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Sustainable intensification of fine-staple cotton (*G. barbadense* L.) production in saline-prone soils through integrated agronomic management

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Introduction: Soil salinity poses a persistent constraint on agricultural productivity in arid and semi-arid irrigated regions, particularly for sensitive high-value crops such as fine-staple cotton (*Gossypium barbadense* L.). Addressing this challenge requires integrated agronomic strategies that simultaneously sustain yield, improve water-use efficiency, and protect soil–water resources under saline field conditions.

Methods: This study evaluated a Sustainable Intensification (SI) strategy for *G. barbadense* production in the saline-prone meadow-takir soils of the Surkhandarya region, Uzbekistan. In a two-year split–split–plot field experiment (2024–2025), we investigated the main and interactive effects of two genotypes (SP-1607 and Termiz-202), two irrigation regimes (70–75–65% vs. 70–80–75% of Field Capacity, FC), and three planting configurations (60 cm single-row; 76 and 90 cm twin-row) on seed cotton yield, water-use efficiency (WUE), soil porosity, and total dissolved solids (TDS) dynamics in the 0–100 cm profile. The 2024 and 2025 growing seasons were characterized by a semi-arid continental climate, with mean temperatures during the vegetative period of 27.6°C in both years and low growing-season precipitation (23.8 mm in 2024 and 31.8 mm in 2025), indicating that irrigation management was the dominant factor controlling root-zone moisture and salinity.

Results: The SP-1607 variety under the intensified 70–80–75% FC regime combined with the 90 cm twin-row configuration (150–160 thousand plants ha⁻¹) produced the highest seed cotton yield (4.82 t ha⁻¹; +32.4% vs. control, *p* < 0.05) and the highest WUE (1.39 kg m⁻³; +25.2%). Seasonal water inputs remained within 3,236–3,452 m³ ha⁻¹ across configurations, reducing water input per ton of fiber by 20.6%. Under the intensified regime, profile TDS declined from 1.232% to 1.090%,

compared with 1.232% to 1.185% under conventional management, suggesting a more favourable short-term salt balance in the root zone. Soil porosity decline was smaller under the intensified package (−1.5 percentage points) than under conventional management (−2.2 percentage points).

Discussion: These site-specific findings from a two-year, single-location trial indicate that the combination of an intensified irrigation threshold, a salt-tolerant genotype, and a high-density planting configuration can concurrently improve yield, water productivity, and short-term soil structural stability in weakly saline meadow-takir soils; however, multi-location and longer-term validation is required before broader recommendations can be made.

KEYWORDS

Central Asia, fine-staple cotton, *Gossypium barbadense*, irrigation management, planting density, soil salinity, sustainable intensification, water-use efficiency

1 Introduction

Global agriculture is currently confronted with the dual imperative of meeting the rising demand for high-quality natural fibers while mitigating the impacts of climate change and soil degradation. Among these challenges, secondary soil salinization remains a critical threat to agricultural sustainability, particularly in the arid and semi-arid regions of Central Asia (Devkota et al., 2022; Baig et al., 2023). In the Aral Sea Basin, over 50% of irrigated lands are affected by varying degrees of salinity, which significantly limits crop productivity and destabilizes the economic security of rural populations. In such environments, designing water-smart production systems that simultaneously sustain yields and protect soil–water resources has become central to the agenda of sustainable food and fiber systems (Devkota et al., 2022; Kihara et al., 2020; Van den Burg et al., 2024).

Within the genus *Gossypium*, *Gossypium barbadense* L. (fine-staple cotton) is highly valued for its superior fiber length, strength, and fineness and therefore commands a premium price on the international market. However, compared to the more widely cultivated *G. hirsutum*, fine-staple cotton exhibits a higher sensitivity to abiotic stressors, specifically osmotic stress and ion toxicity associated with saline soils (Alharbi et al., 2023). Previous research has indicated that soil salinity variations significantly influence cotton growth patterns and nutrient uptake, necessitating specialized management protocols (Li et al., 2022; Heng et al., 2024). This heightened stress sensitivity implies that fine-staple cotton can only be viably grown in salt-affected regions if agronomic management is explicitly tailored to buffer plants against water–salt imbalances during critical growth stages.

Sustainable Intensification (SI) offers a framework for bridging the yield gap in salt-affected irrigated environments without proportional increases in resource inputs or ecological costs (Devkota et al., 2022; Kihara et al., 2020; Van den Burg et al., 2024). In the context of this study, “intensification” refers specifically to increasing plant population density and raising irrigation frequency through moisture-threshold management, while “sustainable” is evaluated against four concurrent criteria: yield per unit area, water-use efficiency, water input per ton of harvested fiber, and stability of soil physical and salinity indicators across seasons. This multi-dimensional framing distinguishes SI from conventional single-factor yield optimization and anchors the study within established frameworks for irrigated dryland agriculture (Devkota et al., 2022; Kihara et al., 2020). While biological amendments such as vermicompost and

microbial inoculants have shown promise in mitigating salt stress (Jiang et al., 2024; Alharbi et al., 2023; Awan et al., 2024), the fundamental agronomic drivers of field-scale SI in saline environments remain irrigation management and plant spatial configuration.

