nsa National Seed Association of India

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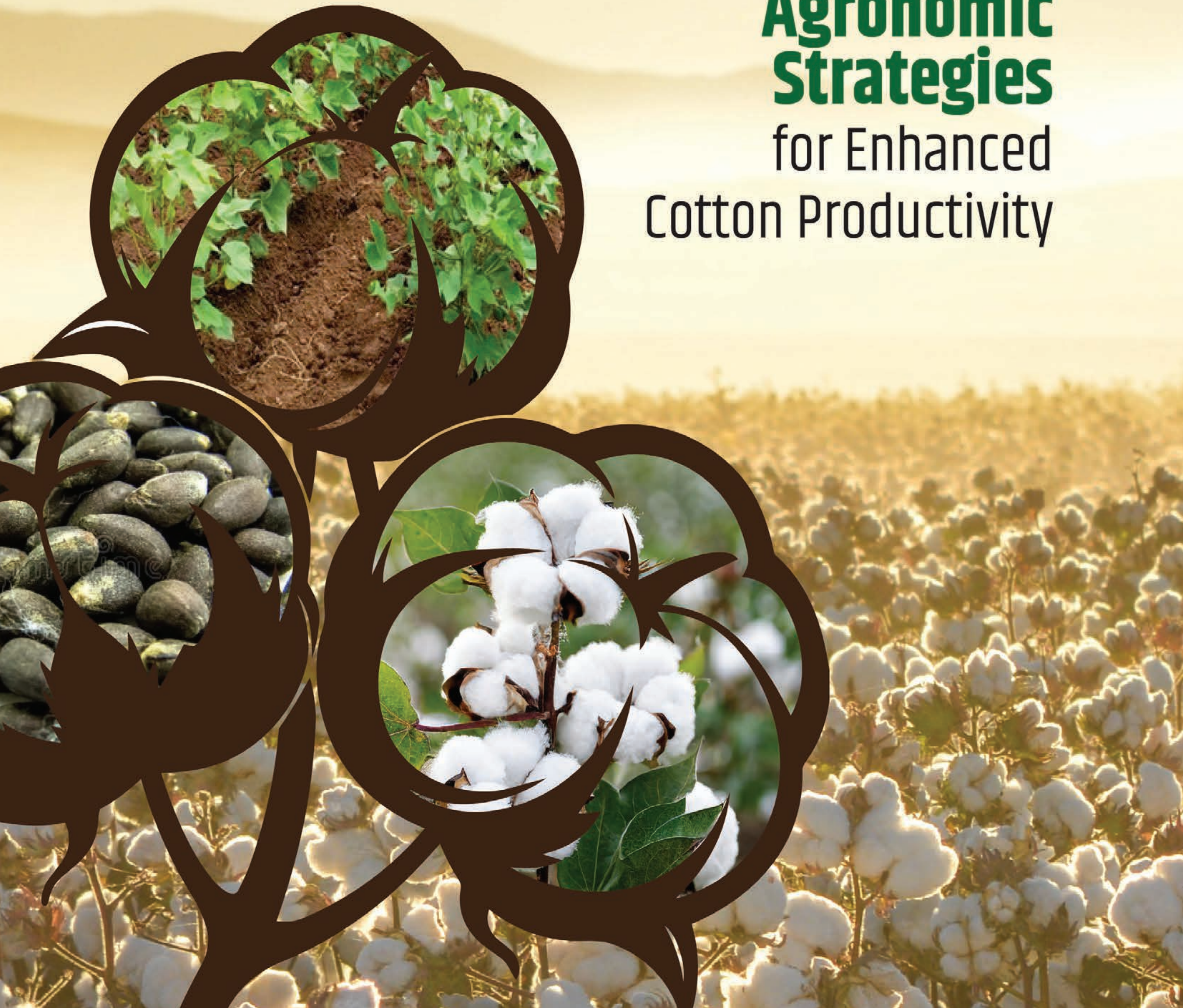
Advances in **Breeding and Agronomic Strategies** for Enhanced Cotton Productivity



ABOUT US

National Seed Association of India (NSAI) is the apex organization representing the Indian seed industry. The vision of NSAI is to create a dynamic, innovative and internationally competitive, research based industry producing high performance, high quality seeds and planting materials which benefit farmers and significantly contribute to the sustainable growth of Indian Agriculture.

The mission of NSAI is to encourage investment in state of the art R&D to bring to the Indian farmer superior genetics and technologies, which are high performing and adapted to a wide range of agro-climatic zones. It actively contributes to the seed industry policy development, with the concerned governments, to ensure that policies and regulations create an enabling environment, including public acceptance, so that the industry is globally competitive.

NSAI promotes harmonization and adoption of best commercial practices in production, processing, quality control and distribution of seeds.

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Message

FROM THE DESK OF PRESIDENT

Among agricultural crops, cotton has gained increasing attention due to the rising demand from the textile industry. However, cotton production in the 21st century faces multiple challenges. Rapid population growth, coupled with the continuous loss of arable land caused by soil erosion, salinization, climate variability, and urbanization, has significantly reduced the cultivable area in the country. Increasing pest/disease and weed problems, climate change challenges, reducing productivity, higher labour cost etc., have been greatly responsible for the declining area of cotton cultivation. This highlights the need to address the emerging challenges and to enhance cotton productivity. This will require focused research initiatives aimed at identifying and overcoming the key constraints limiting yield improvement.

The seed industry plays a critical role in mitigating these challenges by developing high-yielding cotton varieties with improved tolerance to abiotic stresses and enhanced resistance to insect pests and diseases. In addition, the promotion of good agricultural practices and high-density planting systems (HDPS) coupled with mechanization can significantly contribute to improved fiber quality and higher cotton productivity. Introduction and promotion of Kasturi cotton is a major step towards this direction. The seed industry is also expected to assume an even greater responsibility by introducing improved cotton cultivars and ensuring the production and supply of high-quality seeds with superior genetic purity, strong germination capacity, and desirable agronomic traits.

I am happy to see that this edition of "Seed Times" has been brought out on the theme "Advances in Breeding and Agronomic Strategies for Enhanced Cotton Productivity", which is need of the hour. I am sure the readers will have the opportunity to go through quality articles on cotton.

M. Prabhakar Rao

Message

FROM THE DESK OF DIRECTOR (TECHNICAL)

Dear Readers,

The most reputed NSAI quarterly magazine of the seed industry, the Seed Times covers scientific research papers/articles/review articles/information on various aspects related to seed industry. It is widely circulated to all the stakeholders of the seed industry viz., ICAR, SAUs, Central Government Organizations, State Agriculture Departments, Public/ Private Seed Companies etc.

The theme of this Special Issue, 2025 of the Seed Times has been kept as "Advances in Breeding and Agronomic Strategies for Enhanced Cotton Productivity" with the aim to disseminate the knowledge about the emerging approaches towards enhancing the productivity of the Cotton crop shared by eminent scientists and professionals.

Global climate change has emerged as a major constraint to cotton productivity, as the crop is increasingly exposed to a complex interplay of abiotic and biotic stresses that adversely affect yield and fiber quality. These challenges have intensified the need for continuous advances in cotton breeding and the adoption of improved agronomic strategies to sustain and enhance productivity. Significant progress has been made in breeding cotton varieties with improved tolerance to abiotic stresses through molecular breeding and genomics-assisted selection. At the same time, genomic and transgenic approaches have contributed substantially to strengthening resistance against major insect pests and diseases, thereby improving crop stability and reducing production risks. The introduction and large-scale adoption of genetically modified (GM) cotton in major producing countries have transformed global cotton production systems, particularly by reducing dependence on chemical insecticides.

However, the long-term sustainability of GM cotton remains a concern due to the evolving resistance in insect populations and weed biotypes, underscoring the importance of integrated breeding approaches and sound agronomic practices. Alongside public research efforts, private seed companies have assumed a pivotal role by making sustained investments in research and development aimed at enhancing genetic potential, seed quality, and on-farm performance of cotton.

I appreciate the NSAI team for focusing on cotton in this edition of Seed Times, which is need of the hour for the agricultural and economic growth of the country. I am sure this publication will supplement the knowledge and skills of the seed industry personnel in adopting newer seed breeding and production systems to deliver quality seeds to the cotton grower farmers.

I hope the readers will greatly benefit from the magazine.

Wish You all a Happy Reading!

R. K. Tripathi

TABLE OF CONTENTS

Area, Production and Productivity Dynamics of Cotton Cultivation in India

PARDEEP SINGH[1*], SANJEEV KUMAR[2] AND LAXAMI RANI DUBEY[1]
[1]College of Agribusiness Management, Sardarkrushinagar Dantiwada Agricultural University, Sardarkrushinagar, Banaskantha-385 506, Gujarat, India.
[2]Department of Economics and Sociology, Punjab Agricultural University, Ludhiana-141004, Punjab, India

Email: pardeepsingh@sdau.edu.in

Lead Author

DR. PARDEEP SINGH

Assistant Professor (Agricultural Economics), College of Agribusiness Management, Sardarkrushinagar Dantiwada Agricultural University, Gujarat, India

Dr. Pardeep Singh is Assistant Professor (Agricultural Economics) at the College of Agribusiness Management, Sardarkrushinagar Dantiwada Agricultural University (SDAU), Gujarat. He holds a Ph.D. in agricultural economics and has expertise in agricultural sustainability, environmental conservation, and evidence-based policy research. His academic and professional work broadly addresses the challenges posed by climate change to Indian agriculture, with a particular focus on vegetable production systems. His research explores the intersection of climatic vulnerabilities, adaptive strategies, and farm-level decision-making to enhance agricultural resilience and profitability. He has contributed significantly to understanding how environmental and socioeconomic factors influence crop retuins and farm sustainability, especially in the context of hill and mountain agriculture. Through his scientific publications and policy-oriented studies, he advocates for diversified and climate-resilient farming systems, promoting integrated nutrient management and agroecological transitions to support India's long-term food and environmental security.

