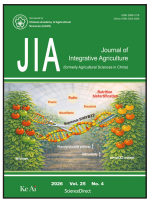
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REVIEW

Multi-objective integrated cotton cultivation (MOICC): A synergistic framework for sustainable production

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Highlights

- Propose multi-objective integrated cotton cultivation (MOICC), a novel paradigm that synergistically balances yields, quality, resource-use efficiency, and environmental sustainability.
- Mechanistically leverages key physiological processes and integrated technologies to achieve concurrent gains in yield, water-use efficiency, and carbon footprint reduction.
- Provides a scalable, globally applicable framework for sustainable cotton production, validated through regional case studies across diverse Chinese agro-ecosystems.

Abstract

Global cotton production faces mounting pressure to reconcile rising fiber demand with urgent sustainability imperatives, including water scarcity mitigation, greenhouse gas reduction, and agrochemical pollution control. Traditional practices, constrained by fragmented objectives and inherent trade-offs among yield, fiber quality, labor efficiency, and ecological impact, struggle to address these systemic challenges. Building upon previous concept of collaborative cultivation, this review for the first time introduces and comprehensively elaborates multi-objective integrated cotton cultivation (MOICC) — also referred to as integrated cotton cultivation (ICC) — a transformative framework centered on three pillars: dynamic trade-off management (e.g., region-specific priority adjustment), systematic technology integration (precision seeding, dense planting, chemical regulation, water-nutrient synergy, and targeted defoliation), and resource circularity (spatiotemporal optimization and waste recycling). MOICC overcomes sustainability bottlenecks by leveraging key physiological mechanisms, including ethylene signaling to enhance stress-resilient seedling establishment, jasmonate-mediated pathways to improve water/nutrient efficiency, canopy light competition coupled with hormonal regulation to eliminate manual pruning, and growth regulators to concentrate boll maturation. Case studies from diverse Chinese agro-ecosystems (e.g., Xinjiang, Yangtze/Yellow River basins) and intercropping systems demonstrate significant synergies: increased yield (8–22%), improved resource efficiency (water use efficiency increased by ≥20%, and nitrogen productivity up to 35 kg kg^{-1}), and enhanced environmental performance (labor reduction of 30–40%, carbon footprint reduction of 24–37%, and agrochemical savings: nitrogen reduction of 15–20% and pesticides reduction of 25%). Crucially, MOICC resolves core conflicts through integrated optimization: yield *vs*. quality (*via* ≥70% inner-position bolls), labor-saving *vs*. eco-safety (precision defoliant timing), and productivity *vs*. emissions (root-zone nitrogen monitoring). Future research priorities include deciphering multi-scale stress adaptation, developing intelligent decision-support systems (e.g., AHP-NSGA-II integration), advancing carbon-neutral value chains, addressing socio-economic adoption barriers, and fostering policy synergy. Overall, MOICC establishes a conceptually globally scalable pathway toward high-yield, superior-quality, resource-efficient, and ecologically sustainable cotton production, with potential applicability to other major cropping systems.

Keywords: cotton (*Gossypium hirsutum* L.), multi-objective integrated cultivation, sustainable agriculture, resource-use efficiency, technology synergy

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1. Introduction

Global climate change is fundamentally reshaping agricultural systems through the increasing frequency of intensity of extreme weather events and increasingly constrained natural resources (Zhang Z G *et al.* 2023). The IPCC Sixth Assessment Report indicates a 37% rise in the global agro-climatic risk index since 1981 (IPCC 2022). Within this context, cotton (*Gossypium hirsutum* L.), a water-sensitive industrial crop anchoring a 2.3 trillion USD global textile value chain, is particularly vulnerable in its production systems (Zhang Z G *et al.* 2023; Demeke *et al.* 2025). Cotton's extensive environmental footprint — accounting for 16% of global insecticide use and 3–5% of agricultural water withdrawals — creates transboundary sustainability pressures across producing and consuming regions (Zhang Z G *et al.* 2023; Vitale *et al.* 2025). Simultaneously, rising sustainability standards in textiles and corporate due diligence regulations necessitate a paradigm shift: moving beyond singular yield maximization towards integrated objectives of high yield, enhanced fiber quality, labor efficiency, and environmental sustainability (Zhang Z G *et al.* 2023; Vitale *et al.* 2025; Zhang Y J 2025a).

Current sustainable cotton initiatives face inherent structural limitations: Organic cultivation reduces chemical inputs but typically results in 30–50% lower yields than conventional systems; certification schemes (e.g., Better Cotton Initiative) improve input efficiency yet seldom address systemic trade-offs; precision technologies optimize isolated objectives while creating new imbalances (Zhang Z G *et al.* 2023; Vitale *et al.* 2025). These fragmented approaches struggle to resolve fundamental conflicts between productivity, resource efficiency, and ecological protection. Moreover, cotton cultivation contributes significantly to agricultural emissions, with cotton field yield-scaled N_2O emissions reaching 621 g N Mg^{-1} — substantially higher than cereal crops (Pan *et al.* 2024). The EU's Corporate Sustainability Reporting Directive (CSRD) and impending carbon border adjustment mechanisms further necessitate accurate carbon footprint quantification and mitigation strategies for the entire cotton value chain, from "seed to garment" (Wang *et al.* 2025).

Despite a 23% increase in cotton yield in China over the past decade, traditional production practices — characterized by high water and fertilizer inputs under extensive management — continue to exhibit critical inefficiencies. Nitrogen partial factor productivity (PFPN) stagnates at approximately 35 kg kg^{-1} in the North China Plain — less than 60% of values typical in developed countries (Feng *et al.* 2022). Similarly, irrigation water productivity (0.45 kg m^{-3}) in Xinjiang, China remains 40% below advanced international benchmarks (Feng *et al.* 2022, 2024; Zhou *et al.* 2023a). Critically, fragmented objective orientations create systemic imbalances: yield-focused strategies exacerbate carbon footprints — reaching 1.4 t CO_2-eq per ton of lint in some Chinese regions compared to a global lint average of 0.9 t CO_2-eq (Yu and Yang 2025). Conversely, labor-saving approaches often compromise fiber quality consistency, evidenced by fiber length coefficients of variation exceeding 8% (Feng *et al.* 2024; Yu and Yang 2025). Recent studies highlight that these trade-offs are often mediated by canopy microclimate and light distribution, where improper management of planting density and canopy architecture can exacerbate stress susceptibility and resource competition (Zhang Y J *et al.* 2025c; Zhou J Y *et al.* 2025). This landscape of unresolved trade-offs underscores the need for integrated solutions.

Building upon our foundational work which first proposed the concept of collaborative cultivation in cotton production (Zhang Y J *et al.* 2025a), this review formally establishes the multi-objective integrated cotton cultivation (MOICC) framework — also termed integrated cotton cultivation (ICC) in subsequent discussions — as the first comprehensive paradigm that unifies dynamic trade-off management, systematic technology integration, and resource circularity. Achieving multi-objective synergy in agriculture hinges on deciphering the "genotype×environment×management" (G×E×M) interaction network to enable dynamic optimization of resource allocation (Zhao *et al.* 2019). Successful multi-objective approaches in the North China Plain wheat–maize system, utilizing process-based models and machine learning, demonstrate potential for 16–19% reductions in water and fertilizer inputs and 20% lower greenhouse gas emissions while maintaining over 90% of yield potential (Xiao *et al.* 2024). This cross-crop success highlights the viability of integrated frameworks and the potential transferability of MOICC/ICC principles beyond cotton systems. In contrast, cotton cultivation often suffers from fragmented technology adoption. While individual innovations — such as drip irrigation under plastic mulch, improving water use efficiency (WUE), mepiquat chloride (DPC) regulation, and reduced labor for plant pruning — show promise, inadequate system integration limits overall benefits. For instance, increased planting density in Xinjiang reduced canopy light penetration, increasing square and boll shedding (Feng *et al.* 2017). Improper defoliant timing in the Yellow River basin decreased fiber strength by 10.6% (Feng *et al.* 2017, 2024). These issues stem not only from agronomic mismanagement but also from a lack of synergy between canopy ecology and stress physiology, as evidenced by recent work on stress interaction mechanisms (Zhang Y J *et al.* 2025c) and light-mediated hormonal regulation (Zhou J Y *et al.* 2025). The core challenges lie in insufficient understanding of dynamic trade-offs: How can integrated technologies dynamically optimize yield-quality trade-offs across canopy architecture and boll development? What systemic approaches reconcile spatiotemporal resource allocation with emissions reduction at field and regional scales? Addressing these questions systematically provides the scientific rationale for developing the MOICC framework.