In Uzbekistan’s Surkhandarya region—a traditional hub for fine-staple cotton—soil salinity and water scarcity interact to suppress yield potential, particularly during the critical flowering and boll-filling stages. Regional agronomic studies from Central Asia confirm that yield variability on saline soils remains substantial and location-specific management strategies are essential (Amirov et al., 2025). The Termiz-202 and SP-1607 varieties were developed through regional breeding programs with the aim of combining high yield potential with improved physiological stability under the abiotic stress conditions typical of southern Uzbekistan. Termiz-202 is the regional cultivar standard, widely grown in the Surkhandarya zone and thus used as the agronomic control. SP-1607 is a newly released genotype selected for superior yield formation and growth stability under moderate salinity stress, with preliminary multi-locational registration trials indicating stronger ion homeostasis and boll retention compared with standard long-staple varieties (Sharif et al., 2019; Li et al., 2025). However, the field-scale SI potential of these genotypes under combined irrigation–density management has not previously been quantified, representing a critical knowledge gap for production planning in saline-prone irrigated drylands.

This study aimed to evaluate the SI potential of *G. barbadense* L. production in saline-prone meadow-takir soils by quantifying the multi-factorial effects of irrigation regime, genotype, and planting configuration on: (i) seed cotton yield; (ii) water-use efficiency and seasonal irrigation input; (iii) soil porosity stability; and (iv) root-zone salinity trends. Specifically, we tested a management package coupling a moisture-threshold-based irrigation algorithm (70–75–65% vs. 70–80–75% FC) with contrasting planting geometries (60 cm single-row; 76 and 90 cm twin-row) and two contrasting genotypes (SP-1607 and Termiz-202). We hypothesized that simultaneously optimizing irrigation frequency, spatial configuration, and genotype would deliver concurrent improvements in all four SI criteria without increasing total seasonal water use.

In irrigated arid regions, improper water management accelerates upward salt migration, deteriorating root-zone conditions and limiting crop productivity, especially in long-term saline irrigation systems (Li et al., 2022; Zhang et al., 2024; Feng et al., 2025). Cotton growth and reproductive development are highly sensitive to osmotic stress, particularly during flowering and boll formation stages, where

salinity disrupts nutrient uptake, photosynthesis, and yield formation (Maryum et al., 2022; Sharif et al., 2019; Muhammad et al., 2024). Despite its superior fiber quality, *Gossypium barbadense* L. remains underexplored in saline agroecosystems, with most studies focusing on *G. hirsutum*, thereby creating a critical knowledge gap regarding genotype-specific responses to integrated irrigation and density management (Feng et al., 2024; Li et al., 2025; He et al., 2022). Addressing this gap requires field-scale evidence on how moisture-threshold-based irrigation and spatial configuration can be combined to deliver SI outcomes specifically for fine-staple cotton in salt-affected drylands.

2 Materials and methods

2.1 Site description and soil characterization

The experiment was conducted over two consecutive growing seasons (2024–2025) at the Surkhandarya Scientific-Experimental Station. The soil is classified as an old-irrigated meadow-takir soil (Aridisols according to USDA Soil Taxonomy). Baseline soil analysis (0–100 cm) indicated a medium-to-heavy loamy texture with an average initial bulk density of 1.41–1.43 g/cm³. The site is characterized by secondary salinization with a total dissolved solids (TDS) content of 1.232%, primarily dominated by sulfate-chloride ions. Under these conditions, groundwater depth ranged from 1.77 to 2.20 m, and capillary rise from the shallow water table contributes to upward salt movement during dry spells (Devkota et al., 2022; Li et al., 2022).

Soil porosity and bulk density were selected as key indicators of soil physical health, as these parameters are widely recognized as

integrative metrics linking management practices to ecosystem services under SI frameworks (Miner et al., 2020; Kihara et al., 2020).

2.2 Meteorological conditions during the experimental period

Meteorological data for the 2024 growing season were obtained from the Termiz Hydrometeorological Monitoring Centre (10-day period records), and for 2025 from the Surxondaryo Regional Meteorological Station (monthly summaries). Both seasons were characterized by a semi-arid continental climate with hot, dry summers typical of the Surkhandarya region (Table 1). In 2024, mean monthly air temperatures during the cotton vegetative period (April–October) ranged from 21.4 °C in April to 33.0 °C in July, with absolute daily maxima reaching 45.3 °C in June. Total in-season precipitation (April–October 2024) was only 23.8 mm, with 12.2 mm falling in April and zero precipitation recorded in June, July, and September, confirming that irrigation was the sole effective water supply during the main growth period. In 2025, a similar seasonal pattern was observed, with mean monthly temperatures ranging from 21.8 °C in April to 30.3 °C in September and absolute maxima reaching 39.0 °C in July. The 2025 season was notably dry at mid-season, with relative humidity in July dropping to approximately 28%, which may have intensified crop water demand during the critical boll formation stage. Total growing-season precipitation for 2025 was approximately 31.8 mm. Soil temperature at 10 cm depth was measured only in 2024, ranging from approximately 22 °C in April to 37 °C in July–August; corresponding 2025 values were not available from public meteorological archives (reference range from 2023 to 2024 station records: 25–37 °C during the vegetation period). The effective heat accumulation (sum of mean daily temperatures ≥10 °C) reached approximately 4,420 °C·day in 2024 and 4,493 °C·day

TABLE 1 Summary of meteorological conditions during the cotton growing seasons (April–October) at the Surkhandarya Scientific-Experimental Station.

