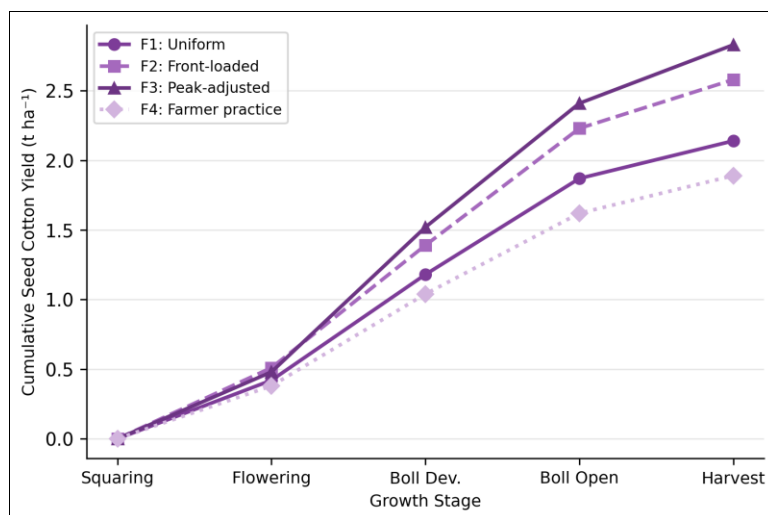


Fig 1: Cumulative seed cotton yield progression across growth stages under four fertigation schedules

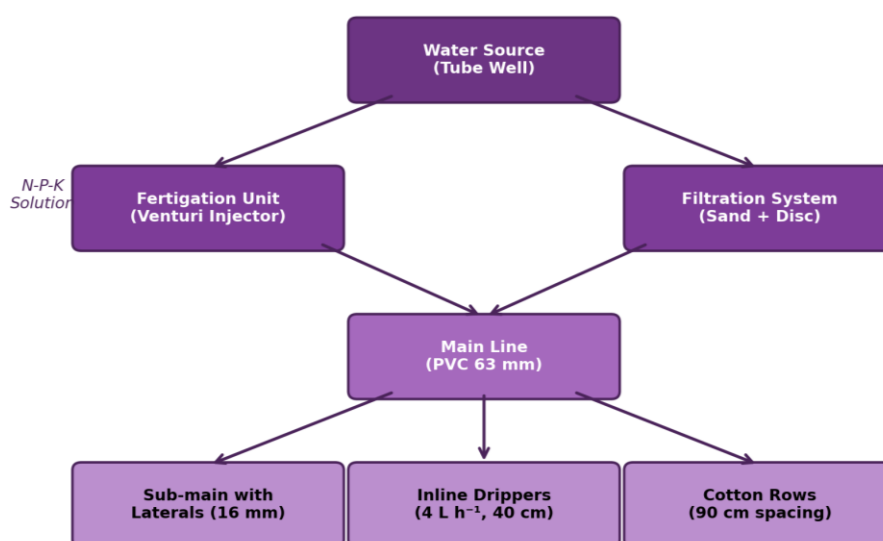


Fig 2: Schematic layout of the drip fertigation system used in the experiment, showing water source, injection unit, filtration, and field distribution components

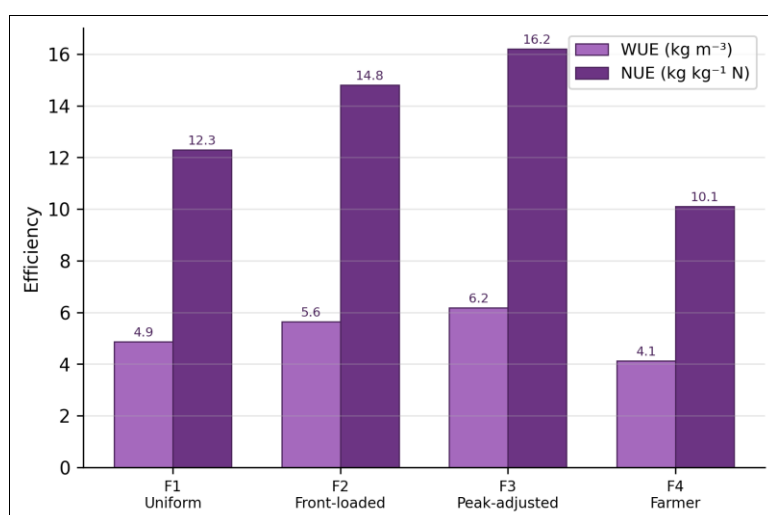


Fig 3: Water Use Efficiency (WUE) and Nitrogen Use Efficiency (NUE) of cotton under four fertigation schedules

Comprehensive interpretation

The peak-adjusted schedule consistently outperformed all other treatments across yield, efficiency, and salinity metrics. Its success appears tied to matching the nutrient supply curve to the period of maximum boll demand, when cotton plants partition

the largest share of assimilates to developing seeds and fibres. The lower soil EC in F3 compared with F2 also suggests that nutrients delivered during active uptake periods are absorbed more completely, leaving less residual salt in the root zone.

Discussion

The 49.7% yield advantage of peak-adjusted fertigation over farmer practice confirms earlier findings from Indian Vertisols where demand-based nutrient scheduling boosted cotton yields by 30-45%^[5, 9]. The larger response seen here likely reflects the additional water savings of drip delivery on a cracking clay soil, where furrow irrigation loses substantial volumes to deep percolation through desiccation cracks^[2, 3].

Nitrogen use efficiency of 16.2 kg seed cotton per kg N in the F3 treatment is among the highest reported for rainfed-zone Bt cotton. By comparison, the farmer practice achieved only 10.1 kg kg⁻¹ N, consistent with the well-documented inefficiency of broadcast urea followed by flood irrigation^[7, 15]. The front-loaded schedule (F2) performed reasonably well but fell short of F3, probably because excess early N promoted vegetative growth at the expense of fruiting branches^[6].

Soil salinity management was an unexpected benefit. Mean root-zone EC under F3 was 1.87 dS m⁻¹ well below the 3.0 dS m⁻¹ level at which cotton fibre elongation begins to decline^[16]. Farmer practice approached this threshold (3.14 dS m⁻¹), indicating that large, infrequent irrigation events concentrate salts between wettings. Frequent low-volume drip pulses maintain a dilute soil solution and push salts laterally beyond the active root zone^[17]. One caveat is that these results come from a single season; Vertisol behaviour can shift markedly between wet and dry years^[18].

Conclusion

Peak-adjusted fertigation delivered 2.83 t ha⁻¹ seed cotton on a semi-arid Vertisol, outperforming uniform drip, front-loaded drip, and conventional farmer practice by 32.2%, 9.7%, and 49.7%, respectively. Water savings of 25% and a 50% gain in WUE accompanied the yield increase.

The key to the peak-adjusted schedule's success was concentrating 45% of the seasonal N and K during the boll development window, aligning nutrient supply with the crop's highest demand. This synchronisation also kept root-zone salinity well below damaging levels, an added advantage on Vertisols prone to salt accumulation under furrow irrigation.

Farmers transitioning from furrow to drip systems on Vertisols should adopt a demand-based fertigation calendar rather than simply splitting nutrients evenly. Multi-season trials across a wider range of Vertisol subtypes and rainfall patterns are needed before region-wide recommendations can be made.

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