To operationalize this conceptual framework, Fig. 1 synthesizes the systemic architecture of MOICC, illustrating how dynamic trade-off management, integrated technological modules, and resource circularity interact through feedback loops to enable adaptive optimization. Complementarily, Table 1 contrasts MOICC with traditional cotton cultivation, highlighting the paradigm shift from isolated, input-intensive practices toward temporally coordinated, efficiency-oriented,

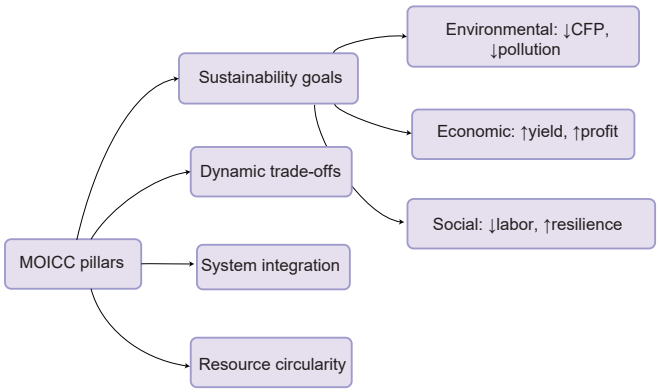


Fig. 1 Systemic framework of multi-objective integrated cotton cultivation (MOICC). The three core pillars — dynamic trade-off management, systematic technology integration, and resource circularity — interact to simultaneously advance environmental, economic, and social sustainability goals. CFP, carbon footprint. Dashed lines indicate feedback loops enabling adaptive optimization. Arrows (↑/↓) denote directional change under MOICC implementation.

and sustainability-driven management. Together, these schematic representations provide a structural overview that links the theoretical foundations of MOICC with its practical implementation pathways.

2. Concept and objectives of integrated cotton cultivation

2.1. Conceptual definition and innovations

MOICC, also referred to as ICC, is a cultivation paradigm centered on the dynamic interactions of G×E×M. It achieves a dynamic balance among multiple production objectives — high yield, enhanced fiber quality, operational efficiency, and environmental sustainability (green) — through the systematic optimization of resource allocation and management timing (Zhang Y J *et al.* 2025a). This approach to dynamic trade-off management is conceptually aligned with decision frameworks like the analytic hierarchy process (AHP) used in sustainable crop rotation assessments, where dimensionless priority vectors quantitatively rank alternatives against conflicting objectives (e.g., yield *vs*. environmental impact) (Werner *et al.* 2014).

MOICC further integrates carbon footprint quantification as a core component, employing accounting frameworks that span the entire cotton lifecycle. For instance, the "seed-to-garment" carbon accounting approach quantifies emissions at each stage (planting, processing, textile manufacturing), revealing that energy consumption and inefficient processing dominate the carbon footprint (Wang *et al.* 2025). Regionally tailored strategies — such as optimizing nitrogen application *via* root-zone monitoring (reducing N_2O by 26–32%) and promoting cotton stalk biochar (sequestering 2.8 t CO_2-eq ha^{-1}) are validated through China's first cotton carbon footprint standard and national pilot projects (Huang *et al.* 2023; Pan *et al.* 2024).

The innovation of MOICC/ICC manifests across three interrelated dimensions:

Multi-objective synergy MOICC overcomes single-objective limitations by enabling coordinated realization of yield enhancement, fiber quality optimization, labor efficiency, and environmental protection (Zhang Y J *et al.* 2025a).

Technology system integration Discrete technologies — precision seeding, dense planting, chemical regulation, and water-fertilizer coupling — are integrated into a cohesive "sowing-management-harvest" chain. For instance, integrated cultivation practices in Xinjiang reduce labor costs by approximately 35% while maintaining seed cotton yields above 6,750 kg ha^{-1} (Feng *et al.* 2024).

Resource circular synergy MOICC optimizes spatiotemporal resource flows to create synergistic loops. In Xinjiang, the integrated "dense-dwarf-early maturation" system (high-density planting+chemical regulation+drip fertigation under mulch) enhances canopy photosynthesis, aligns growth with peak light/heat, and boosts light use efficiency by more than 20%. This system dynamically supplies water/nutrients by growth stage, saving 30–50% water while significantly improving nitrogen and phosphorus use efficiency. Plastic mulching facilitates earlier sowing, while precise irrigation during flowering/boll setting coupled with late-stage water control promotes concentrated maturity — collectively creating synergistic cycles of light, temperature, water, and nutrients during critical phases (Dong 2019; Feng *et al.* 2024). This resource optimization has driven Xinjiang's historic yield increase, establishing it as a global resource-efficiency exemplar. Parallel synergies occur in other regions: 1) in the North China Plain, integrated drip fertigation combined with straw returning has increased WUE by 20% and achieved an annual soil organic carbon sequestration rate of 0.48 Mg ha^{-1}, echoing the resource synergy observed in wheat–maize systems (Xiao *et al.* 2024). 2) long-term straw return with moderate nitrogen fertilization (e.g., 150 kg N ha^{-1}) enhances soil organic carbon sequestration and improves seedcotton yield stability by reducing yield variability coefficients, demonstrating synergistic resource circularity (Li *et al.* 2025).

Compared to the traditional "high-input, low-synergy" cultivation model (Table 1), MOICC resolves three fundamental contradictions through technological coupling and resource optimization:

Yield-quality conflict Traditional dense planting often

Table 1 Systemic comparison of traditional cultivation and multi-objective integrated cotton cultivation (MOICC)

Dimension	Traditional cultivation	MOICC
Objective orientation	Single objective (e.g., high yield)	Dynamic multi-objective optimization
Technology logic	Isolated, additive application	Integrated technologies with temporal linkage
Resource efficiency	High input, low efficiency	Precise matching, circular synergy
Environmental impact	Diffuse pollution, high emissions	Emission reduction, carbon sequestration

leads to canopy closure and reduced fiber strength. MOICC employs targeted DPC application to regulate fruiting branch angle and internode length, improving light penetration, increasing the proportion of inner-position bolls (≥70%), and enhancing pre-frost flower ratio and boll maturation concentration (Nie *et al.* 2021).

Labor-saving *vs*. environmental protection conflict While chemical topping and defoliation save labor, they carry residue risks. MOICC utilizes boll development thermal time models for precise application timing, improving topping efficacy and defoliation rates (≥92%) while significantly reducing overall agrochemical use (Yu *et al.* 2022). This precision management mitigates potential environmental trade-offs associated with labor-saving chemicals.

High yield *vs*. carbon emissions trade-off Excessive nitrogen application can elevate the carbon footprint to 3.5 kg CO_2-eq per kg of lint. MOICC employs real-time root-zone nitrogen monitoring combined with drip fertigation (e.g., regulated by a –20 kPa matric potential threshold) to optimize nitrogen application rates to 275–307 kg ha^{-1}, achieving over 20% nitrogen reduction while enhancing nitrogen translocation efficiency. This strategy maintains yield, reduces soil nitrate residues and N_2O emissions, and lowers carbon emission intensity by 24% (Xiao *et al.* 2025; Yu and Yang 2025).