Month	Mean temp (°C)	Abs. Max temp (°C)	Mean min temp (°C)	Total Precip (mm)	Rel. humidity (%)	Soil temp 10 cm (°C)
2024 growing season (Termiz Hydrometeorological Centre)						
April 2024	21.4	37.5	9.4	12.2	43	22.2
May 2024	26.0	39.7	13.7	0.5	45	27.6
June 2024	32.1	45.3	19.9	0.0	27	35.5
July 2024	33.0	44.6	21.9	0.0	27	37.3
August 2024	30.1	43.1	18.5	1.2	28	36.1
September 2024	24.2	41.0	13.5	0.0	34	29.9
October 2024	20.8	35.6	9.4	9.8	57	23.4
2025 growing season (Surxondaryo Regional Meteorological Station)						
April 2025	21.8	24.8	12.0	13.3	48	24.4
May 2025	27.6	31.1	17.0	2.5	38	31.2
June 2025	29.6	35.2	20.0	0.0	30	33.7
July 2025	30.2	39.0	23.0	0.0	28	35.0
August 2025	30.0	36.7	20.0	0.0	30	34.8
September 2025	30.3	32.5	16.0	6.2	34	34.8
October 2025	19.2	26.6	10.0	9.8	52	21.5

Source: Termiz Hydrometeorological Monitoring Centre. The 2024 dataset was summarized from 10-day meteorological records of the Termiz Hydrometeorological Centre, whereas the 2025 dataset was compiled from monthly observations of the Surxondaryo Regional Meteorological Station. In both years, the cotton growing period was marked by very limited precipitation and hot, dry summer conditions, indicating that irrigation remained the principal source of water for crop development in this semi-arid cotton-growing zone.

in 2025, both exceeding the minimum threshold ($\sim 3,500$ °C·day) required for full maturation of *G. barbadense* L. in this region. The Year effect on treatment rankings was non-significant ($p > 0.05$, ANOVA), indicating that the minor inter-annual climatic differences did not alter the relative performance of the management packages tested.

In 2024, we used 10-day observational records from the Termiz Hydrometeorological Monitoring Centre because these data included soil temperature at 10 cm depth and relative humidity at a high temporal resolution for the experimental area. In 2025, the full 10-day archive from Termiz was not yet available in processed form, whereas complete monthly summaries for the same agro-climatic zone were accessible from the Surxondaryo Regional Meteorological Station. We therefore used the most complete and quality-controlled dataset available for each season, while ensuring that both sources represented the same cotton-growing region and climatic regime.

2.3 Determination of soil hydro-physical properties

To ensure high precision in irrigation scheduling, the Field Capacity (FC) was determined *in situ* using the field-saturation method (Kachinsky's method). Experimental plots (2×2 m) were saturated until constant weight, followed by covering with a plastic film to prevent evaporation. Soil moisture was monitored every 24 h until the drainage of gravitational water ceased (typically 72–96 h), at which point the gravimetric water content was recorded as 100% FC. In the subsequent calculations, FC values were determined separately for each 10 cm layer down to 100 cm and then averaged for the active root zone layers used in the irrigation algorithm.

The bulk density (d) was measured using the core method (100 cm^3 cylinders) in 10 cm increments down to 100 cm. These parameters were used to convert gravimetric moisture into volumetric units for net irrigation depth calculations and to derive soil porosity classes that serve as SI indicators of soil structural stability.

2.4 Irrigation scheduling algorithm and calculation

Irrigation was triggered based on a depletion-based threshold algorithm. Soil moisture content (θ_{act}) was monitored gravimetrically every 10 days and before/after each scheduled event in the 0–70 cm and 0–100 cm soil profiles.

The net irrigation depth (m) was calculated using a modified Kostyakov-type water balance formulation to maintain soil moisture within the specified thresholds (70–75–65% and 70–80–75% of FC):

$$m = 100 \cdot H \cdot d \cdot (\theta_{fc} - \theta_{act}) \quad (1)$$

where m is the net irrigation depth ($\text{m}^3 \text{ ha}^{-1}$), H is the depth of the active soil layer (0.7 m during vegetative stages and 1.0 m during flowering/boll-filling), d is soil bulk density (g cm^{-3}), θ_{fc} is the target soil moisture at field capacity (expressed as % of dry soil weight), and θ_{act} is the actual soil moisture before irrigation.

The 70–80–75% FC regime was operationalized as follows: soil moisture was not allowed to drop below 70% of FC during the early vegetative stage, 80% during the critical flowering–fruiting stage, and

75% during the maturation stage. This high-frequency, low-volume approach was designed to maintain a consistent “salt-dilution” effect in the root zone by preventing excessive drying and associated upward capillary movement of salts (Devkota et al., 2022; Li et al., 2022). In contrast, the conventional 70–75–65% FC regime reflects the locally recommended practice that allows slightly deeper depletion during maturation, which may increase the risk of surface salt accumulation in dry years.

The chosen thresholds (70–75–65% and 70–80–75% FC) were derived from regional recommendations for cotton irrigation on saline soils and from preliminary trial data at the same station. Although a full sensitivity analysis of alternative thresholds was beyond the scope of this field experiment, the two regimes represent contrasting management philosophies—conventional low-frequency versus intensified high-frequency irrigation—that allow us to quantify the trade-offs between water-use efficiency, salt leaching, and yield stability under SI objectives.

2.5 Experimental factorial layout

The study followed a split-split-plot design. Main plots were assigned to irrigation regime (Conventional: 70–75–65% FC vs. Intensified: 70–80–75% FC). Sub-plots were assigned to genotype (Termiz-202 and SP-1607). Sub-sub-plots were assigned to planting geometry, including a conventional 60 cm single-row system and two twin-row (paired-row) systems with inter-row spacings of 76 cm and 90 cm.

Each plot measured 120 m^2 (20×6 m), and each treatment was replicated four times. A 2 m buffer zone was maintained between plots to prevent lateral water movement and nutrient leaching crossover. All treatments received uniform fertilization and pest management according to regional best practices for fine-staple cotton.

The split-split-plot structure was explicitly accounted for in the subsequent analysis of variance (ANOVA), with irrigation assigned to main plots, genotype to sub-plots, and planting geometry to sub-sub-plots. This design allowed us to disentangle the main effects and interactions ($I \times V$, $I \times D$, $V \times D$) on key SI indicators, including seed-cotton yield, water-use efficiency, soil porosity, and TDS dynamics. ANOVA results for the principal variables are summarized in the Results section using F -values, p -values, and partial eta-squared (η_p^2) effect sizes to support transparent interpretation of treatment effects.