Abstract

India occupies the largest area under cotton cultivation in the world, yet its productivity remains significantly lower than that of many major cotton-producing countries. This article examines long-term trends in cotton area, production, and yield across major cotton-growing states in India. The analysis reveals that while cotton production has increased substantially over the past four decades, the growth has been driven mainly by productivity gains during the 2000s following the adoption of Bt cotton and improved crop management practices. However, yield growth has slowed in recent years, and large inter-state disparities persist. The states with better irrigation and technological adoption exhibit relatively higher productivity and economic viability, whereas rainfed regions face high production risks, rising costs, and yield instability. The findings highlighted structural, technological, and management constraints that continue to limit productivity gains in Indian cotton. Addressing this, cotton crop requires region-specific technological interventions, diversification beyond Bt cotton, strengthened integrated pest management, and supportive policy measures aimed at improving farm profitability and sustainability.

Keyword: Bt cotton, cost of production, productivity, yield

Introduction

Cotton (*Gossypium* spp.) is one of the most important commercial fibre crops in India and occupies a central position in the country's agrarian economy, industrial development, and rural livelihoods. Cotton, also known as the "White Gold," provides raw material to the textile industry, supports a vast agro-based value chain, and generates substantial employment in farming, processing, marketing, and allied activities. India occupies a dominant position in the global cotton economy in terms of cultivated area, accounting for the largest acreage of 12.35 million hectares during TE 2024, which represents about 39 per cent of the world's total cotton area. This is followed by the United States, China, Pakistan, Brazil, Uzbekistan, and Burkina Faso. Despite this overwhelming dominance in area, India ranks only second in global cotton production, contributing 15.47 million tonnes or 16.90 per cent of world output (FAO, 2025). India ranks as low as 48th globally in cotton productivity, with an average yield of only 1.25 t/ha during TE 2024, far below leading cotton-producing countries. In contrast, countries such as China achieve productivity levels as high as 6.59 t/

ha, followed by Israel, Turkey, Australia, Mexico, Bangladesh, Brazil, Kyrgyzstan, and Nicaragua (FAO, 2025). The persistence of such wide yield differentials highlights that land availability alone does not ensure competitiveness in cotton production. Instead, productivity-enhancing factors such as technology adoption, irrigation, pest management, institutional support, and production efficiency play a decisive role.

The crop is grown across rainfed, irrigated, and semi-arid regions, resulting in substantial regional heterogeneity in yield performance, technology adoption, and exposure to production risk. Over the past few decades, cotton cultivation in India has experienced significant technological transformations, particularly with the introduction of hybrid cotton, the commercialization of Bt cotton, and improvements in agronomic and pest management practices. These interventions led to a sharp rise in cotton production during the 2000s, driven primarily by yield improvements rather than area expansion. However, the initial productivity gains associated with technological change have weakened in recent years. Yield growth has decelerated, and large inter-state disparities in productivity, cost of cultivation, and profitability have persisted or even widened (Rajput et al. 2023). Factors such as pest resistance, especially to Bt cotton, rising incidence of sucking pests, climatic variability, soil fatigue, increasing input costs, and environmental stress have emerged as major constraints to sustaining productivity growth (Venugopalan 2019 and Ashraf et al. 2024). Moreover, the dominance of rainfed cotton cultivation in several major producing states exposes farmers to high yield volatility and income instability, reinforcing the productivity instability at both national and regional levels. These challenges emphasise the importance of systematically examining long-term trends in cotton area, production, and yield, along with an assessment of economic viability across states, which becomes crucial for understanding the causes of India's cotton productivity instability. Identifying regional patterns, yield gaps, and cost inefficiencies is crucial for evaluating the effectiveness of past technological interventions and for designing region-specific strategies that enhance sustainable productivity. In addition, assessing the economic viability of cotton cultivation across states is crucial for determining whether productivity gains translate into improved farm incomes, particularly under conditions of rising cultivation costs and market uncertainty.

In this context, the present study analyses the growth performance of cotton cultivation in India with a specific focus on changes in area, production, and yield across major cotton-growing states. It also evaluates the economic viability of cotton cultivation by examining costs, returns, and breakeven thresholds at the state level. By integrating productivity analysis with economic outcomes, the study seeks to provide policy-relevant insights into the structural constraints shaping India's cotton sector.

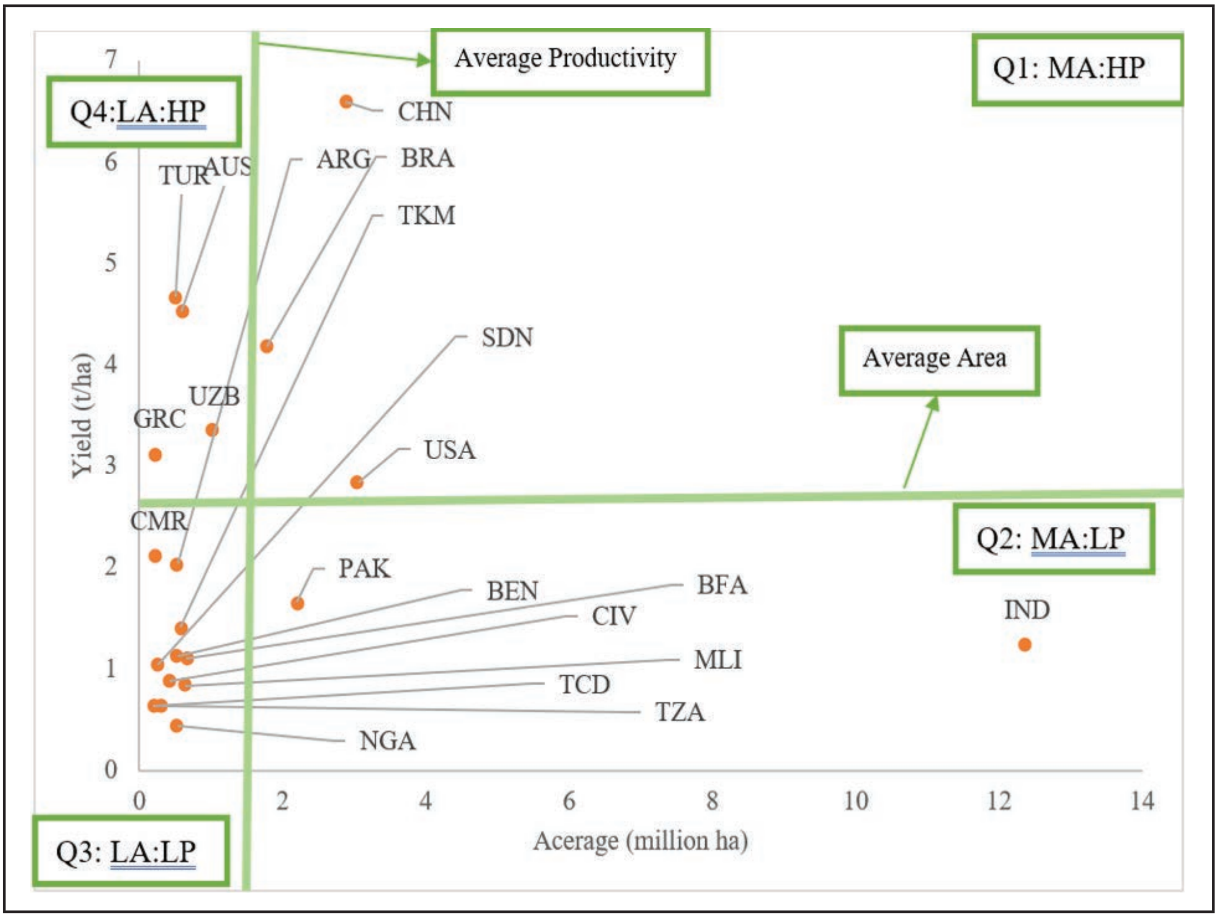
Global Cotton Productivity Scenario: Explanation and Discussion

The global cotton productivity reflects the striking divergence between the extent of area under cotton cultivation and the productivity levels achieved across the top 20 countries that contribute 93.41% area in TE 2024-25. The quadrant classification is based on the average cotton area (1.48 million ha) and average productivity (2.23 t/ha) computed across 20 major cotton-producing countries. The vertical and horizontal reference lines represent these global averages and divide countries into four categories: LA:LP, MA:LP, LA:HP, and MA:HP. Figure I classifies cotton-producing countries into four quadrants and highlights a larger cultivated area does not necessarily have higher productivity.

Countries falling under quadrant-II MA:LP (More Area: Low Productivity), such as India, and Pakistan, account for a substantial share of the global cotton area but exhibit relatively low yields. This is largely attributed to rainfed cultivation, smallholder dominance, sub-optimal input use, pest domiance (notably bollworms and sucking pests) and limited mechanization. In many of these regions, yield gains have stagnated despite expansion in area, emphasizing structural and technological constraints. In contrast, countries categorized as quadrant-4 LA:HP (Lesser Area: High Productivity), including Australia, Turkey, Uzbekistan, and Greece, achieve significantly higher yields with comparatively smaller areas. These countries benefit from advanced seed technologies, efficient irrigation systems, precision farming, integrated pest management (IPM), strong research-extension linkages, and mechanized harvesting. Their experience demonstrates that productivity-led growth, rather than area expansion, is the primary driver of competitiveness in global cotton production.