Collectively, MOICC establishes a novel framework that resolves fundamental conflicts (yield-quality, labor-eco-safety, productivity-emissions) through integrated optimization — a conceptual breakthrough beyond fragmented traditional approaches (Table 2).

2.2. Core objective system

MOICC is guided by the overarching goals of high yield, superior quality, operational efficiency, ecological soundness, and production safety. Quantifiable thresholds are set for each dimension:

Synergy of yield and quality Ensuring high yield (e.g., ≥6,000 kg seed cotton ha^{-1} in Xinjiang, China; ≥4,500 kg seed cotton ha^{-1} in the Yangtze and Yellow River basins), while optimizing boll spatial-temporal distribution (inner-position boll ratio≥70%) and regulating fiber development. Machine-harvested cotton should achieve a defoliation rate≥92% and seed cotton trash content≤8%, enabling simultaneous improvement in yield and quality (Zhang Y J *et al.* 2025a).

Synergy of labor-saving and resource efficiency Mechanization should replace manual labor (mechanization rate≥90%), simplifying management processes (reducing operations like branch pruning and thinning by 3–4 times) and lowering production costs (labor reduction by 30–40%). Concurrently, the efficiency of utilizing light, temperature, water, and nutrients must be enhanced (e.g., WUE increased by ≥20%) (Zhang Y J *et al.* 2025a).

Synergy of green and sustainable production Chemical inputs should be reduced (nitrogen fertilizer reduced by 15–20%, pesticides reduced by 25%). Plastic film recovery (recovery rate≥85%) and straw returning (≥4,500 kg ha^{-1}) must be promoted. Through nitrogen optimization and renewable energy utilization, carbon emission intensity should be reduced by 24–37% (Yu and Yang 2025), achieving ecologically friendly and sustainable production. This reduction is critical given projected climate-driven increases in greenhouse gas intensity (GHGI) for cotton in arid regions like Xinjiang, where GHGI may rise by 25–55% by 2100 under high-emission scenarios (Zhou H *et al.* 2025).

Synergy of stress resilience and yield stability Through varietal selection, technological adaptation, and management practices like application of exogenous melatonin and intertillage (Zhang Y J *et al.* 2023; Zhang *et al.* 2024), cotton's adaptability to stresses like drought, waterlogging, and salinity should be enhanced (e.g., seedling emergence rate≥80% in saline–alkali soils; reduction of waterlogging-induced yield loss by 16.5%), ensuring yield stability with an inter-annual fluctuation rate≤15% (Zhang Y J *et al.* 2024, 2025a).

In essence, the core of MOICC lies in achieving synergistic benefits across multiple objectives through dynamic balancing. It extends beyond maximizing yield and quality in

Table 2 System comparison of sustainability performance: Traditional cotton cultivation *vs*. multi-objective integrated cotton cultivation (MOICC)[1)]

Dimension	Indicator	Traditional cultivation	MOICC	Sustainability implication
Environmental	Carbon footprint (kg CO_2-eq kg^{-1} lint)	1.4–3.5	0.9–1.8	Significant reduction in global warming potential (GWP)
	Nitrogen use (kg N ha^{-1})	300–350	240–280	Reduced nitrogen leaching and N_2O emissions
	Pesticide use (kg a.i. ha^{-1})	8.5	6.4	Biodiversity protection and ecotoxicity risk mitigation
	Plastic film recovery rate (%)	<50	≥85	Microplastic pollution control; circular economy promotion
Resource efficiency	Water use efficiency (kg m^{-3})	0.45	0.54–0.75	Water scarcity mitigation (SDG 6)
	Nitrogen productivity (kg kg^{-1})	25–30	30–35	Enhanced nutrient cycling efficiency
	Light use efficiency (%)	15–18	20–25	Optimized photosynthetic resource capture
Economic & Social	Labor input (d ha^{-1})	120–150	75–90	Reduced labor intensity; improved livelihoods (SDG 8)
	Yield stability (CV, %)	20–25	10–15	Enhanced climate resilience; income security
	Net profit increase (%)	Baseline	22–69	Economic viability improvement

[1)] Comparative analysis of sustainability indicators between traditional cotton cultivation and the MOICC framework. Data are primarily derived from regional case studies in China (e.g., Xinjiang and the Yellow River Basin, China) and demonstrate MOICC's synergistic improvements across environmental performance, resource efficiency, and socio-economic dimensions. Sources: Yu and Yang (2025), Feng *et al.* (2024), Lu *et al.* (2017), and Chi *et al.* (2023).

monoculture cotton, aiming to enhance the overall productivity and comprehensive benefits of multi-cropping systems across diverse ecological regions and planting patterns. Applicable to both monoculture cotton and intercropping/relay cropping systems, MOICC provides a robust theoretical and technical foundation for achieving high-quality, green, and sustainable development of the cotton industry.

2.3. Guiding principles and implementation pathways

Achieving multi-objective synergy requires adherence to four core principles:

Principle of dynamic objective trade-offs Inherent trade-offs exist among objectives. Balancing yield with sustainability requires rational fertilization/irrigation, while yield-quality reconciliation demands precise management (Zhang Y J *et al.* 2025a). MOICC dynamically adjusts priorities regionally, emphasizing water/fertilizer conservation with high yield in the Northwest Inland, and labor-saving with yield stability in the Yellow River Basin (Feng *et al.* 2024; Zhang Y J *et al.* 2025a).

Principle of complementary technology synergy This overcomes antagonism by designing synergistic combinations. "dense planting+chemical regulation+water-nutrient synergy" suppresses overgrowth while boosting water/nutrient efficiency (Nie *et al.* 2021). Coordinated precision monoseeding, dense planting, and mechanical harvesting enhance efficiency and reduce labor (Dai *et al.* 2017).

Principle of resource circular linkage Synergistic resource optimization is fundamental. MOICC constructs "soil–crop–waste" loops: cotton stalk biochar enhances soil organic matter and reduces leaching risks (Wu F Q *et al.* 2023). Rational regulation of water, soil, and fertilizer lowers costs, increases yield, and safeguards ecology (Dong 2019). Water-nutrient synergy and systemic chemical regulation ensure balanced growth, minimizing resource waste (Feng *et al.* 2024). This principle is key to mitigating the environmental footprint of cotton production.

Principle of systemic resilience management Climate-resilient strategies using models (e.g., APSIM) establish thresholds (e.g., N≤300 kg ha^{-1}; residual film≤75 kg ha^{-1}) (Xiao *et al.* 2024). Intelligent monitoring enables sustainable control (Li *et al.* 2022). During square-flowering drought, phased deficit irrigation (restoring soil water from 40 to 60%) triggers compensation, limiting yield loss ≤8% and optimizing WUE (Yang *et al.* 2014). This principle ensures stability under increasing climate variability.

The essence of MOICC collaboration lies in the dynamic objective balance, complementary technology synergy, optimized resource configuration, and holistic "crop-environment-management" linkage. Adherence optimizes factor allocation, promotes resource-efficient utilization, and safeguards yield sustainably (Dong *et al.* 2014; Dong 2019; Zhang Y J *et al.* 2025a).

3. Physiological and ecological basis of integrated cotton cultivation

The multi-objective synergy inherent in crop production systems is fundamentally rooted in the dynamic interactive network of G×E×M. This network drives the systemic balance of yield formation, resource allocation, and stress adaptation through three core mechanisms: source–sink coordination, population-level compensation, and stress response (Zhang *et al.* 2013). The theoretical framework of MOICC focuses on elucidating the spatiotemporal coupling patterns of these mechanisms, providing a scientific foundation for technology integration (Zhao *et al.* 2019).