2.6 Calculation of sustainable intensification indicators

To operationalize the Sustainable Intensification (SI) framework at field scale, we quantified a set of composite indicators capturing productivity, water-use efficiency, and soil–salt dynamics under each treatment combination. Seed-cotton yield (kg ha^{-1}) was determined from the central harvest rows of each plot and converted to per-hectare values based on the effective harvested area.

Irrigation water use ($\text{m}^3 \text{ ha}^{-1}$) was calculated as the sum of net irrigation depths ($\text{m}^3 \text{ ha}^{-1}$) applied over the season according to Equation 1. Water-use efficiency (WUE) was calculated as the ratio of seed-cotton yield to seasonal irrigation water use (Equation 2):

$$WUE = \frac{Y}{I} \quad (2)$$

where Y is seed-cotton yield (kg ha^{-1}) and I is seasonal irrigation input ($\text{m}^3 \text{ ha}^{-1}$). Water input per ton of fiber ($\text{m}^3 \text{ t}^{-1}$) was estimated by

combining seed-cotton yield with the measured lint turnout for each variety and treatment.

Soil porosity (%) was computed from bulk density measurements using standard relationships between particle density and bulk density, and evaluated at multiple depth intervals (0–30, 0–50, 0–70, 0–100 cm) at the beginning and end of the season. Changes in profile-averaged porosity over the season (Δ porosity, percentage points) were used as an SI indicator of soil structural stability under different irrigation–density regimes.

Soil salinity was assessed using total dissolved solids (TDS, %) measured in saturated paste extracts from composite samples at 0–100 cm depth. For each treatment, we calculated initial and final TDS values and their relative change over the season to represent the direction and magnitude of salt accumulation or leaching (Δ TDS). Together, yield, WUE, water input per ton of fiber, Δ porosity, and Δ TDS were synthesized in a comparative SI indicator table (Table 2) to contrast conventional management (Termiz-202, 70–75–65% FC, 60 cm single-row) with the proposed intensified management package (SP-1607, 70–80–75% FC, 90 cm twin-row). Although TDS (%) was the primary salinity metric used in this study, following the convention of Uzbekistan's national soil monitoring standards, approximate electrical conductivity (EC, dS m^{-1}) values were calculated using the empirical relationship $\text{EC} (\text{dS m}^{-1}) \approx \text{TDS} (\%) \times 8.0$, yielding initial soil EC values of approximately 9.9 dS m^{-1} —classifying the site as weakly to moderately saline according to FAO/USDA criteria. We acknowledge that direct EC measurement would improve comparability with the international literature, and recommend this as a standard practice in future studies.

2.7 Statistical analysis

All data were subjected to three-way analysis of variance (ANOVA) in a split-split-plot design, with irrigation regime (I) assigned to main plots, genotype (V) to sub-plots, and planting geometry (D) to sub-sub-plots. Each treatment was replicated four times ($n = 4$). The statistical model included main effects of I, V, and D, as well as all two-way ($I \times V$, $I \times D$, $V \times D$) and the three-way ($I \times V \times D$) interaction terms; the Year (Y) effect and its interactions with treatment factors were tested as an additional stratum. The assumption of normality was assessed using the Shapiro–Wilk test ($p > 0.05$ for all variables). Homogeneity of variance was confirmed using Levene's test ($p > 0.05$). No data transformations were required. When ANOVA indicated significant effects ($p < 0.05$), treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level. Effect sizes were calculated as partial eta-squared (η_p^2) to quantify the practical importance of each factor. Statistical analyses were performed using

IBM SPSS Statistics v.28. Values reported in tables and figures are means $\pm$ standard deviation unless otherwise specified.

3 Results

3.1 Impact of management on soil physical properties

The integrated agronomic management significantly influenced the soil's physical condition. In the control plots (Termiz-202, 70–75–65% FC), profile-averaged soil porosity in the 0–100 cm layer decreased by 2.2 percentage points (from 49.4 to 47.2%) over the season. Under the optimized SI package (SP-1607, 70–80–75% FC, 90 cm twin-row), the decline in profile porosity was smaller, at 1.5 percentage points (from 49.4 to 47.9%). Within the two-year scope of the experiment, this indicates a modest but more favorable short-term trend for soil structural stability under the intensified management, which is consistent with reports that optimized canopy cover and root distribution in intensified systems may help stabilize soil physical condition in saline environments (Li et al., 2022).

3.2 Irrigation water use and consumption patterns

Water consumption varied significantly across the irrigation regimes and genotypes. For the SP-1607 variety under 76 cm spacing, seasonal water consumption reached $3,376 \text{ m}^3 \text{ ha}^{-1}$, whereas across all intensified treatments (70–80–75% FC) seasonal irrigation inputs ranged between 3,236 and $3,452 \text{ m}^3 \text{ ha}^{-1}$. Despite the more frequent irrigation intervals required to maintain higher moisture levels, the total seasonal water use remained within this sustainable threshold, depending on the planting configuration. On average, the intensified regime reduced water input per ton of harvested fiber by 20.6% relative to the conventional practice (Table 2), without increasing total water applied per hectare. This balance between higher moisture maintenance and controlled seasonal limits likely helped reduce the risk of upward capillary salt movement (Devkota et al., 2022).

3.3 Physiological and growth response

The SP-1607 variety exhibited a more robust growth response to the 70–80–75% FC regime compared to the standard Termiz-202. At

TABLE 2 Sustainable Intensification (SI) indicators for fine-staple cotton production.