The quadrant-1 MA:HP (More Area: High Productivity) includes China and Brazil, reflecting an ideal scenario where countries combine extensive cotton area with high productivity. Such cases indicate strong institutional support, favorable agro-climatic conditions, and sustained public and private investment in technology and infrastructure. On the other end, quadrant-3 LA:LP (Lesser Area: Low Productivity) countries such as Burkina Faso, Mali, Turkmenistan, Nigeria, Benin, Argentina, Côte d'Ivoire, United Republic of Tanzania, Sudan, Cameroon, and Chad remain marginal contributors to global cotton output due to both limited area and low productivity. These regions often face agro-climatic stress, resource constraints, and poor access to quality inputs and markets, making cotton a secondary or risky crop choice.

Overall, the study highlights that global cotton production is not constrained by land availability but by productivity differentials. The findings suggest a clear policy implication: shifting focus from area expansion to yield enhancement through region-specific technologies, climate-resilient varieties, improved pest and water management, and stronger extension systems. For major cotton-growing countries trapped in the MA:LP quadrant, addressing this productivity gap is crucial for improving farm incomes, resource-use efficiency, and global cotton competitiveness (FAO, 2025).



Note: LA:LP- Lesser area: Low Productivity; MA:LP- More area: Low Productivity; LA:HP- Lesser area: High Productivity; MA:HP- More area: High Productivity; IND: India; USA: United States of America; CHN: China; PAK: Pakistan; BRA: Brazil; UZB: Uzbekistan; BFA: Burkina Faso; MLI: Mali; AUS: Australia; TKM: Turkmenistan; NGA: Nigeria; BEN: Benin; ARG: Argentina; TUR: Turkey; CIV: Côte d'Ivoire; TZA: United Republic of Tanzania; SDN: Sudan; GRC: Greece; CMR: Cameroon; TCD:Chad.
Source: (FAO, 2025)

Figure 1: Global Productivity Scenario in Cotton Crop

Growth in area, production, and yield of the cotton crop

Over the past four decades, cotton cultivation in India has experienced substantial structural and technological transformations, reflected in significant changes in area, production, and productivity across major cotton-growing states (Table 1). At the all-India level, the area under cotton expanded steadily from approximately 7.9 million hectares in TE 1982/83 to 12.28 million hectares in TE 2024/25, indicating a long-term annual growth rate of 1.49 per cent. This expansion was not uniform across decades: while the 1980s witnessed a marginal decline in area, the 1990s and 2000s recorded strong positive growth, largely driven by the diffusion of Bt cotton and the development of improved hybrids. However, the pace of area expansion moderated after 2010, indicating near saturation of cultivable land and increasing competition from alternative crops.

Table 1: State-wise changes in area, production, and Yield under the cotton crop

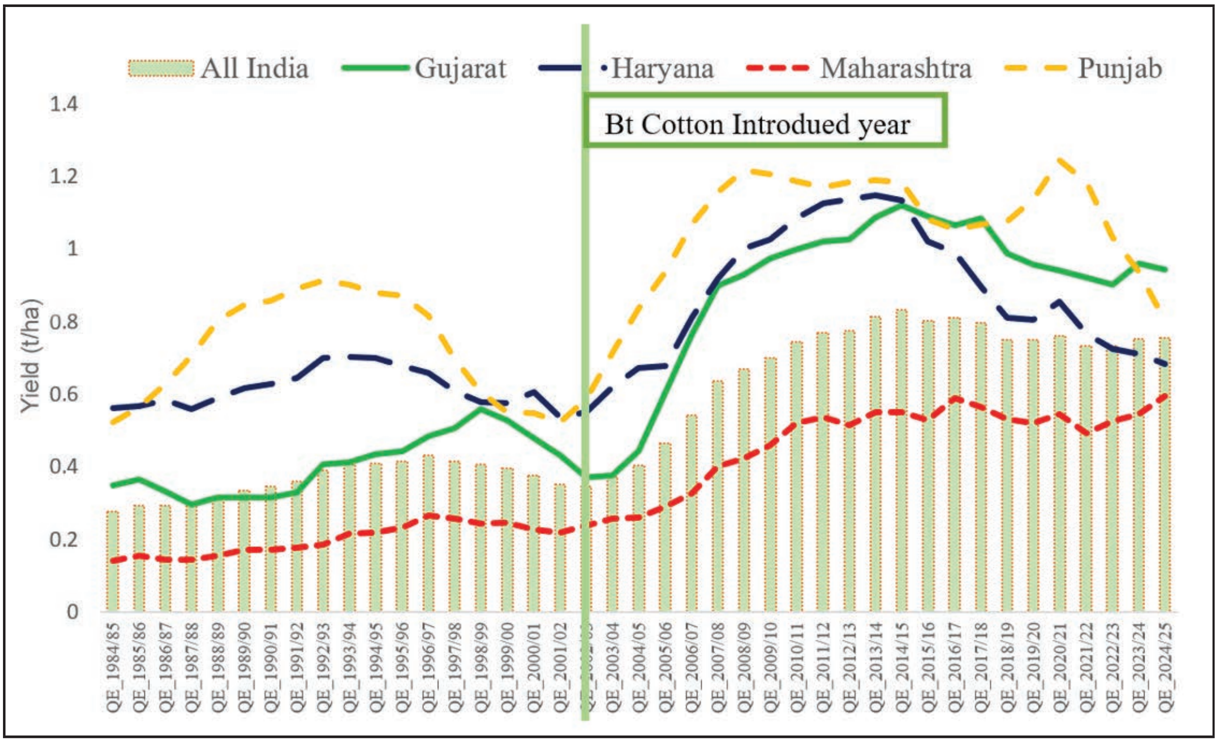
Particulars	TE 1982/83	TE 1990/91	TE 2000/01	TE 2010/11	TE 2024/25	1980/81 to 1989/90	1990/91 to 1999/00	2000/01 to 2009/10	2010/11 to 2024/25	1980/81 to 2024/25
	Acreage ('000 ha)					Area Growth (%)				
All India	7.92	7.49	8.86	10.26	12.28	-1.26	2.71	2.03	0.43	1.49
Andhra Pradesh	0.45	0.64	1.11	1.58	2.38	4.26	6.33	4.29	1.38	4.52
Gujarat	1.53	1.07	1.60	2.48	2.51	-5.09	6.02	5.59	-0.81	2.24
Haryana	0.35	0.46	0.56	0.48	0.52	3.47	2.07	-2.09	-0.29	1.15
Maharashtra	2.67	2.66	3.18	3.53	4.13	-0.33	2.85	1.38	0.33	1.38
Punjab	0.69	0.73	0.50	0.52	0.21	0.50	-2.04	1.31	-7.54	-2.44
	Production (' 000 t)					Production Growth (%)				
All India	2.16	2.89	3.21	7.64	9.33	2.79	2.30	13.61	-0.49	4.39
Andhra Pradesh	0.20	0.25	0.46	1.17	1.89	-1.05	3.85	10.65	1.32	6.55
Gujarat	0.52	0.44	0.69	2.45	2.39	-6.69	10.36	25.84	-2.59	5.78
Haryana	0.21	0.31	0.34	0.53	0.36	4.63	-1.35	8.21	-4.14	2.21
Maharashtra	0.42	0.53	0.72	1.84	2.47	2.86	6.72	13.48	0.63	5.40
Punjab	0.35	0.62	0.26	0.62	0.14	9.54	-11.20	9.08	-10.64	-1.14
	Yield (t/ha)					Yield Growth (%)				
All India	0.27	0.39	0.36	0.74	0.76	4.10	-0.40	11.35	-0.92	2.85
Andhra Pradesh	0.44	0.39	0.41	0.74	0.80	-5.10	-2.33	6.10	-0.06	1.95
Gujarat	0.34	0.41	0.43	0.99	0.95	-1.68	4.09	19.18	-1.79	3.46
Haryana	0.60	0.66	0.61	1.10	0.69	1.12	-3.35	10.52	-3.87	1.05
Maharashtra	0.16	0.20	0.23	0.52	0.60	3.20	3.76	11.94	0.30	3.96
Punjab	0.52	0.85	0.52	1.18	0.69	9.00	-9.35	7.68	-3.35	1.33

Source: GOI, 2026 (a)

State-wise trends reveal divergent regional dynamics. Andhra Pradesh emerged as one of the fastest-growing cotton-producing states, with acreage increasing more than fivefold over the study period and a robust long-term growth rate of 4.52% per annum. Gujarat also experienced a strong revival after a sharp contraction during the 1980s, benefiting significantly from hybrid cotton adoption, improved irrigation access, and supportive market conditions. Maharashtra, traditionally the largest cotton-growing state, showed relatively modest but consistent area growth, reflecting the dominance of rainfed cotton and prevailing agro-climatic constraints. In contrast, Punjab recorded a sharp and sustained decline in cotton acreage, particularly after 2010, with a negative long-term growth rate of –2.44 per cent, largely attributable to rising pest pressure (especially whitefly), high production risks, and a shift towards alternative crops.

Cotton production in India increased dramatically from 2.16 million tonnes in TE 1982/83 to over 9.33 million tonnes in TE 2024/25, registering an annual growth rate of 4.39 per cent. This surge was particularly pronounced during the 2000s, when production growth exceeded 13 per cent per annum, highlighting the transformative impact of technological change. The growth was driven primarily by the adoption of Bt cotton hybrids and improved crop management practices. Institutional support mechanisms, such as the Kisan Credit Card, facilitated timely access to inputs, while regulated market reforms improved price realisation. Andhra Pradesh, Gujarat, and Maharashtra emerged as major contributors to this production boom. Gujarat, in particular, recorded exceptional production growth during the 2000s, reflecting substantial yield gains and better realisation of genetic potential. Conversely, Punjab's cotton production exhibited high volatility and an overall declining trend in the long run, mirroring the contraction in area and persistent yield instability.