3.1. Synergistic regulation of sowing and seedling establishment

Precision monoseeding optimizes seedling establishment by spatially positioning seeds (hill spacing: (10±0.5) cm) and controlling sowing depth (2.0–2.5 cm). This creates an optimal soil emergence pressure (0.15–0.3 MPa) and a dark microenvironment, activating the ethylene signaling pathway key factor EIN3. This activation induces a 3.2-fold upregulation of the hypocotyl thickening gene *ERF1* and a 2.8-fold upregulation of the hook formation gene *HLS1*. These genetic responses remodel the auxin gradient distribution by regulating polar auxin transport (*GhPIN1a* increased by 47%), optimizing the hypocotyl hook angle to (115±5)°, and elevating seedling emergence rates to 92% (Kong *et al.* 2018, 2024). This mechanism exhibits significant adaptability under stress: in coastal saline soils, furrow planting (ridge height: 20 cm) induces a root-zone "salt-avoidance effect" (reducing furrow electrical conductivity by 35%), lowering the Na^+/K^+ ratio below 0.8 and increasing seedling emergence to 85% (Kong *et al.* 2016; Zhou *et al.* 2023b). In arid areas, the "dry sowing with delayed emergence irrigation" technique (direct precision seeding into dry soil without pre-sowing irrigation, followed by minimal drip irrigation (5 mm) once optimal soil temperature is reached) increases soil temperature by 2.5°C and reduces seed-zone salt concentration by 40%, boosting germination potential by 30% (Dai *et al.* 2024).

3.2. Population optimization theory: Synergy of dense planting with chemical regulation eliminates manual pruning

Dense planting optimizes population structure within limited space by increasing planting density (e.g., 18,000 plants ha^{-1}). Under high density, canopy base light intensity falls below 300 μmol m^{-2} s^{-1}, activating the shade-avoidance response mediated by phytochrome B (phyB). This suppresses the expression of the gibberellin biosynthesis gene *GA20ox* (65% reduction), consequently decreasing the internode elongation rate by 31% (Li *et al.* 2019). Chemical regulation *via* DPC suppresses auxin biosynthesis gene *GhYUC5* (52% reduced expression) and cytokinin transporter gene *GhIPT3* (48% reduction) in apical meristems, weakening apical dominance and enabling natural termination of fruiting branches (topping rate: 90%) (Dong 2019). The synergistic application of dense planting and chemical regulation optimizes the leaf area index (stabilized at 4.2–4.8), maintains canopy transmittance above 65%, reduces boll shedding to 28%, and facilitates pruning-free management (Nie *et al.* 2021). This synergistic approach of dense planting combined with chemical regulation optimizes the leaf area index (stabilized at 4.2–4.8),

maintains canopy transmittance above 65%, reduces boll shedding to 28%, and thereby eliminates the need for manual pruning (Nie *et al.* 2021). This synergy is a cornerstone of MOICC's labor-saving objective.

3.3. Interaction mechanism of water-nutrient synergy and resource efficiency enhancement

Partial root-zone irrigation (PRI) enhances resource efficiency through heterogeneous water distribution in the root zone. In drip-irrigated cotton under mulch, roots in the dry zone synthesize jasmonoyl-isoleucine (JA-Ile), which is transported *via* the phloem to the wet zone. JA-Ile activates the aquaporin gene *GhPIP2;7* (4.1-fold upregulation), increasing root hydraulic conductance by 1.8-fold (Luo *et al.* 2019). Concurrently, drought stress induces the synthesis of peptide GhCEP1 in the dry zone. Xylem-transported *GhCEP1* upregulates nitrate transporter gene *GhNRT2.1* (3.3-fold increase), enhancing nitrogen uptake efficiency by 25% (Kong *et al.* 2017). This maintains over 90% of the yield potential even under a 20% nitrogen reduction, providing a theoretical basis for water-nutrient synergy and efficiency gains (Xiao *et al.* 2024).

3.4. Theory of synergistic defoliation and boll opening for concentrated maturation

DPC suppresses gibberellin synthesis, shortening the flowering-to-boll opening period by 7 days and achieving a concentrated maturation rate (boll opening within 7 days) of 85% (Dong 2019). The defoliant thidiazuron (TDZ) acts by inhibiting the auxin transporter PIN1 (72% activity reduction) while inducing ethylene synthase ACO (5.2-fold upregulation). This disrupts the hormonal balance in the abscission zone, accelerating abscission layer formation and reducing defoliation time to 48 hours (Li *et al.* 2022). The synergistic application of DPC and TDZ achieves efficient defoliation and promotes concentrated maturity, which is crucial for mechanized harvesting and quality preservation.

3.5. Compensation theory: Stress adaptation and yield stability

Cotton exhibits remarkable plasticity through source-sink rebalancing under stress. It has been demonstrated that targeted removal of early fruits (e.g., 10 basal bolls) under waterlogging stress at early flowering can reduce yield loss by 25% through enhancing compensatory growth and delaying leaf senescence (Zhang Y J *et al.* 2025b). Under high-density planting (e.g., 22,500 plants ha^{-1}), plants compensate by reducing bolls per plant (–25%) but increasing boll weight (+12%), stabilizing population yield (coefficient of variation <10%) (Dai *et al.* 2015; Zhou *et al.* 2023a). This plasticity stems from source–sink feedback regulation: restricted sink strength leads to sucrose accumulation in leaves, activating GhSnRK1 kinase to suppress vegetative growth and promote assimilate partitioning to bolls (Dai *et al.* 2015; Zhou *et al.* 2023b). The inherent yield stability under stress underpins MOICC's multi-objective synergy (Zhou *et al.* 2023b).

Collectively, these mechanisms — ethylene-mediated seedling establishment, jasmonate-enhanced water-nutrient efficiency, hormonal-regulated pruning-free architecture, and stress-induced compensatory growth — constitute the physiological and ecological foundation MOICC. By systematically leveraging these processes, MOICC bridges crop physiology with integrated management strategies, resolving core conflicts among yield, quality, labor efficiency, and sustainability.

4. Key technologies for MOICC

MOICC technologies adhere to the principles of temporal coordination, spatial adaptation, and resource linkage. They achieve efficiency gains through integrated management across sowing regulation, growth management, and harvest optimization. The innovation lies in dismantling technological silos: temporal coordination of drip irrigation under mulch with chemical regulation boosts water and nutrient use efficiency by 25%, while the closed-loop residual plastic film recovery coupled with stalk returning reduces the carbon footprint by 32% (Wu F Q *et al.* 2023; Feng *et al.* 2024).

4.1. Precision seeding and stress-resilient seedling establishment technology

This technology leverages the auxin gradient regulation mechanism (mediated by *GhPIN1a*) governing hypocotyl hook formation through three-dimensional spatial control. Spatial optimization is achieved *via* hill-drop monoseeding with precisely controlled hill spacing of (10±0.5) cm. This method significantly reduces seed distribution variation to a coefficient of variation (CV)≤15% and increases robust seedling emergence by 28% compared to conventional drill seeding methods (Kong *et al.* 2018). Depth control at 2.0–2.5 cm creates optimal soil pressure conditions of approximately 0.2 MPa. This precise depth activates ethylene signaling pathways that promote hypocotyl thickening, enhancing early seedling vigor (Kong *et al.* 2024). For salinity adaptation in Northwest China, the system combines "dry sowing with delayed emergence irrigation" methodology with staged drip irrigation. This involves applying three post-sowing irrigation increments (5 mm+8 mm+10 mm) alongside an optimized drip line layout configuration (63 cm+13 cm). This integrated approach effectively suppresses salt ascent, maintaining root-zone electrical conductivity (EC)≤3.5 dS m^{-1} while simultaneously upregulating the *GhSOS1* gene by 2.1-fold. This genetic response enhances sodium ion (Na^+) efflux capacity by 40%, collectively achieving a reliable emergence rate of 85% under challenging saline conditions (Zhou *et al.* 2023b; Dai *et al.* 2024).