Indicator	Conventional management (Termiz-202, 70–75–65% FC, 60 cm)	Sustainable intensification (SP-1607, 70–80–75% FC, 90 cm Twin-row)	Improvement/trend
Yield (kg/ha)	3.64	4.82	+32.4%
WUE (kg/m ³)	1.11	1.39	+25.2%
Soil porosity change (%)	–2.2% (49.4% → 47.2%)	–1.5% (49.4% → 47.9%)	Better structure retention
Salinity trend (TDS %)	1.232% → 1.185%	1.232% → 1.090%	Enhanced leaching
Water input per ton fiber (m ³ /t)	901.3	715.7	–20.6% Water saving

Values are means $\pm$ standard deviation of four replications averaged across two growing seasons (2024–2025). Different lowercase letters within each parameter row indicate significant differences between management packages at $p < 0.05$ (Tukey's HSD test). The yield and WUE values for the conventional and SI packages represent the extreme treatments (Termiz-202, 70–75–65% FC, 60 cm single-row vs. SP-1607, 70–80–75% FC, 90 cm twin-row); intermediate treatment means are reported in the main ANOVA results (section 3.6).

the flowering stage, the plant height and the number of sympodial branches were significantly higher in the intensified management plots ($p < 0.05$; data not shown). This stronger growth response under high-frequency irrigation suggests that maintaining higher soil moisture (80% FC during the critical flowering stage) may help dilute salt concentrations in the soil solution and thereby reduce osmotic stress, a pattern consistent with the findings of Alharbi et al. (2023).

3.4 Yield performance and sustainable intensification

The key result of this study was the yield response to the integrated management factors. The highest seed-cotton yield was recorded in the SP-1607 plots under the 70–80–75% FC irrigation regime, particularly when combined with the 90 cm twin-row configuration. Compared to the conventional 60 cm single-row system (Termiz-202, 70–75–65% FC), both twin-row configurations (76 and 90 cm) demonstrated improved spatial efficiency, with the 90 cm twin-row showing the highest yield response. Across two seasons, the optimized SI package (SP-1607, 70–80–75% FC, 90 cm twin-row) increased mean seed-cotton yield by 32.4% relative to the conventional control (Table 2), while maintaining similar seasonal irrigation inputs. This combination produced significantly higher yields than the control ($p < 0.05$), suggesting that the interaction between genotype and optimized moisture-density management was an important driver of yield gains under saline-prone conditions. The results suggest that, under the conditions of the present study, shifting from conventional management to the intensified 70–80–75% FC regime combined with the SP-1607 variety may improve productivity without compromising short-term soil-water balance (Jiang et al., 2024).

3.5 Sustainable intensification indicators

To evaluate the overall efficiency of the integrated management system, a set of Sustainable Intensification (SI) indicators was calculated, comparing the conventional practice (Control) with the optimized system (SP-1607 variety, 70–80–75% FC irrigation, and 90 cm twin-row spacing). As summarized in Table 2, the SI package increased seed-cotton yield from 3.64 to 4.82 t ha⁻¹ (+32.4%) and WUE from 1.11 to 1.39 kg m⁻³ (+25.2%), while reducing water input per ton of fiber from 901.3 to 715.7 m³ t⁻¹ (–20.6%). Changes in profile-averaged soil porosity (0–100 cm) were modest in both systems, but the SI treatment showed a smaller decline (–1.5 vs. –2.2 percentage points), indicating better structural retention. At the same time, TDS in the 0–100 cm layer decreased from 1.232 to 1.090% under SI, compared with 1.232–1.185% under conventional management, suggesting enhanced salt removal and a more favorable short-term salt balance.

For each SI indicator, values represent treatment means computed across four replicates and two seasons, and are presented to compare the relative performance of the conventional and optimized management packages under the conditions of this experiment.

3.6 Factor interactions and year effects

The multi-factorial ANOVA revealed significant main effects for Variety (V), Irrigation regime (I), and Planting density (D), as well as several key interactions ($p < 0.05$). The partial eta-squared (η_p^2) values indicated that Irrigation regime had the largest effect size on yield

($\eta_p^2 = 0.68$), followed by the V $\times$ I interaction ($\eta_p^2 = 0.42$). Taken together, these effect sizes suggest that precise water management was a major driver of yield performance in this saline *G. barbadense* system (Li et al., 2022) and that SI outcomes were more strongly influenced by irrigation-genotype interactions than by planting density alone.

3.6.1 Interaction effects (V $\times$ I and I $\times$ D)

The interaction between Variety and Irrigation (V $\times$ I) was highly significant for seed cotton yield ($F = 12.45$, $p < 0.01$). While both varieties responded positively to the intensified 70–80–75% FC regime, the magnitude of response was significantly greater in SP-1607 compared to Termiz-202. This indicates that the genetic potential of the new genotype is specifically unlocked under higher moisture availability, which serves to mitigate the localized salinity stress.

Furthermore, a significant interaction was observed between Irrigation and Density (I $\times$ D). The 90 cm twin-row configuration reached its maximum yield potential only when paired with the 70–80–75% FC regime. Under the control irrigation (70–75–65% FC), the higher density in the 90 cm plots led to slight intra-specific competition, reducing the number of bolls per plant. This pattern suggests that SI gains in this system primarily arise when high-frequency irrigation is combined with the salt-tolerant SP-1607 genotype and adequately high plant density, rather than from any single factor alone (Devkota et al., 2022).