Despite only moderate expansion in cultivated area, cotton production in India increased sharply, underscoring the decisive role of productivity growth. National average yield nearly tripled from 0.27 t/ha in TE 1982/83 to 0.76 t/ha in TE 2024/25, growing at an annual rate of 2.85 per cent. Yield growth accelerated markedly during the 2000s, coinciding with the widespread adoption of Bt cotton, the Kisan Credit Card scheme, reforms under the APMC Act, and improved agronomic practices. Gujarat and Maharashtra recorded particularly strong yield gains, transforming from low- to medium-high productivity states. Haryana also achieved high yield levels; however, recent decades have witnessed stagnation and decline due to pest resurgence and environmental stress. Punjab, despite historically high yields, experienced a deterioration in productivity after 2010, raising concerns about the sustainability of intensive cotton production systems.



Source: GOI, 2026 (a)

Figure: II State-wise trends in cotton yield (TE 1984/85–TE 2024/25)

The figure highlights pronounced divergence in yield trajectories across major cotton-growing states, reflecting differences in irrigation access, technological adoption, and production risk. Gujarat stands out as a high-performing state, recording a sharp and sustained rise in cotton yield, particularly during the 2000s, driven by rapid technological adoption, better irrigation coverage, and effective crop management. Maharashtra, despite being predominantly rainfed, also demonstrated notable yield improvements, reflecting gradual technological penetration and improved farmer practices, although its yield levels continue to remain below those of irrigated states. Haryana and Punjab historically exhibited relatively higher cotton yields, attributable to assured irrigation and intensive input use. However, Figure 1 indicates a stagnation and subsequent decline in yields in these states after 2010. This reversal is largely associated with increasing pest incidence-especially whitefly-soil fatigue, rising input costs, and environmental stress. Andhra Pradesh presents a contrasting pattern, with steady yield improvements over time, reinforcing its growing importance as a major cotton-producing state.

Overall, the results indicate that while technological advancements have significantly enhanced cotton productivity at the national level, substantial yield gaps persist across states, pointing to uneven diffusion of technology and region-specific constraints. These disparities suggest considerable scope for improving national cotton output through targeted interventions aimed at stabilizing and enhancing yields in lagging regions, particularly rainfed and stress-prone areas. While the initial decades benefited from acreage expansion in central and southern India, recent growth has relied primarily on yield improvements. However, the deceleration in yield growth after 2010 and the emerging inter-state disparities point to new challenges, including pest resistance, climatic variability, rising input costs, and policy constraints. These trends suggest that sustaining future growth in cotton production will require renewed emphasis on integrated pest management, varietal diversification beyond Bt cotton, region-specific technological interventions, and supportive price and risk-mitigation policies. Overall, the analysis shows that while technological progress has significantly improved cotton productivity at the national level, inter-state disparities in yield and cost efficiency remain pronounced. These differences underline the importance of evaluating productivity gains alongside the cost of cultivation and economic viability, particularly in regions facing rising input costs and yield instability. The following section examines these economic dimensions in detail.

Economic viability of the cotton crop

The results revealed that an assessment of the cost of cultivation and economic viability of cotton across major producing states revealed interstate differences in profitability, cost efficiency, and production risk. Although cotton remains one of the most important commercial crops in India, the findings clearly indicate that its economic performance is far from uniform and is highly dependent on regional production environments. Punjab state emerges as the most economically viable cotton-growing state, despite incurring the highest total cost of cultivation (₹106,421/ha). The superior productivity (22.7 q/ha) and relatively favorable output prices, which together result in the highest gross returns (₹177,465/ha) and a robust net farm income of ₹71,044/ha. The low cost of production per quintal at both total cost and A_2+FL levels further indicates efficient resource use, largely driven by assured irrigation, better input responsiveness, and intensive crop management. This confirms that high-cost cotton systems can remain profitable when supported by high and stable yields.

Table 2: State-wise economic feasibility of cotton crop

Particulars	Andhra Pradesh	Gujarat	Haryana	Maha-rashtra	Punjab
Operational Cost	66141.15	64901.1	53095.9	76303.5	57768.0
Fixed Costs	37570.32	25392.3	24755.4	18406.9	48653.2
Total Cost [11+12]	103711.47	90293.4	77851.4	94710.4	106421.2
Cost A_2+FL	72764.8	66343.4	53951.3	76896.1	63191.2
Value of Main Product (Rs./ha)	117246.78	116909.5	83816.4	86267.0	172643.3
Value of By- Product (Rs./ha)	-	1012.6	3524.4	1022.2	4821.4
Gross Return	117246.8	117922.1	87340.9	87289.1	177464.7
Yield (t/ha)	16.6	15.0	11.4	12.9	22.7
Price (Rs./Qtls)	7060.1	7879.7	7694.9	6777.1	7828.8
Cost of Production at the total cost (Rs./Qtls)	6245.1	6033.5	6858.9	7353.3	4694.8
Cost of Production at A2+FL (Rs./Qtls)	4381.6	4433.1	4753.2	5970.2	2787.7
Farm Business Income	55390.5	65824.4	49815.9	22708.0	127057.7
Family Labour Income	18171.4	40976.2	25860.8	4893.7	79049.4
Net Farm Income	13156.3	27628.7	8063.4	-11673.3	71043.5
Farm Investment Income	50754.4	52476.8	33444.6	10393.0	119051.9
Breakeven Output (Qtls/ha)	12.2	7.2	8.2	21.6	9.2
Breakeven Output (Rs./ha)	86194.0	56474.2	63138.1	146256.8	72134.1
Output Input Ration	1.13	1.31	1.12	0.92	1.67

Source: GOI, 2026(b)

Gujarat state also demonstrates economic feasibility, though under a comparatively lower-cost and medium-productivity system. With total costs of ₹90,293/ha and yields of 15 q/ha, the state achieves a positive net farm income (₹27,629/ha) and an output-input ratio of 1.31. The relatively low breakeven output (7.2 q/ha) suggests lower production risk, making cotton cultivation economically sustainable even under moderate yield fluctuations. This highlights the role of technological adoption and institutional support in enhancing profitability without excessively increasing costs. In contrast, Maharashtra presents a case of economic stress, despite its large share of the national cotton area. The state records high operational costs (₹76,304/ha) combined with moderate yields (12.9 q/ha), resulting in the highest cost of production (₹7,353/q). The extremely high breakeven output (21.6 q/ha) highlights the vulnerability of rainfed cotton systems, where farmers face both yield instability and rising input costs.

Price realization and breakeven thresholds also play a crucial role in shaping the economic outcomes of cotton cultivation. Although market prices remain broadly comparable across states, differences in yield levels significantly influence the cost of production and the breakeven output required to cover costs. Punjab state farmers not receiving the highest price but getting benefits from very high productivity, resulting in the lowest cost of production per quintal and a relatively low breakeven output (9.2 q/ha). This implies that Punjab farmers can recover their cultivation costs even under moderate yield shortfalls, making cotton cultivation relatively less risky. Gujarat, with slightly higher price realization and moderate yields, exhibits the lowest breakeven output (7.2 q/ha), indicating a relatively stable and resilient production system capable of withstanding yield variability. In Haryana, cotton crop have lower yield performance substantially raises its breakeven output requirement (8.2 q/ha), placing cotton cultivation close to the margin of economic viability. Although price realization in Haryana is comparable to other states, the higher cost per unit of output means that even small declines in yield or price can push farmers into losses. Overall, the comparison underscores that price advantages alone are insufficient to ensure profitability; rather, productivity-driven reductions in unit costs and lower breakeven output levels are critical for sustaining farm incomes and reducing production risk in cotton cultivation.

Even minor adverse shocks could render cotton unprofitable, emphasizing the need for careful policy attention. Overall, the results demonstrate that productivity gains at the national level mask significant economic disparities at the state level. While technological progress has improved yields, rising costs and uneven yield realization have constrained profitability, particularly in rainfed regions. The evidence emphasises the need for region-specific interventions aimed at cost reduction, yield stabilization, and risk mitigation to ensure the long-term economic sustainability of cotton cultivation in India.

Conclusion

India has largest acreage under the cotton crop in the world, but yields remain far below global benchmarks, limiting both farmer incomes and national competitiveness. The analysis shows that technological interventions have delivered significant gains in the past, but their impact has weakened over time due to pest resistance, climatic stress, rising input costs, and uneven adoption across regions. Bridging the gap between area and productivity requires a shift from expansion-oriented strategies to productivity- and sustainability-focused interventions. Strengthening integrated pest management, promoting region-specific and climate-resilient varieties, reducing dependence on a narrow technological base, and improving extension and risk-mitigation mechanisms are critical. Equally important is enhancing economic viability through cost-efficient production systems and stable market support. Resolving India's cotton productivity will depend on the ability to combine technological innovation with sound policy and institutional support, ensuring that cotton cultivation remains both productive and profitable for farmers across diverse agro-climatic regions.

Reference

Ashraf, S., Ch, K. M., & Ashraf, I. (2024). Yield Decline and Resistance Development in Sucking Pests of Cotton in the Context of Unwise Spraying Techniques. *Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences*, *61*(2): 133-148.

FAO. (2026). Food and Agriculture Organization, United States.