4.2. Dense planting with chemical regulation for pruning-free management

This integrated approach combines canopy light management with hormonal regulation to eliminate the need for manual pruning. It utilizes a high-density planting architecture of 22,500 plants ha^{-1}, arranged in three rows per plastic film with 76 cm row spacing. This configuration compensates for reduced bolls per plant by significantly increasing the number of productive fruiting branches (Dai *et al.* 2015). Chemical regulation synergy is achieved through foliar application of DPC (120 g ha^{-1}) during peak squaring. This treatment

suppresses the gibberellin biosynthesis gene *GA20ox*, reducing its expression by 58%. This hormonal control shortens internode length to (3.8±0.3) cm and achieves a natural (self-topping) rate of 92%, effectively eliminating the need for manual topping (Dong 2019). Furthermore, this system establishes a critical light-fertilizer linkage. When coupled with a strategic 20% nitrogen reduction and implemented in a wide-narrow row arrangement (66 cm+10 cm), it ensures adequate light penetration to the canopy base, maintaining light intensity≥450 μmol m^{-2} s^{-1}. This optimized environment reduces boll shedding to just 25% while simultaneously saving approximately 35 labor-days per hectare normally required for pruning. Importantly, these efficiencies are achieved without sacrificing yield, consistently maintaining production levels≥6,000 kg ha^{-1} (Nie *et al.* 2021; Feng *et al.* 2024).

4.3. Water-nutrient synergy and efficiency enhancement technology

This technology leverages root-zone signaling to optimize water and nutrient delivery. In Northwest China's cotton regions, the alternate partial root-zone drying (APRD) irrigation method is employed. This technique maintains high-water zones at 60% of field capacity and low-water zones at 40%. This controlled stress induces jasmonate signaling, which activates the aquaporin gene *GhPIP2;1* and boosts hydraulic conductance by 2.1-fold (Luo *et al.* 2019). For nitrogen optimization, a basal-to-topdressing nitrogen ratio of 2:8 is used. Controlled-release nitrogen fertilizer is applied at a rate of 180 kg N ha^{-1} during peak boll setting, guided by real-time monitoring to ensure root-zone nitrate-N levels stay below 50 mg kg^{-1}. This strategy achieves a PFPN of 35 kg kg^{-1}, representing a 40% improvement over conventional practices, while also significantly reducing N_2O emissions without compromising yield (Xiao *et al.* 2024; Yu and Yang 2025). In the Yellow River Basin, specifically for late-spring sown cotton, a single application of fast-release fertilizer (15-15-15 N-P_2O_5-K_2O) at early flowering combined with DPC regulation at peak squaring increases boll opening concentration to 80% and achieves 25% water savings (Zhang Y J *et al.* 2025a). Field validations in Xinjiang demonstrate that synergistic water-nutrient management reduces irrigation by 9–14% and nitrogen inputs by 19–22%, while lowering emissions by 26–32% and increasing yields by 10–16%. This is achieved through smart irrigation systems combined with straw returning and nitrification inhibitors, forming a replicable high-yield, low-carbon production paradigm (Li *et al.* 2023).

4.4. Precision defoliation and boll-opening regulation technology

This approach utilizes thermal time models and hormone interactions to achieve precise management. Boll-opening timing is determined by applying thidiazuron (TDZ) at 450 g ha^{-1} once accumulated growing degree days reach 1,400°C d. TDZ inhibits the auxin transporter PIN1 (reducing its activity by 70%), thereby disrupting the hormonal balance in the abscission zone (Li *et al.* 2022). Defoliation synergy is enhanced by adding ethephon at 900 mL ha^{-1}. This combination effectively promotes abscission layer formation, leading to defoliation rates of up to 95% (Dong 2019; Li *et al.* 2022). To ensure fiber quality, defoliants are applied during the fiber development stage when bolls are at least 35 days old. This timing guarantees fiber strength remains ≥31 cN/tex and stabilizes micronaire values at 4.2±0.2 (Dong 2019).

4.5. Synergistic optimization of planting patterns technology

This technology enhances system resilience through strategic species interactions and spatio-temporal configurations. In the Yangtze River Basin's rapeseed–cotton rotation areas, a shift from relay intercropping to direct mechanical seeding of short-season cotton varieties (e.g., CCRI 425) before June 10th, at a density of 90,000 plants ha^{-1}, combined with systematic DPC regulation, achieves a pre-frost boll opening rate of 90% (Lu *et al.* 2017). Intercropping synergy is achieved with wide-strip cotton//peanut planting in a 4:6 ratio. This configuration boosts Proteobacteria abundance by 35% through root interactions, significantly enhancing nitrogen cycling (Chi *et al.* 2023). Furthermore, carbon–nitrogen synergy is realized by utilizing biological nitrogen fixation from legume crops (providing 85 kg N ha^{-1}), which replaces 30% of synthetic fertilizer nitrogen. This reduces the system's nitrogen footprint by 24% and achieves a land equivalent ratio (LER) of 1.38 (Chi *et al.* 2023). Implemented in the Yellow River Basin, this pattern also increases annual soil organic carbon sequestration by 0.35 Mg ha^{-1} (Lv *et al.* 2024).

The MOICC framework integrates temporal, spatial, and resource dimensions — synergizing technologies like precision seeding with root-zone irrigation and defoliation timing — to achieve unprecedented efficiency gains (e.g., 25% water savings, 32% carbon reduction). This integrated technological portfolio operationalizes the physiological principles outlined in Section 3, translating mechanistic understanding into practical multi-objective gains.

5. Implementation and impacts: Regional case studies

The core of MOICC lies in the deep coupling of technological modules rather than their additive application, with its efficacy validated through representative regional case studies. Systemic optimization practices in diverse Chinese agro-ecosystems (e.g., Xinjiang and the Yangtze and Yellow River basins) demonstrate how MOICC simultaneously advances yield, resource efficiency, and environmental goals.

5.1. Xinjiang cotton region: Synergistic evolution of three-generation technology systems

The generational leap in Xinjiang cotton cultivation exemplifies the synergistic logic of "dynamic objective optimization and systematic technology integration". The first-generation (1G) technology utilized plastic mulching for soil warming, rational dense planting (e.g., over 180,000 plants ha^{-1}), and DPC chemical regulation, which collectively enhanced light and thermal resource utilization efficiency, extended the boll-setting period, and increased the pre-frost boll ratio to approximately 85% (Feng *et al.* 2017; Dong

2019). The second-generation (2G) technology integrated drip irrigation systems under mulch with root-zone moisture and nutrient monitoring, enabling precise water and fertilizer regulation. This approach elevated WUE to over 0.75 kg m^{-3} and PFPN to 35 kg kg^{-1}, significantly outperforming traditional methods (Feng *et al.* 2024). The third-generation (3G) technology further deepened integration through precision monoseeding, systemic DPC regulation for topping-free management, and efficient defoliation (e.g., synergistic thidiazuron-ethephon application), reducing the system carbon footprint by 24% and labor input by ~35 labor-day ha^{-1} (Wu *et al.* 2023; Feng *et al.* 2024). This emission reduction approaches the 37% upper limit of global mitigation potential achievable through nitrogen management in cotton fields (Yu and Yang 2025). Nevertheless, climate projections indicate that Xinjiang's cotton production will face escalating trade-offs: despite potential yield gains (+11.6–14.1%), irrigation water requirements and carbon emissions are projected to rise significantly by mid-century (+4.3–5.6% for IWR; +38.5–41.6% for GWP) under SSP245/SSP585 scenarios (Zhou H *et al.* 2025). These findings underscore the urgency of integrating MOICC's water–carbon synergy technologies (e.g., APRD irrigation, biodegradable mulch) to mitigate future environmental costs.