3.6.2 Analysis of year effect (2024 vs. 2025)

ANOVA indicated that the Year effect on yield was non-significant ($p > 0.05$), suggesting that treatment rankings remained stable across both seasons despite moderate inter-annual climatic variability. Although slight variations in early-season temperatures occurred in 2024, the overall trend of SP-1607 outperforming the control under intensified regimes remained stable. The consistency of these results across two seasons increases confidence in the agronomic package under the conditions of the Surkhandarya region.

3.6.3 Effect size and statistical power

Partial eta-squared (η_p^2) values showed that irrigation regime had the largest effect size on yield ($\eta_p^2 = 0.68$), followed by the V $\times$ I interaction ($\eta_p^2 = 0.42$). These values indicate that irrigation management was the strongest experimental driver of yield response in the present study (Li et al., 2022; Figure 1).

4 Discussion

The sustainable intensification of fine-staple cotton (*G. barbadense* L.) in saline-prone environments requires a sophisticated synergy between genetic potential and precise resource management. Our findings demonstrate that the newly developed SP-1607 variety, when coupled with an intensified 70–80–75% FC irrigation regime and a 90 cm twin-row planting scheme, significantly outperforms traditional cultivation methods in terms of yield, water-use efficiency, and salt-balance regulation. In contrast to many previous studies that optimized either genotype or single agronomic factors in isolation, this

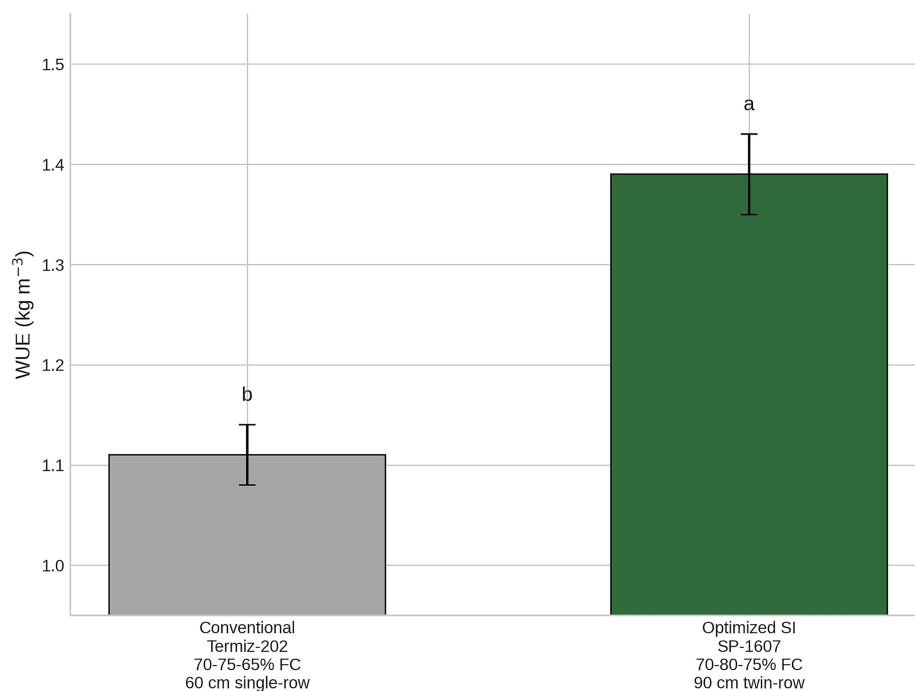


FIGURE 1

Comparison of water-use efficiency (WUE, kg m⁻³) between the conventional management package (Termiz-202, 70–75–65% FC, 60 cm single-row) and the optimized sustainable intensification package (SP-1607, 70–80–75% FC, 90 cm twin-row). Bars represent two-year means (2024–2025) ± standard deviation. Different lowercase letters indicate significant differences at $p < 0.05$ according to Tukey's HSD test.

work evaluates a fully integrated management package and quantifies its multi-dimensional SI outcomes under on-farm conditions.

4.1 Genotype-environment interaction and salt tolerance

The superior performance of SP-1607 compared to the standard Termiz-202 underscores the importance of genotype selection in mitigating abiotic stress. While soil salinity in the study area was classified as “weakly saline” (1.232% dry residue), the cumulative effect of osmotic stress can severely limit the growth of sensitive *G. barbadense* species. As highlighted by Sharif et al. (2019), the genetic architecture of cotton determines its physiological plasticity under stress. The resilience of SP-1607 may be attributed to its enhanced ability to maintain ion homeostasis, a trait that is likely important for stable growth and reproductive performance under saline conditions (Sharif et al., 2019). The stronger response of SP-1607 under intensified irrigation suggests a genotype-specific ability to exploit improved soil moisture conditions, consistent with recent genomic and physiological evidence of enhanced salt tolerance in *G. barbadense* (Li et al., 2025; Feng et al., 2024). Taken together, these results indicate that breeder-selected salt-tolerant genotypes can only realize their full SI potential when combined with irrigation regimes that actively buffer plants against transient peaks in osmotic stress.

4.2 Irrigation regimes and salt dilution dynamics

The adoption of a 70–80–75% FC irrigation regime represents a strategic shift in water management for saline-prone cotton production. Conventional deficit irrigation recommendations are designed

to maximize water savings; however, in environments where shallow groundwater and low rainfall sustain a persistent upward capillary flux of salts, reducing soil drying frequency during the critical flowering stage may help limit osmotic stress by diluting salt concentrations in the soil solution—a mechanism that, while consistent with the salt-dilution hypothesis of Devkota et al. (2022) and Li et al. (2022), is interpreted here as an inferred process based on the observed TDS trends rather than on direct soil solution measurements. By reducing the extent of soil drying during critical growth stages, the intensified regime likely limited upward capillary salt movement in the root zone; this interpretation is consistent with the observed TDS decline under the 70–80–75% FC regime (1.232% → 1.090%) compared with conventional management (1.232% → 1.185%). Direct measurement of soil solution ion concentrations at different depths would be needed to confirm this mechanism quantitatively (see section 4.6 for limitations).