GOI. (2026a). Directorate of Economics and statistics, Department of Agriculture Cooperations and Farmers Welfare, Ministry of Agriculture and Farmers Wlfare, Government of India. https://desagri.gov.in/statistics-type/five-year-estimates/.

GOI. (2026b). Directorate of Economics and statistics, Department of Agriculture Cooperations and Farmers Welfare, Ministry of Agriculture and Farmers Wlfare, Government of India. https://desagri.gov.in/document-report-category/cost-of-cultivation-production-estimates/

Rajput, A., Raghuwanshi, P. S., & Chaturvedi, P. (2023). Dynamics of area, production and productivity of cotton crop in India. *Current Agriculture Research Journal*, *11*(2): 563-567

Venugopalan, M. V. (2019). Avenues to Improve Farm Income from Cotton under Changing Climatic Scenario. *PKV Research Journal, 43*, 1: 1-8

Mechanisation of Cotton Harvesting in India: Challenges and Way Forward

S. K. SHUKLA[1], V. G. ARUDE[2], A. S. M. RAJA[2*], KIRTI JALGAONKAR[3], SHARMILA PATIL[4]
[1]Director, ICAR-Central Institute for Research on Cotton Technology (CIRCOT), Mumbai;
[2]Principal Scientist, ICAR-CIRCOT, Mumbai;
[3]Senior Scientist, ICAR-CIRCOT, Mumbai;
[4]Scientist, ICAR-CIRCOT, Mumbai

Email: asmraja164751@gmail.com

Lead Author

DR. A S M RAJA

Principal Scientist & Head
Quality Evaluation and Improvement Division
ICAR-Central Institute for Research on Cotton Technology, Adenwala Road, Matunga
Mumbai-400019

Dr. A.S.M. Raja, Ph.D., is Principal Scientist and Head of the Quality Evaluation and Improvement Division at ICAR–Central Institute for Research on Cotton Technology, Mumbai. With over 25 years of research experience, his work encompasses sustainable textile technologies, cotton fibre quality improvement, and medical textiles. He has published 60 papers in reputed journals, holds 4 patents, and has successfully completed more than 20 projects, with 5 currently ongoing. He serves as Principal Investigator for Fibre Quality under the All India Coordinated Research Project on Cotton and as Project Coordinator for the Consortia Research Platform on Natural Fibres, contributing significantly to advancing fibre research and sustainable innovations in the textile sector.

Introduction

Cotton harvesting in India is predominantly carried out manually and remains one of the most expensive operations in cotton cultivation. Hand-picking of cotton is an extremely laborious and tiresome task. A grownup person may pick about 50–60 kg of seed cotton per day (Arude et al., 2024). Over the last 4–5 years, the cost of manual cotton picking in major cotton-growing regions of India has nearly doubled, reaching Rs. 10–12 per kg of raw cotton harvested for the first and second pickings while it is Rs 15-16 per kg of raw cotton for the third and last cotton pickings. The cost of cotton harvesting accounts for about 15% of the total cotton selling price, considering an average cotton selling price of ₹8,000 per quintal. Furthermore, the poor availability of labours during peak harvesting periods, compelling many farmers to shift from cotton to alternative crops such as soybean, maize, and rice, where suitable mechanical harvesting options are readily available. Delays in cotton harvesting due to labour scarcity often result in deterioration of fibre quality, increased field losses, and delayed sowing of the subsequent crops.

The rising cost of manual harvesting has significantly affected the competitiveness of Indian cotton in the global market. Cotton from major exporting countries such as Brazil, Australia, and United States is priced considerably lower than the Indian cotton. Indian cotton prices are approximately 10–20% higher than international prices, making Indian cotton less competitive in the current global market scenario. This anomaly has pushed India into becoming a net importer of cotton in 2024, for the first time in over two decades. Earlier, India primarily imported ELS cotton, as it was not produced in sufficient quantities domestically. Currently, even long-staple cotton, which is abundantly cultivated in India, is being imported in large volumes.

The higher cost of Indian cotton can be attributed to several structural constraints, including low ginning outturn (33–34% compared to 40–42% in major cotton-producing countries), low productivity (approximately 450 kg ha^{-1} against world average of about 740 kg ha^{-1} and nearly 2,000 kg ha^{-1} in leading cotton-producing nations) and high production costs arising largely from labour-intensive operations such as manual picking and weeding. Furthermore, extensive manual handling during harvesting and post-harvest operations leads to higher levels of contamination and increased occurrence of seed coat neps, which adversely affect fibre quality and processing efficiency.

In contrast, countries such as Australia, Brazil, Turkey, United States, China, etc. have achieved higher cotton productivity and improved fibre quality through the widespread adoption of mechanised cotton harvesting systems. The success of mechanisation in these countries is supported by higher plant populations, specialised agronomic practices and the effective use of growth regulators, defoliants, and other crop management chemicals (Heinicke and Grove, 2008). Studies have also demonstrated that mechanised cotton harvesting has considerable potential to enhance productivity and reduce production costs under Indian conditions (Konduru et al., 2013).

In view of escalating labour costs, labour shortages, declining global competitiveness and the demonstrated success of mechanised harvesting in other cotton-producing countries, the mechanisation of cotton harvesting has become a necessity for ensuring the sustainability and profitability of cotton cultivation in India.

Cotton picking mechanism

There are mainly two types of cotton harvesters i.e. picker and stripper harvesters commercially used worldwide. The picker harvesters are designed to selectively remove mature, open bolls using spindles, fingers, or prongs, while minimising damage to plant foliage and avoiding unopened bolls while stripper harvesters remove cotton bolls more aggressively using components such as belts, fingers, combs, steel rolls, or brushes, which strip the cotton along with burrs and plant debris, resulting in comparatively higher levels of foreign matter in the harvested cotton. Typically, machine-picked cotton contains about 10-12% trash, while stripped cotton contains 25-30% trash, compared to only 0.5–1% trash in hand-picked cotton on raw cotton basis. Mechanical cotton pickers require medium plant height i.e. around 1.0-1.2 m with minimum branches and bushes i.e. spreading into 0.5-0.6 m diameter for efficient and viable harvesting of cotton crops. Countries that employ mechanical cotton pickers have developed suitable plant genotypes having required plant physiology amenable for mechanical picking. Cotton varieties with the right plant architecture and height, amenable for mechanical harvesting need to be developed for mechanical pickers to work efficiently and effectively.

Cotton harvesting machines

Over the years, several approaches have been explored to improve the efficiency of cotton harvesting while preserving plant integrity and maintaining fibre quality. The selection of harvesting mechanisms and technologies varies across regions, largely influenced by the type of cotton cultivated and the prevailing agronomic practices. The detail difference (Williford et al., 1994 & Majumdar et al., 2020) in cotton picker and cotton stripper harvesting system is shown in Table 1.

Table 1. Integrated Comparison of Cotton Pickers and Cotton Strippers

Parameter / Feature	Cotton Picker	Cotton Stripper
Basic principle	Picks only fully opened bolls using spindles	Strips both opened and unopened bolls along with plant material
Initial, running & maintenance cost	High	Low
Machine adjustment & setting	Very few adjustments	Many adjustments required
Picking efficiency	85-90%	97-99%
Trash content in seed cotton	10–12%	25–30%
Effect on fibre quality	Non-significant deterioration	Slight deterioration
Plant height suitability	90–120 cm	60–90 cm
Suitability for mechanization level	High-input, commercial farming	Low-input, small & medium farms
Ginning requirement	Normal ginning with standard cleaning	Requires enhanced pre-cleaning in ginning
Overall lint quality	Superior	Moderate
Field loss potential	Low	Higher

Robotic cotton pickers are not yet commonly used in practice, and research on their development is still at a nascent stage. Robotic cotton pickers are generally conceptualized as comprising three main components: a cotton boll detection system, a picking mechanism, and a mobile rover or platform (Thapa et al., 2024).

Adoption of Cotton Harvesting Machines

Cotton harvesting is fully mechanised in countries such as Australia, Brazil, United States, etc. Moreover, substantial mechanisation is also is place in several countries such as Turkey, Uzbekistan, China, Argentina, etc. The commercially available cotton harvesters in these countries are large machines designed primarily for extensive fields. For Indian conditions, where small landholdings predominate, single-row cotton picker were developed by *M/s John Deere* in 2012 represents one of the initial attempts toward mechanical cotton harvesting with the capacity of 0.5 acre per hour and were successfully demonstrated in farmers' fields for 3–4 consecutive years (Fig.1). This machine enabled selective picking of open cotton bolls and demonstrated the technical feasibility of mechanized harvesting in well-managed fields with uniform crop geometry.

Fig. 1. Single-row cotton picker

Recently, M/s Tirth Agro Pvt. Ltd (Shaktiman), Rajkot, Gujarat has developed a 2-row spindle-type cotton picker specifically designed for small Indian farms (Fig. 2). This machine has demonstrated satisfactory field performance, achieving a harvesting capacity of approximately 1 acre per hour while consuming 15 litres of diesel. The manufacturer has also exported these pickers to Turkey, where they are being successfully used for cotton harvesting.

Fig. 2. Two-row cotton picker

In addition, a brush-type cotton stripper was developed in 2017 through collaborative efforts of Mahindra & Mahindra (M&M), ICAR-Central Institute for Cotton Research (CICR), Nagpur and ICAR-Central Institute for Research on Cotton Technology (CIRCOT), Mumbai (Fig. 3). This machine operates on a stripping mechanism with the 2 acre/h of capacity. Since, this machine operated on the stripping principle, it generates about 25-30% trash content in the harvested cotton.