Integrated application of these technologies in the Manas River Basin in Xinjiang increased seed cotton yield to 7,500 kg ha^{-1} and fiber length uniformity to 84.5% while saving 30% water and 15% nitrogen (Fig. 2). Despite these gains, challenges persist, including slowing yield growth rates and residual plastic film pollution exceeding 250 kg ha^{-1} (Feng *et al.* 2024). However, MOICC's integrated residue film recycling (recovery rate≥85%) directly addresses this pollution challenge. Future advancements require deeper integration of intelligent agricultural machinery (e.g., unmanned aerial vehicle (UAV)-based nitrogen diagnosis) with biotechnology, including molecular breeding of salt-tolerance genes like *GhSOS1a* (Zhang P *et al.* 2025). Concurrently, optimizing cotton straw management — particularly conversion to biomass fuel rather than field return or burning — can further reduce the system carbon footprint by enhancing biogenic carbon storage and offsetting fossil energy use (Sun *et al.* 2024). The establishment of a global cotton soil emission database further supports MOICC optimization, identifying soil pH and C/N ratio as key levers to reduce N_2O emission factors (Pan *et al.* 2024; Yu and Yang 2025).

5.2. Yangtze and Yellow River basins: Summer-direct-seeding of early maturing cotton

To address high labor costs in double-cropping systems, direct-seeding of early-maturing cotton (short-season cotton) after rapeseed/wheat harvest in the late spring or early summer can achieve transformation through multiple synergies. Mechanized direct-seeding of early maturing varieties (e.g., CCRI 425) in early June at high densities (≥90,000 plants ha^{-1}), combined with DPC application during peak squaring, shortens the growth period to ≈105 days and ensures a 90% pre-frost boll ratio, eliminating resource-intensive nursery and transplanting stages (Lu *et al.* 2017; Zheng *et al.* 2022). Recent field evidence from the Yangtze River Basin demonstrates that optimizing plant density (e.g., ~12 plants m^{-2}, equivalent to ~120,000 plants ha^{-1}) in wheat–cotton direct seeding systems significantly enhances canopy photosynthetic capacity, improves sink/source ratio, and increases biomass partitioning to reproductive organs, thereby maximizing seed cotton yield under high-density conditions (Chen *et al.* 2025). Resource efficiency is enhanced through seed-fertilizer drilling with controlled-release fertilizers, improving nitrogen use efficiency to 42% while reducing nursery land allocation (Lu *et al.* 2017; Zheng *et al.* 2022). Economically, this model trades modest yield penalties for substantial ecological benefits: in the Yellow River basin, although seed cotton yield is 14.5% lower than in traditional relay cropping, labor costs decrease by 47%, driving a 69.2% increase in net profit (Lu *et al.* 2017). In the Yangtze Basin, mechanization rates rise by ≈60%, pesticide use declines by ≈25%, and comprehensive economic benefits improve by ≈30% (Zheng *et al.* 2022).

5.3. Cotton-legume alternate intercropping system

This model overcomes the obstacles of continuous cropping



Fig. 2 Demonstration fields of multi-objective integrated cotton cultivation (MOICC) in Xinjiang (left) and Shandong (right), China.

through species interactions and annual rotational planting. A 4:6 cotton–peanut wide-strip configuration (5.5 m bandwidth) increases *Bradyrhizobium* abundance in peanut rhizospheres, enabling biological nitrogen fixation to replace 20% of chemical nitrogen inputs without compromising yield (Chi *et al.* 2023). Recent evidence from a six-year cotton–soybean alternate strip intercropping (ASI) system demonstrates that such spatiotemporal diversification can increase cotton and soybean yields by 28 and 21%, respectively, achieving a LER of 1.26 — surpassing traditional intercropping (1.13) — through optimized light, water, and nutrient partitioning (Lv *et al.* 2025). Ridge planting of peanut (~10 cm height) combined with flat cotton planting creates a three-dimensional canopy that optimizes light penetration and enhances system-level light-use efficiency (Chi *et al.* 2023). Annual positional swapping of cotton and legumes also reshapes soil microbiomes, increasing fungal diversity while suppressing pathogens like *Fusarium*, which mitigates soil-borne diseases and reduces insecticide use by 10–20% (Chi *et al.* 2023; Lv *et al.* 2024). Moreover, ASI significantly enhances soil health, increasing soil organic carbon by 21% and arbuscular mycorrhizal fungi colonization by 83–87%, while reducing cumulative N_2O emissions by 18–23% in cotton strips through optimized nitrogen cycling and microbial suppression of denitrification (Lv *et al.* 2025). Demonstrations in the Yellow River basin achieved a LER greater than 1.1 for the entire intercropping system, with seed cotton yield increasing by 22% (reaching 6,300 kg ha^{-1}) and peanut yield maintained at levels comparable to monoculture (Chi *et al.* 2019). The system also enhanced natural pest control through enriched predator insect communities (Chi *et al.* 2023; Lv *et al.* 2023) (Table 3).

5.4. Cross-crop insights: Synergistic optimization in wheat-maize systems

Multi-objective practices in the North China Plain wheat–maize system offer valuable paradigms for MOICC. Crucially, precision nitrogen management (Xiao *et al.* 2024) directly informs MOICC's dynamic resource optimization framework through three key approaches: Spatially gridded resource optimization uses high-resolution soil mapping (~1 km^2) to enable variable nitrogen fertilization: rates increase by 30% in low-fertility zones (soil organic matter<10 g kg^{-1}) but decrease by 40% in high-nitrate zones (>80 mg kg^{-1}), reducing regional nitrogen use by ≈16% while maintaining 97% yield potential (Xiao *et al.* 2024). Temporally coupled water–carbon synergy employs APSIM models to determine irrigation thresholds, such as applying 60 mm when soil moisture falls below 55% during wheat jointing, which improves WUE to 1.8 kg m^{-3}. Full straw returning after maize tasseling further sequesters 0.48 Mg C ha^{-1} annually, offsetting system emissions (Xiao *et al.* 2024). Building upon these resource optimization strategies, the recently proposed flooding-smart adaptation (FSA) framework (Qiu *et al.* 2025) further enhances systemic climate resilience by integrating crop physiological adaptations with agronomic practices, offering a scalable pathway to mitigate economic losses and stabilize productivity in flood-prone regions. Intelligent decision-making integrates algorithms like XGBoost and NSGA-II to dynamically balance yield stability (inter-annual fluctuation<8%), resource efficiency, and carbon mitigation even under future climate scenarios (Xiao *et al.* 2024), thereby synergistically achieving multiple objectives of high yield, quality, and stress resistance.

The cross-crop insights from wheat–maize systems provide actionable strategies to enhance MOICC's core pillars of dynamic trade-off management and systematic technology integration. Precision reclamation of saline soils exemplifies spatial resource optimization — applying targeted gypsum (15 t ha^{-1}) to high-salinity patches (EC>8 dS m^{-1}) improves seedling emergence by 40% (Zhou *et al.* 2023b), directly addressing yield-stability trade-offs in stressed environments like Xinjiang. Boll development thermal time models (≥1,400°C d) enable temporal precision in defoliation, synchronizing boll opening and reducing fiber quality losses by 10.6% in the Yellow River Basin (Dong 2019) — a critical solution for reconciling labor efficiency with quality objectives. The FSA framework (Qiu *et al.* 2025) operationalizes this synergy by advocating phenology-aligned planting calendars to avoid peak flood risks during sensitive stages

Table 3 Regional implementation benefits of multi-objective integrated cotton cultivation (MOICC) across diverse agro-ecosystems in China[1)]

Region	Core challenge	MOICC solution	Key sustainability gains[2)]	Scalability insight
Xinjiang (arid)	High water consumption, plastic pollution, carbon footprint	Drip irrigation under mulch+precision regulation+plastic film recovery	WUE ↑30% (0.75 kg m^{-3}) Plastic recovery rate≥85% Carbon footprint ↓32%	Requires smart water-fertilizer systems and biodegradable mulch adoption
Yangtze Basin (humid)	High labor costs in double-cropping systems	Mechanized direct-seeding of short-season cotton after rapeseed+concentrated maturation	Labor ↓47% Pesticides ↓25% Economic benefit ↑30%	Suitable for smallholder mechanization; needs early-maturing varieties for multi-cropping
Yellow River (saline)	Salinization and poor seedling establishment	Furrow planting for salt avoidance+emergence drip irrigation	Seedling emergence ↑40% *GhSOS1* expression ↑2.1-fold	Saline soil remediation technology exportable to Central Asia/North Africa
Cotton–legume intercrop	Continuous cropping obstacles and high N inputs	Wide-strip intercropping+biological N fixation via rotational planting	Nitrogen reduction 20% Land equivalent ratio (LER)=1.38 Soil pathogens ↓30%	Legume diversity enhances system resilience (SDG 15)

[1)] Region-specific MOICC adaptations and their contributions to sustainable cotton production. Solutions are tailored to agro-ecological challenges, with quantified sustainability gains highlighting scalability potential.
[2)] WUE, water use efficiency. Arrows (↑/↓) denote directional change under MOICC implementation.

and by promoting diversified intercropping systems with complementary flood-tolerance strategies, thereby reducing yield volatility by 18–32%. Intelligent platforms integrating UAV remote sensing (normalized difference vegetation index (NDVI)<0.62 for senescence alerts) and soil sensors operationalize real-time resource circularity, mirroring the water–carbon synergy achieved in wheat–maize systems (Xiao *et al.* 2024).