Furthermore, the integration of such regimes can be enhanced by biological amendments. While our study focused on agronomic management, the synergy between high-frequency irrigation and soil amendments like vermicompost (Alharbi et al., 2023) or microbial inoculants (Jiang et al., 2024) could provide a secondary layer of protection against osmotic shock, suggesting a pathway for future integrated research. The better performance of the 70–80–75% FC regime is consistent with previous studies showing that maintaining higher soil moisture during critical growth stages may help dilute salt concentrations and stabilize yield formation in saline environments (Zhang et al., 2023; Zhang et al., 2025; Wang et al., 2025). Nevertheless, we acknowledge that our thresholds represent only one feasible configuration; a full process-based analysis of water–salt transport and alternative threshold sets will be required to generalize these recommendations across wider salinity and climate gradients (Figure 2).

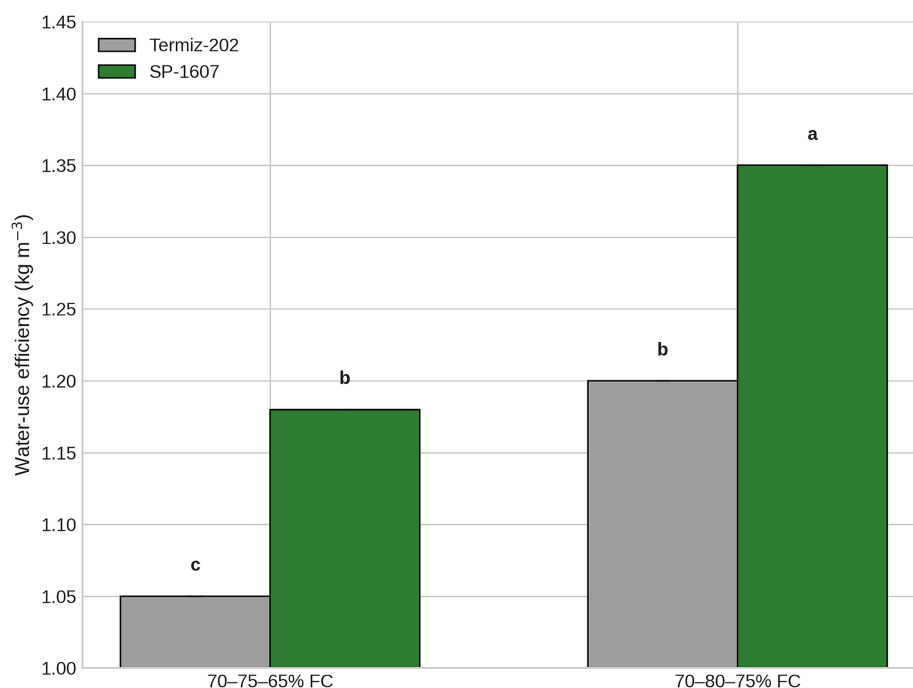


FIGURE 2

Comparative analysis of water-use efficiency (WUE, kg m⁻³) between Termiz-202 and SP-1607 genotypes under two irrigation management regimes (70–75–65% and 70–80–75% of field capacity). Values represent means over the 2024–2025 growing seasons. Different lowercase letters above the bars indicate significant differences at $p < 0.05$ according to Tukey's HSD test.

4.3 Planting density and canopy microclimate

The adoption of the 90 cm twin-row planting scheme (150–160 thousand plants ha⁻¹) proved to be a decisive factor in yield optimization. This planting arrangement likely promoted more rapid canopy closure compared to the conventional 60 cm single-row system and the narrower 76 cm twin-row configuration. A closed canopy reduces direct soil evaporation, thereby mitigating the accumulation of salts at the soil surface. This canopy-mediated moderation of soil surface exposure may be particularly important for *G. barbadense*, which is more sensitive to heat and salt stress than *G. hirsutum*. Our results corroborate the framework of Sustainable Intensification, where increasing plant density does not necessarily lead to resource exhaustion if paired with proportional increases in nutrient and water inputs (Devkota et al., 2022). High-density planting enhanced canopy closure, reducing soil evaporation and secondary salinization, a mechanism previously reported in arid cotton systems under optimized spatial configurations (Vitale et al., 2025; Song et al., 2025). In contrast to studies focusing on *G. hirsutum*, our data show that extra-long staple cotton can also benefit from such high-density arrangements provided that irrigation is managed to avoid intra-specific competition under saline conditions.

4.4 Soil physical health and sustainability

An important observation was that the optimized SI package did not worsen short-term soil physical status despite producing higher yield and WUE. Compared with the conventional management package, the optimized treatment showed a smaller decline in profile-averaged soil porosity (–1.5 vs. –2.2 percentage points), suggesting better short-term structural retention under intensified management. This suggests that high-density planting, by increasing the root biomass per

unit volume, may provide a biological “tilling” effect, improving soil physical properties over the long term. This is consistent with the findings of Jiang et al. (2024), who noted that improving soil physical structure is a prerequisite for sustained cotton productivity in salt-affected lands. Moreover, soil biological activity and nitrogen cycling processes are sensitive to salt accumulation, and maintaining adequate soil moisture may help preserve these functions (Zhou et al., 2023). Improved soil porosity under intensified management indicates that high-density cotton systems may exert a biological structuring effect on saline soils, supporting long-term sustainability of irrigated agroecosystems (Jiang et al., 2024; Alharbi et al., 2023). From an SI perspective, the smaller decline in profile porosity (–1.5 vs. –2.2 percentage points) under the optimized package complements the gains in yield and WUE, suggesting that productivity increases were not accompanied by an evident short-term penalty in soil physical condition.