Fig. 3. Brush type cotton stripper

Although cotton harvesters suitable for small farms in Indian conditions have been developed and successfully demonstrated by M/s John Deere, M/s New Holland Tractors and M/s Tirth Agro, the adoption of mechanised cotton harvesting in India remains a distant goal. Research in this area has been ongoing in both private organisations and government institutions for more than two decades. While several issues have been addressed, there are still certain challenges that need to be resolved to make cotton harvesting mechanisation a reality in India.

Challenges in Adoption of Mechanical Cotton Harvesting

1. High Cost of Cotton Seeds for Sowing

In our country, cotton is typically cultivated at wider spacing, requiring about two packets of cottonseed (450 g each) per acre for sowing. However, if cotton is to be harvested mechanically, nearly six packets of seed per acre are required. The primary reason for this threefold increase is that mechanical harvesting demands plants with restricted height and fewer bolls per plant. In order to achieve this plant geometry, a higher plant population is necessary, which in turn requires a larger quantity of cottonseeds for sowing. In India, mostly hybrid cottonseeds are being used through which maintaining plant geometry amenable to mechanical harvesting is difficult. The cost of seed is also a limiting factor for adaptation. In contrast, countries where mechanical cotton harvesting is widely adopted predominantly use varieties rather than hybrids. Hence, there is need to develop and promote cotton varieties for promotion of mechanisation of cotton harvesting in India.

2. Synchronize boll opening

It is normal practice in India to harvest the cotton crops in 3-4 pickings because of occurrence of multiple flowering and fruiting of cotton that lead to development of 3-4 flushes of cotton bolls (Bhagwat, 2014). It is not viable to operate the mechanical harvesters more than once primarily because of high fuel cost and shedding of leaves from plants due to defoliant applications. Hence, there are needs of suitable cotton varieties or methods for achieving more than 95% synchronise boll opening at a time. n countries where mechanical cotton harvesting is practiced, synchronized boll opening is achieved through the use of specially developed varieties and chemical defoliants/maturity regulators. Hence, there is need to work on developing suitable varieties and use of chemicals for achieving the synchronise boll opening. Recently, scientists have reported encouraging success in achieving synchronized boll opening in large-scale trials conducted by ICAR-CICR, Nagpur under the High Density Planting System (HDPS).

3. Defoliation

It is required to artificially shed the cotton leaves using certain chemicals called as defoliants or harvest aids in order to eliminate the main source of stain and trash to enter the cotton while harvesting. Defoliation also helps in improving lint grades, reduces moisture, improves storage of cotton and opens the green and unopened bolls (Leon et al., 2013). There are a number of chemicals used for defoliation of cotton meant for mechanical harvesting (Barber et al., 2013). Drop Ultra® is the most popular defoliant used worldwide; however, this chemical is not manufactured in India. Strong correlation of Drop Ultra® with weather temperature is also a matter of great concern.

Recently, ICAR-CIRCOT in association with a private entity attempted to use Paraquat based desiccant for defoliation of leaves at their experimental fields. It resulted in trash content in the mechanically harvested cotton to the range of 12-15% which is around 50% less than the trash content previously achieved through application of different defoliation chemicals including Drop Ultra®. The result obtained are more or less similar to the trash content found in the countries where mechanical harvesting is successfully operational for several years. This study has shown a major achievement in the bottleneck of mechanisation of cotton harvesting in India.

4. Development and optimization of ginning system for processing of mechanically harvested cotton

Mechanization in cotton harvesting poses various challenges viz. developing varieties amenable for cotton harvesting, development of suitable defoliants and growth regulators, development of appropriate harvester, quality aspects, development and optimization of technology for cleaning and processing of mechanically harvested cotton.

In the last two decades, significant work has been done to address aforesaid issues in public and private sectors. Despite all these efforts, cotton mechanization could not become successful in India. Non-availability of machines and technologies for cleaning and processing of mechanically harvested cotton for Indian conditions is one of the main reasons for its non-adoption. Mechanically harvested cotton contains about 15-20% trash as compared to 2-3% in handpicked cotton. In foreign countries these trashes are removed using a set of pre and post cleaning machinery in order to remove different types of trashes viz. sticks, burrs, bracts, green & dry leaves present in the machine harvested cotton.

To promote cotton mechanization in India, there is need to develop indigenous machines/technology for cleaning and ginning of the machine harvested cotton in order to bring down the trash content from 15-20% to acceptable level in order. Trash components such as sticks, burrs, leaves, limbs, bracts and fines trashes need to be removed from the seed cotton so that the gin stands operate at peak efficiency and without excessive downtime. Seed cotton cleaning is often necessary to obtain optimum grades and market values. The amount of cleaning and extracting machinery required to satisfactorily clean cotton varies with the initial trash content of the seed cotton.

In foreign countries, pre-cleaning machines such as cylinder cleaner, stick machine, saw band cleaner and impact cleaner and post cleaning machines such as cylinder type lint cleaner, air jet lint cleaner and saw type lint cleaner are employed to achieve the desired level of cleaning of machine harvested cotton. The indigenous pre-cleaning and post-cleaning machines working on the similar principle need to be developed. At present, a cylinder-type pre-cleaner and a post-cleaner are used for processing of the handpicked cotton. In contrast, processing of the machine-harvested cotton requires three to four additional specialised pre-cleaning machines based on combing and extracting principles, air-jet cleaners and batt-saw cleaners. These machines are essential to handle the significantly higher trash content in mechanically harvested cotton. These machines need to be optimized for crop and machine parameter to maximize cleaning efficiency, to bring down trash levels and contamination at par with international level of 1 to 2% and to preserve the fibre quality.

The machine harvested cotton contains high moisture to the tune of 12-15%. Hence, drying of the seed cotton to moisture level of 6% before its cleaning is very much required to obtain its efficient cleaning. The tower dryer technology is primarily used for drying of seed cotton before pre-cleaning. Therefore, indigenous technology of development of tower dryer needs to be developed and optimized for Indian cotton. The optimum moisture content of around 8% is required during ginning as well as bale pressing in order to obtain highest ginning efficiency and to maintain fibre quality and bale weight during pressing. Hence online humidification system needs to be developed and optimized for Indian conditions.

In India; Double Roller (DR) ginning technology is used for ginning of entire handpicked cotton. Suitability of DR gin needs to be assessed for ginning of mechanically harvested cotton. Worldwide saw ginning technology is used for ginning of the mechanically harvested cotton, possibility of shifting to saw ginning and rotary knife ginning technology need to be explored. Moreover, the process protocol for cleaning and ginning of machine harvested cotton need to be established for Indian cotton to bring trash content to acceptable level. Research on development of indigenous machinery and technology for pre-cleaning, drying and humidification, ginning and post-cleaning for machine harvested cotton under Indian conditions would bring instil confidence among stakeholders for adoption of this mechanization of cotton harvesting. The recommended machinery for appropriate processing of the mechanically harvested cotton is given in Fig. 4.