These regional implementations (primarily in China) demonstrate, for the first time, scalable synergies across yield (↑22%), resource efficiency (WUE ↑≥20%), and sustainability (carbon ↓24–37%), providing a validated proof of concept. The principles are transferable to other major cotton regions (e.g., India, the U.S., and Brazil) by adapting technological modules to local climates, soils, and socio-economic contexts. The integration of the FSA framework (Qiu *et al.* 2025) into MOICC further strengthens its capacity to achieve synergistic high yield, quality, and multi-stress resistance by leveraging physiological and agronomic synergies.

5.5. Challenges and limitations in MOICC implementation

While MOICC demonstrates transformative potential for sustainable cotton production, its broader adoption faces systemic and emerging challenges rooted in historical, technological, and socio-economic contexts.

Historically, cotton research prioritized breeding for yield and fiber quality over agronomic innovations, leading to fragmented environmental management (Zhang Z G *et al.* 2023). This legacy persists in regions like Xinjiang, where high-input practices remain entrenched despite proven ecological risks (Feng *et al.* 2024; Zhou H *et al.* 2025). Shifting focus toward integrated agro-ecological solutions requires overcoming path dependency and reorienting policy incentives (McClelland *et al.* 2025).

Technologically, MOICC lacks mature decision-support frameworks for dynamic multi-objective optimization. Existing models (e.g., APSIM, NSGA-II) exhibit >15% error in simulating intercropping resource competition and fail to fully resolve trade-offs among yield, quality, and emissions (Xiao *et al.* 2024). Crucially, field-validated protocols for synergistic technology integration — such as precision defoliation timing with water-nutrient synergy — remain nascent, limiting scalability beyond pilot regions (Dong 2019; Yu *et al.* 2022).

Integration with digital agriculture is notably underdeveloped. While foundational technologies (e.g., the internet of things (IoT) sensors, UAVs) exist, their deployment in MOICC lags due to high costs, data interoperability issues, and inadequate farmer training (Li *et al.* 2022). Real-time root-zone monitoring and cloud-based decision platforms — essential for optimizing irrigation or nitrogen regimes — are rarely implemented at scale, particularly among smallholders (Li *et al.* 2022; Xiao *et al.* 2024).

Furthermore, significant socio-economic barriers hinder adoption, especially for smallholders. The high initial investment for precision equipment (e.g., drip irrigation systems, seeders) and limited access to digital tools (e.g., UAVs, sensors) in resource-constrained regions are major impediments. While MOICC reduces long-term input costs, the upfront investment can be prohibitive without enabling mechanisms such as government subsidies for smart machinery, the formation of farmer cooperatives, and phased technology introduction.

These challenges are further compounded by: 1) dependence on synthetic growth regulators (e.g., DPC, TDZ), which may disrupt soil microbiomes and require eco-friendly alternatives (Wu *et al.* 2023); 2) inadequate consideration of lifecycle sustainability impacts, particularly manufacturing emissions from inputs like plastic mulch (Zhang Z G *et al.* 2023; Sun *et al.* 2024); 3) the current underrepresentation of integrated pest and disease management (IPM) strategies within the MOICC framework, which is critical for comprehensive sustainability; and 4) limited model robustness under climate uncertainty, potentially exacerbating water–carbon tradeoffs in arid regions (Zhou *et al.* 2025).

Addressing these gaps requires interdisciplinary research on stress-resilient cultivars, affordable digital tools, and policy frameworks that incentivize circular resource use (e.g., subsidies for biodegradable mulch). Concurrently, developing inclusive adoption models — such as subsidized machinery services and farmer co-operatives — is essential to overcome socio-economic barriers. Without resolving these limitations, MOICC's potential for systemic sustainability remains constrained.

6. Conclusion and outlook

MOICC establishes a credible pathway toward carbon neutrality by innovating carbon sink methodologies (e.g., "cotton lifecycle carbon sequestration" patents) and leveraging carbon trading markets. Pilot projects in Xinjiang convert emission reductions into tradeable assets, generating carbon credits from yield-enhancing, low-carbon technologies (e.g., up to 32% reduction in footprint *via* film recycling) (Pan *et al.* 2024). MOICC (or ICC) represents a transformative paradigm with significant potential for sustainable cotton production. Its core innovation lies in achieving synergistic improvements in yield, fiber quality, economic benefit, and ecological sustainability through three pillars: dynamic trade-off management (e.g., optimizing soil moisture thresholds during squaring-flowering), systematic technology integration (e.g., synchronizing dense planting with chemical regulation and water-nutrient synergy), and resource circularity (e.g., cotton stalk recycling sequestering 0.35 Mg C ha^{-1}) (Dong 2019; Feng *et al.* 2024; Lv *et al.* 2024). By building on traditional cultivation successes while integrating ecological principles, MOICC resolves inherent conflicts in conventional systems — notably reconciling high yield with superior quality and environmental stewardship. Regional implementations confirm MOICC elevates yields by 8–22% (Feng *et al.* 2024), enhances resource use efficiency by 25–40%, and reduces carbon footprints by 24% (Chi *et al.* 2023; Wu *et al.* 2023; Feng *et al.* 2024; Zhang Y J *et al.* 2025a), thereby providing a robust foundation for the industry's green transition.

Nevertheless, current MOICC systems require refinement in precision, intelligence, and resilience to abiotic stresses, especially for complex intercropping systems. Emerging research on compound stress interactions, such as the

antagonistic effect of shading on waterlogging damage through canopy cooling, provides crucial mechanistic insights for enhancing system resilience under concurrent stresses (Zhang Y J *et al.* 2025c). Future climate change compounds these challenges: while warming and elevated CO_2 may temporarily enhance cotton yields (e.g., +14.1% in Xinjiang by the 2060s under SSP245), they simultaneously increase irrigation water demand (+4.3–5.6%) and system-level global warming potential (+38.5–41.6%) (Zhou H *et al.* 2025). Three critical bottlenecks persist: 1) insufficient mechanistic understanding of molecular networks governing source–sink coordination and stress compensation (Zhang *et al.* 2022; Zhou *et al.* 2023b); 2) imprecise intelligent decision-support, with >15% error in simulating intercropping resource competition (Xiao *et al.* 2024); and 3) absent industry-chain carbon neutrality pathways, particularly given processing dominates cotton's carbon footprint (62% *vs*. cultivation) (Zhang Z G *et al.* 2023; Yu and Yang 2025). To address these challenges, priority research directions include: Developing intelligent decision systems integrating real-time data and multi-attribute methods (e.g., AHP) for sustainability trade-offs (Werner *et al.* 2014); Optimizing straw-to-nitrogen ratios to maximize soil carbon sequestration under climate variability (Li *et al.* 2025); Advancing industry-chain carbon neutrality via integrated biomass valorization (Sun *et al.* 2024). Recent multi-objective crop rotation models demonstrate synergistic economic-ecological trade-offs (e.g., >60% diversity gains with <5% income loss), providing transferable frameworks for cotton optimization (Pontes *et al.* 2024).