4.5 Limitations and applicability of the findings

Several limitations of this study must be acknowledged to define the appropriate scope of the conclusions. First, the experiment was conducted at a single site (Surkhandarya Scientific-Experimental Station) over two growing seasons (2024–2025). The site represents weakly saline meadow-takir soils with a specific groundwater depth range (1.77–2.20 m) and a sulfate-chloride salinity profile. The proposed management package is therefore most directly applicable to comparable environments in southern Uzbekistan, and its performance under moderately or strongly saline soils, different groundwater regimes, or contrasting climatic conditions cannot be inferred from the current data. Multi-location, multi-year trials are required before broader agronomic recommendations can be made. Second, salinity was assessed using bulk TDS (%) from saturated paste extracts across

the 0–100 cm profile. Ionic profiling (Na^+ , Cl^- , SO_4^{2-} , HCO_3^-) and depth-resolved measurements would provide more mechanistic insight into salt distribution dynamics; these are recommended for future studies, alongside direct EC (dS m^{-1}) measurement. Third, no fiber technological analysis (HVI measurements: fiber length, strength, micronaire, uniformity) was conducted for the specific treatment combinations in this experiment. Accordingly, no fiber quality claims are made from this study's data; future work should integrate HVI analysis to test the quality-stability hypothesis of SP-1607 under the evaluated management treatments. Fourth, the irrigation thresholds tested (70–75–65% and 70–80–75% FC) were selected based on regional practice and preliminary trial data. A systematic sensitivity analysis of alternative threshold configurations and a full water–salt transport model (e.g., HYDRUS-1D) would be needed to generalize these findings across different salinity and groundwater gradients. Fifth, the economic viability of the intensified package—including the costs of more frequent irrigation events relative to the premium value of SP-1607 fiber—was not assessed. An economic analysis is a necessary precondition for farmer-level scaling recommendations.

4.6 What can be scaled?

The SP-1607 genotype demonstrated robust physiological plasticity, making it a suitable candidate for further evaluation in the saline-prone meadow-takir soils of southern Uzbekistan and comparable environments. Specifically, the 90 cm twin-row spatial configuration combined with an intensified irrigation regime (70–80–75% FC) may be considered a promising management package for environments with comparable salinity levels and groundwater regimes, subject to local validation. This “high-density + high-frequency” model is scalable because it creates a favorable microclimate that actively buffers the plant against osmotic shock, thereby supporting more stable cotton productivity under fluctuating salinity levels. Within the study conditions, this package simultaneously enhanced yield, WUE, and soil–salt balance, fulfilling multiple SI criteria.

4.7 What should NOT be scaled?

Conversely, the traditional 60 cm single-row spacing and low-frequency irrigation cycles (e.g., the conventional 70–75–65% FC regime) appear less suitable where the primary goal is sustainable intensification under saline conditions. Our data suggest that under-density leads to excessive soil surface evaporation, which accelerates the upward capillary movement of salts, effectively “trapping” the root zone in a high-salinity layer. Furthermore, the cultivation of fine-staple cotton without adequate moisture buffering during flowering may increase production risk in weakly to moderately saline fields, particularly where shallow groundwater and evaporative salt accumulation are present.

4.8 Final outlook

Ultimately, the transition from resource-intensive to precision-oriented management appears to be a rational strategic direction for improving cotton performance under saline-prone irrigated conditions. If validated under broader field conditions, the combination of SP-1607, 90 cm twin-row planting, and the 70–80–75% FC regime may support improved economic returns while maintaining the ecological integrity of the soil–water nexus. Future work should focus on embedding this

package within broader water-allocation and salinity-management policies, supported by economic evaluations and process-based modeling to guide scaling across heterogeneous dryland landscapes.

5 Conclusion

This two-year, single-location field experiment provides site-specific evidence that a synchronized management package — combining the SP-1607 genotype with an intensified 70–80–75% FC irrigation regime and a 90 cm twin-row planting configuration — can simultaneously improve seed cotton yield (+32.4%), water-use efficiency (+25.2%), and short-term soil structural stability in weakly saline meadow-takir soils of the Surkhandarya region, Uzbekistan. These outcomes are consistent with the multi-dimensional criteria of Sustainable Intensification (SI), as all four evaluated SI indicators (yield, WUE, water input per ton of fiber, and soil porosity change) improved under the intensified management package relative to the conventional control. The findings are encouraging but must be interpreted within the constraints of the study: a single experimental site, two growing seasons, weakly saline soils (initial TDS $\approx 1.23\%$; EC $\approx 9.9 \text{ dS m}^{-1}$), and the absence of fiber technological measurements. Multi-location, multi-year trials across a broader salinity gradient are required before the management package can be recommended for wider adoption.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

KB: Conceptualization, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. SN: Data curation, Investigation, Validation, Writing – review & editing. SabI: Formal analysis, Methodology, Writing – review & editing. GY: Investigation, Validation, Writing – review & editing, Resources. DS: Investigation, Validation, Writing – review & editing. OT: Writing – review & editing, Formal analysis, Resources. NO: Data curation, Validation, Writing – review & editing. NK: Formal analysis, Resources, Writing – review & editing. ST: Data curation, Formal analysis, Project administration, Visualization, Writing – review & editing. ZK: Investigation, Writing – review & editing. IK: Investigation, Resources, Writing – review & editing. SaiI: Data curation, Validation, Writing – review & editing. JO: Investigation, Supervision, Writing – review & editing. MK: Resources, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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