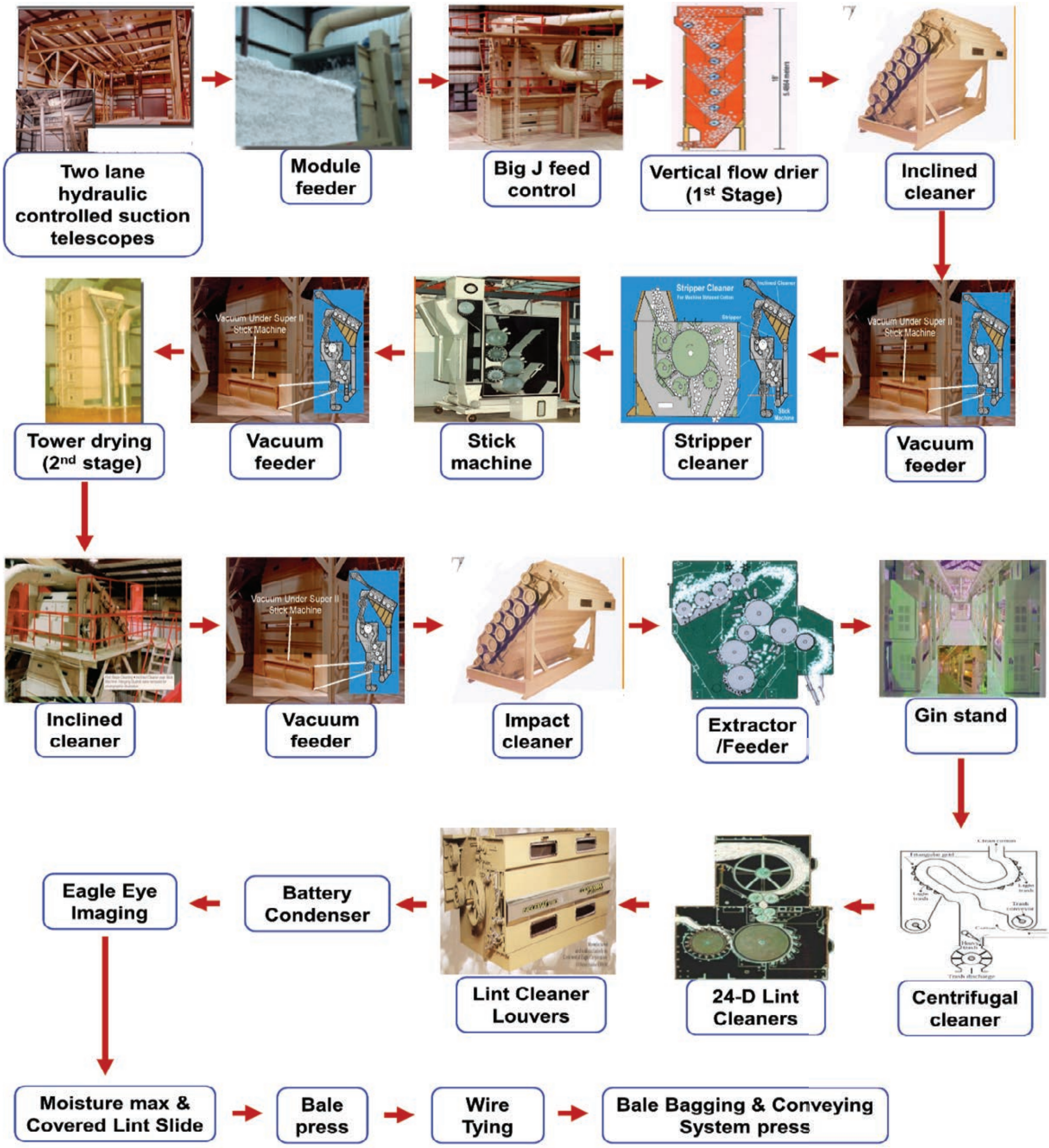


Fig. 4. Recommended machinery for processing of mechanically harvested cotton

5. Increased cost of Investment for Ginning Factories

In order to accommodate the additional pre-cleaning and post-cleaning machinery needed for removal of the high trash content present in the mechanically harvested cotton, the establishment cost of ginning factories may increase by 40–45%, rising from Rs. 7–8 crore to Rs. 10–11 crore for 10-12 bales/h capacity. Globally, ginners have been reluctant to promote mechanical cotton harvesting, as it not only increases their capital investment but also requires them to handle 5–10 times more trash compared to handpicked cotton. Additional cleaning machinery is installed only when ginners have no alternative but to process mechanically harvested cotton.

Way Forward for Successful Adoption of Mechanical Cotton Harvesting in India

For the successful adoption of mechanical cotton harvesting in India, cotton productivity needs to be considerably enhanced so as to offset the additional costs incurred on the application of defoliants, growth regulators, boll openers, additional cleaning systems, and increased maintenance requirements. Along with productivity enhancement, there is a need to develop suitable cotton varieties that are amenable to mechanical harvesting in order to reduce the cost of sowing and make the technology affordable for Indian farmers.

Improving boll opening percentage is another critical requirement, which can be achieved through genetic improvement or the application of suitable chemicals, thereby reducing field losses during mechanical harvesting. In addition, significant research efforts are required to optimise defoliant application practices to minimise the amount of foreign matter harvested along with seed cotton.

In addition to field-level interventions, the ginning process plays a crucial role in the successful adoption of mechanical cotton harvesting. Mechanically harvested cotton generally contains higher levels of trashes. Upgrading ginning unit with advanced pre-cleaning, drying, post-cleaning equipment is essential for viable ginning of the mechanically harvested cotton. There is strong need of hour to indigenously develop and optimise the sets of pre-cleaning, post cleaning and allied machinery required for the ginning of the mechanically harvested cotton. Moreover, there is need to demonstrate the successful ginning operation to the stakeholders in few ginneries across the India by providing substantial financial grants to the ginneries.

To achieve the goal of mechanised cotton harvesting in India and enhance the global competitiveness of Indian cotton in terms of productivity, fibre quality and cost of production, strong governmental support is indispensable. Such support can be effectively channelled through the recently launched Cotton Productivity Mission of the Government of India.

References:

Arude V. G., Shukla S. K., Deshmukh P. S., Satankar V., Potdar R. R., Pandirwar A. P., Senthilkumar T., Ramkrushna G. I., Majumdar G., Raja R. 2024. Validation of field performance of commercial hand hald mechanical cotton picker at Nagpur region for assessing its effectiveness for small holder farmers. Journal of Cotton Research Development, 38(2):243-251.

Barber, L. T., Hayes, R. M., Dodds D. M. and Reynolds D. B. 2013. Mid-South cotton defoliation guide. In Mid-South cotton defoliation guide, 3-10: University of Arkansas, Cooperative Extension Service Printing Services, United States Department of Agriculture.

Bhagwat, R. 2014. Cotton survived excess rains, thrived on late rains. In Cotton survived excess rains, thrived on late rains, Times of India, April 29, 2014. Nagpur: Times of India, April 29, 2014.

Heinicke, C. and Grove W. A. 2008. Machinery has completely taken over: the diffusion of the mechanical cotton picker, 1949–1964. Journal of Interdisciplinary History xxxix: 65-96.

Konduru, S., Yamazaki F. and Paggi M. 2013. A study of mechanization of cotton harvesting in india and its implications. Journal of Agricultural Science and Technology: 9.

Leon, R. G., Wright D. L. and Brecke B. J. 2013 Cotton defoliation and harvest aid guide. In 2013 Cotton defoliation and harvest aid guide: IFAS Extension, University of Florida, United States of America.

Majumdar G., Singh S. B., Shukla S. K. 2020. Seed production, harvesting, and ginning of cotton. Cotton production, 2020 by John Wiley & Sons Ltd, in: Khawar Jabran and Bhagirath Singh Chauhan, first ed., John Wiley & Sons Ltd, pp. 145–174.

Mishra P. K., Sharma, A., Prakash, A. 2023. Current research and development in cotton harvesters: A review with application to Indian cotton production systems. Heliyon, 9:e16124.

Thapa, S., Rains, G. C., Porter, V. M., Lu, G., Wang, X., Mwitta, C., Virk, S. S. 2024. Robotic multi-boll cotton harvester system integration and performance evaluation. MDPI AgriEngineering, 6:803-822.

Williford J. R., Brashears A. D., Barker G. L. 1994. Cotton production, harvesting, and storage. Cotton ginners handbook, rev. U.S. Department of agriculture, Agricu. andbook 503:11–15pp.

Seed Quality Assurance in Cotton: Challenges and Opportunities

DEBASHIS PAUL[1*], V SANTHY[2] AND PRATIK DHAKADE[3]
[1,2,3]ICAR-Central Institute for Cotton Research, Nagpur, Maharashtra, India

Email: deba.13.paul@gmail.com

Lead Author

DR. DEBASHIS PAUL

Scientist (Seed Science and Technology)
ICAR-Central Institute for Cotton Research, Nagpur, Maharashtra, India

Dr. Debashis Paul, Scientist (Seed Science and Technology), is currently affiliated with the ICAR-Central Institute for Cotton Research, Nagpur, India. Dr. Paul possesses interest in Seed Technology, Seed Production, Plant Physiology and Crop Improvement. His core research areas include seed dormancy, seed deterioration and storage, with a strong focus on assessing seed quality through emerging technologies like Artificial Intelligence and Machine Learning. He is also actively involved in seed priming, DUS testing and studying the impact of climate change on seed quality. His work has contributed significantly to agricultural science, evidenced more than 50 publications and over 250 citations on his research profile.

Abstract

Cotton is an important cash crop, cultivated globally for its natural fibre and valuable by-products like oil and livestock meal. The fundamental requirement of a successful crop is high-quality seed; production of quality seed is a multidimensional process with numerous challenges. This article explores the hurdles and opportunities in meeting quality cotton seed. The biological nature of the plant such as its indeterminate fruiting habit itself is a major challenge, which causes seeds to mature at different rates. Adverse weather and a wide range of pests and diseases also affect seed quality. The seed production and processing face significant challenges such as maintenance of genetic purity improper post-harvest handling, and inadequate storage are significant. There is also lack of accurate vigour testing methods commonly followed in cotton. Cotton being the only transgenic crop cultivated in India, supply of spurious seeds with non-approved transgenic events are also rampant in open market. However, technological innovations can be adapted to overcome these challenges which are discussed in the article. Advanced tools such as deep learning, hyperspectral imaging, and micro-CT can provide rapid, non-destructive seed quality assessments. Seed enhancements techniques including priming and coating can improve germination and provide early protection. IoT and blockchain technology can create transparent supply chains to combat the sale of fake seeds. This approach is more effective when supported by stronger regulatory frameworks, targeted farmer education on proper post-harvest practices and quality indicators. In essence, a strong focus on producing genetically pure, physically sound, and physiologically vigorous seeds is fundamental to achieving sustainable cotton production.

Keywords: *Cotton, Hyperspectral Imaging, Seed Quality, Seed certification, Vigour assessment*

Introduction

Cotton is a unique cash crop producing not only natural fibre but also cooking oil, medicinal compounds and meal for livestock (Abdurakhmonov 2013). It is grown in tropical and sub-tropical regions of more than 80 countries. India stands 1st in the world in cotton acreage with 12.07-million-hectare area under cotton cultivation. India is one of the leading cotton producers, with an annual output exceeding 6 million tonnes (Chauhan et al., 2023). Among the four cultivated species of cotton, two (*Gossypium arboreum* and *G. herbaceum*) are diploids and two (*G. hirsutum* and *G. barbadense*) are tetraploids. India is the only country where all the cultivated species and some of their hybrid combinations are commercially grown. A strong foundation in cotton cultivation begins with high-quality seed, which is a primary determinant of yield and profitability. Seed quality assurance in cotton is a process that encompasses every stage, from breeding, production and protection to post-harvest handling and distribution (Paul et al., 2025). This article discusses key challenges and opportunities in ensuring cotton seed quality, focusing the critical role of technology, regulation and farmer awareness.

Challenges in Cotton Seed Quality Assurance

Biological and Environmental Factors

Indeterminate Fruiting behaviour: Ensuring the quality of cotton seed is fraught with challenges, many of which are inherent to the crop's biology and the environmental conditions. Cotton plants have a long, indeterminate fruiting period, which means bolls mature at different times on the same plant. The time of harvesting (picking) is a crucial factor determining the yield, fibre quality and seed quality parameters *viz.* seed vigour, viability and storability in field crops (Gwathmey et al. 2016). This leads to a wide variation in seed maturity at harvest, with immature seeds being weaker and more susceptible to damage.