Future research and implementation should prioritize the following interconnected pathways to realize MOICC's full potential:

First, deciphering mechanisms of multi-scale interactions is essential. This involves elucidating hormone signaling (e.g., JA/ethylene-mediated source–sink coordination) and quantifying co-expression networks of key genes (e.g., *GhNRT2.1* for nitrogen uptake; *GhSUT1* for assimilate transport) (Kong *et al.* 2017; Luo *et al.* 2019; Zhang *et al.* 2022).

Second, unraveling G×E×M interactions demands systematic study of how cultivars, climate, soil, and management practices (e.g., row spacing, irrigation, chemical regulation) synergistically affect boll number, weight, and fiber quality (Dong 2019; Nie *et al.* 2021). This knowledge is critical for tailoring region-specific optimization strategies and adapting MOICC principles globally.

Third, elucidating stress adaptation mechanisms requires investigating physiological responses to drought and salinity. Recent studies on compound stress offer new perspectives; for instance, understanding how shading modulates hormonal and transcriptional responses to alleviate waterlogging damage can inform strategies for managing multiple concurrent stresses (Zhang Y J *et al.* 2025c). Physiological threshold models for compensatory growth under combined salt-drought stress (Kong *et al.* 2016; Zhang *et al.* 2022; Dai *et al.* 2024) will ensure stable yield and quality (inter-annual fluctuation≤15%) under adversity (Dai *et al.* 2015; Dong 2019; Zhou *et al.* 2023b).

Fourth, developing and deploying intelligent decision-support systems is crucial. These must integrate multi-source data from remote sensing (e.g., LAI, canopy temperature), in-situ soil sensors (e.g., moisture, EC), and meteorological stations. Building a real-time management platform by fusing APSIM modeling with UAV multispectral imagery (e.g., NDVI<0.62 signaling early senescence) and root-zone sensors (e.g., triggering topdressing at nitrate-N <50 mg kg^{-1}) can establish a real-time management platform (Dong 2019; Xiao *et al.* 2024). Advanced multi-objective optimization algorithms, such as NSGA-II and XGBoost, should be employed to dynamically balance yield (≥90% potential), quality (fiber uniformity>84%), resource efficiency, and emissions (carbon footprint reduction to ≤1.8 kg CO_2-eq kg^{-1} lint) (Wu F Q *et al.* 2023; Feng *et al.* 2024; Xiao *et al.* 2024). Recent advances in multi-objective mixed-integer linear programming (MOMILP) demonstrate their efficacy in resolving economic-ecological trade-offs, such as optimizing crop rotations to achieve >60% increase in crop diversity with <5% net income loss while enhancing land utilization (Pontes *et al.* 2024). Such computational frameworks provide transferable methodologies for MOICC's dynamic trade-off management (Wu *et al.* 2023; Feng *et al.* 2024; Xiao *et al.* 2024). Recent advances in multi-objective mixed-integer linear programming (MOMILP) demonstrate their efficacy in resolving economic-ecological trade-offs, such as optimizing crop rotations to achieve >60% increase in crop diversity with <5% net income loss while enhancing land utilization (Pontes *et al.* 2024). Such frameworks provide transferable methodologies for MOICC's dynamic trade-off management.

Fifth, optimizing the industry-chain carbon footprint requires systemic accounting and mitigation from planting to final product distribution (Zhang Z G *et al.* 2023; Yu and Yang 2025). At the planting stage, key innovations include the application of cotton-stalk biochar (sequestering 2.8 t CO_2-eq ha^{-1}) and the widespread adoption of biodegradable mulch (residual film≤45 kg ha^{-1}) (Wu *et al.* 2023; Feng *et al.* 2024). However, strategies leveraging biological nitrogen fixation (e.g., legume intercropping) require careful long-term monitoring of soil N_2O fluxes, as recent analyses indicate that legume cover crops combined with no-tillage may transition from near-term mitigation to a net source of greenhouse gas emissions in certain regions by the end of the century (McClelland *et al.* 2025). At the processing stage, bio-enzyme refining (40% energy reduction) and carbon capture, utilization, and storage (CCUS) technologies are critical for decarbonizing the downstream value chain.

Finally, establishing synergistic policy frameworks is imperative for broad adoption. These frameworks must incorporate spatially differentiated standards that account for critical local predictors, such as soil nitrogen status and clay content (McClelland *et al.* 2025), alongside tangible incentives. The implementation of regional technical benchmarks (e.g., "Water-Carbon Synergy Technical Regulations" targeting WUE≥0.65 kg m^{-3} and C sequestration ≥0.3 Mg ha^{-1}; Feng *et al.* 2024) should be coupled with robust carbon credit trading mechanisms (50 CNY t^{-1} CO_2-eq) and targeted subsidies for smart machinery (e.g., ≥30% cost coverage; Xiao *et al.* 2024). Creating MOICC-specific carbon credits will further accelerate global scalability. Concurrently,

strengthening "industry–university–research" networks through initiatives like "Science and Technology Backyards" is to shorten technology adoption cycles to 2–3 years.

In summary, this study pioneers MOICC/ICC as a transformative paradigm, establishing for the first time a tripartite framework — dynamic trade-off management, systematic technology integration, and resource circularity — that systemically resolves conflicts intrinsic to conventional cotton production (Fig. 3). By synthesizing cutting-edge multidisciplinary advances, MOICC represents a paradigm shift toward sustainable intensification, moving beyond fragmented approaches to deliver a systemic solution. Through dynamically balancing objectives, integrating synergistic technologies, and optimizing resource cycles, this framework effectively reconciles productivity with environmental stewardship and socio-economic viability. Its successful regional implementation underscores MOICC's potential as a scalable pathway for transforming global cotton production. Realizing this potential requires concerted efforts in refining technologies (particularly chemical input reduction and IPM integration), developing accessible decision tools, implementing supportive policies (e.g., carbon farming incentives, subsidies for smallholders), fostering value chain collaboration, and pursuing continuous climate adaptation. MOICC provides a robust scientific foundation for steering the cotton industry toward a more sustainable and resilient future while offering a replicable model for sustainable intensification in global agriculture — thereby significantly contributing to overarching agricultural sustainability goals.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

Data availability

All data generated or analyzed during this study are included in this published article.

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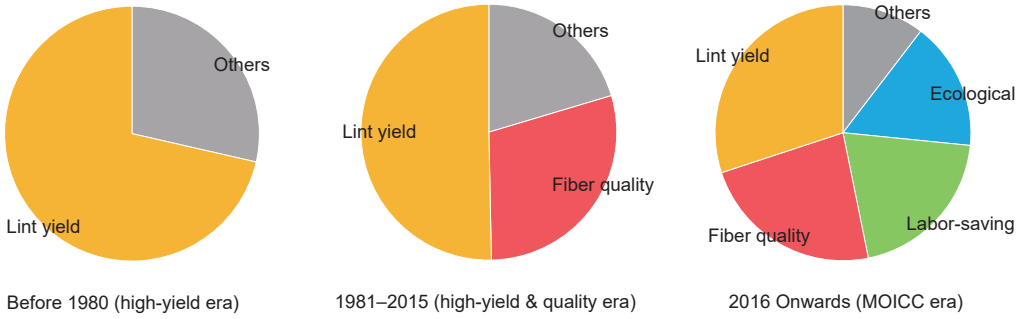


Fig. 3 Evolution of cotton cultivation objectives: From yield maximization towards integrated sustainability goals. Demonstrates progression from singular yield focus to multi-objective optimization, reflecting industry prioritization of sustainability, efficiency, and quality alongside productivity. MOICC, multi-objective integrated cotton cultivation.

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