Prevailing weather conditions: Cotton's open bolls are highly vulnerable to adverse weather, especially rainfall during harvest. Excess moisture, high humidity, and high temperatures can accelerate seed deterioration in the field, leading to a lipid peroxidation, a key indicator of seed quality decline (Deho et al. 2012). Earlier studies reported seed quality parameters are affected by the pre harvest climatic factors (Kumari et al., 2024). The negative effect of high temperature on seed quality was also reported in field pea, soybean and cotton crops (Maity et al., 2023).

Pests and Diseases: Seed-borne pathogens and pests, such as bollworms and fungi, can directly infect seeds; reducing their viability and serving as a source of disease for the next crop cycle. Inadequate pest management during the seed production phase is a significant threat in quality seed production. (Kumar et al., 2025) observed the formation of 'double seeds' in hibernating pink bollworm which resulted in loss of seed germination in cotton seeds. (Gade et al., 2021) also mentioned about the initial seedling blight and wilting caused due to *Rhizactonia* and *Phytophtohra* in soybean.

Production and Processing Issues

Genetic Purity: Maintaining genetic purity is very important, especially for hybrid cotton. Cross-pollination, inadequate isolation distances between fields, and mechanical mixing during ginning and processing may deteriorate the genetic integrity of the seed. Maintenance breeding has emerged as a specialized branch of plant breeding dedicated for preserving the genetic and physical purity of these varieties, ensuring sustained productivity and quality in cotton cultivation. Seed multiplication with low genetic purity will lead to loss of genetic identity and seed quality. The schematic representation of genetic purity maintenance is provided in figure 1.

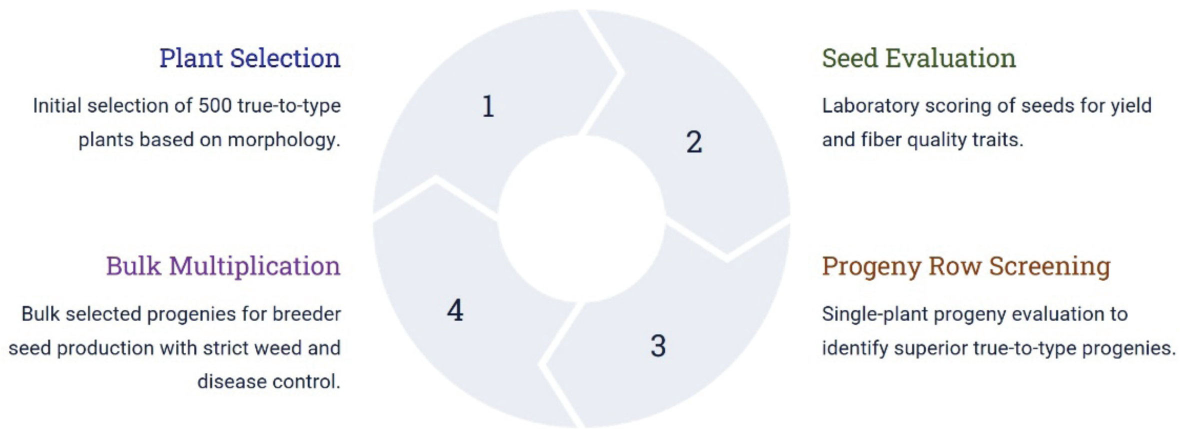


Figure1: The schematic representation of genetic purity maintenance

Post-Harvest Handling and Seed processing: Improper handling after harvest is a major cause of quality loss. Cotton must be dried to an appropriate moisture content (12% or less) before ginning and storage. Seed damage can also occur during ginning if the machinery is not properly adjusted. Seed processing is another integral part of seed quality assurance. Proper processing may increase the germination by more than 20% in cotton depending on initial seed quality. The higher good seed recovery was achieved through specific gravity separator was also reported in castor (Chandraprakash et al., 2019).

Storage Conditions: Storing cotton seed, particularly on-farm storage, is a significant challenge. Uncontrolled environments with high temperature and humidity, as well as exposure to storage pests, lead to deterioration of seed viability and vigour. The primary regulator of all the activities during storage is relative humidity (RH), which serves as a crucial element in preserving viability. Maintaining dry conditions reduces the metabolic rate of the seed. Changes in storage conditions leads to alteration of ROS oxidation and lipid peroxidation, which also determine the rate of ageing and shelf life of seed (Pirredda et al., 2023).

Regulatory and Market Challenges

Seed Standards and Seed Certification: The improper enforcement and adoption of seed certification standards may also result in poor seed quality assurance. In some areas, a lack of awareness or a reliance on uncertified seed sources from private growers can undermine quality control. In India, *Bt* cotton presently occupies more than 95% of the total cotton cultivated area; recommended with the planting of structured refuge of the same non-*Bt* cotton hybrid iso-line at the periphery of the *Bt* cotton field. Structured refuge compliance is lacking due to farmers' lack of understanding of its significance, along with other challenges like non-isogenic 'refugia' seeds and asynchronous agronomy between main and refuge crops. To tackle the situation the government introduced 'Refugia in Bag', which mandates 5–10% non-*Bt* seeds blended with 90–95% *Bt* seeds in every BG-II hybrid seed packet being sold in the market from June 2020. However, farmers concern about improper seed proportions led to qualitative ELISA testing of 180 seeds (Santhy et al., 2024), revealing that some of evaluated hybrids did not adhere to recommended 'refugia' proportions, which may be due to improper dispensing and blending methods during seed packaging. The study emphasizes the need for standardizing blending procedures to ensure adherence to 'Refugia in Bag' standards for all stakeholders (Paul et al., 2024a).

Spurious Seeds: The prevalence of counterfeit and poor-quality seeds in the market poses a major risk to farmers. These seeds often fail to meet germination and genetic purity standards, leading to poor crop stand, reduced yields, and significant financial losses. After the GoI approval for transgenic cotton cultivation, the sale of impure Bt cotton seeds was so rampant that illegal seed trade would only have caused cotton yield loss of Rs. 250 crores each year (Kranti 2013). ICAR-CICR played a significant role in restricting the sale of spurious seed packets through the rapid *Bt* detection kits it developed as well as functioning truly as a referral laboratory for disputed *Bt* seed testing in cotton. ICAR-CICR, Nagpur by being a referral laboratory for testing *Bt* seeds under dispute has played an important role in controlling the marketing of such seeds. Federation of Seed Industry of India (FSII) and National Seed Association of India (NSAI) have highlighted the sudden surge in cultivation of illegal HTBT Cotton since 2021 especially in major cotton growing states such as Maharashtra, Gujarat, Andhra Pradesh and Telangana. Since these are sold illegally without any Govt regulatory approval, there is no accountability on the quality of the seed being supplied to farmers (Global Agriculture 2021; https://www.global-agriculture.com/agriculture-industry/disastrous-consequences-of-surge-in-cultivation-of-illegal-htbt-cotton-fsii-nsai-write-to-goi-to-take-immediate-action/).

Limited Vigour testing procedures: Standard germination tests, while required by law in many places, are often conducted under ideal conditions and may not accurately predict field emergence, especially in harsh environments. Though the vigour tests like Accelerated Ageing, Controlled deterioration was recommended by 'International seed testing Association' (ISTA) for Soybean and Mustard crops but still not optimized for other important field crops (https://www.seedtest.org/).

Opportunities for Improving Seed Quality Assurance

The challenges facing cotton seed quality assurance can be addressed with technological innovations, enhanced regulatory frameworks and improved farmer education.

Technological Advancements

Advanced Seed Testing: New technologies are making seed quality assessment more accurate and efficient (Hegde et al., 2025). Deep learning models, for instance, can analyse seed images to detect defects and predict quality with high accuracy and speed. (Zhao et al., 2021) reported the real-time classification of soybean seeds based on deep learning methods can achieve high-precision and low-cost application, with a total sorting accuracy of 98.87%. Similarly, machine learning models could achieve a prediction accuracy of seed germination testing approximately 97.9%, 94.2% and 94.3% for *Zea mays*, *Secale cereale* and *Pennisetum glaucum* respectively, as observed by (Genze et al., 2020).

Seed enhancements and priming treatments: Seed priming and seed coating are powerful techniques to boost seed performance. Priming involves controlled hydration of seeds to kickstart metabolic processes, leading to faster and more uniform germination. Seed coatings can deliver fungicides, insecticides, and micronutrients directly to the seed, protecting it from early-season pests and diseases and ensuring a healthy start. During the process of priming, different sub cellular changes occur like biochemical, molecular and physiological changes during germination. This is due to the slow imbibition of water by seeds, but ceases the water uptake before radicle protrusion. (Varier et al. 2010) has noted that several proteins like globulin, cruciferin are only detected during priming. Moreover, green nano priming, chitosan based biopriming epitomizes the synergistic integration of cutting-edge nanotechnology with nature's wisdom, transcending applications in crop enhancement to encompass green nano-pesticides, nutrient solubilization and quality optimization (Aggarwal et al., 2025).

Micro-CT (micro-computed tomography) and High throughput imaging technology: At present, all the seed quality assessment protocols are destructive, time consuming and labour intensive. There is need to develop protocols which are quick, accurate and non-destructive for timely supply of quality seeds. Reports suggest that developed countries such as USA and China use imaging and machine learning technologies for genetic purity and storability assessment in several crop seeds i.e. rice, soybean and groundnut. Micro-CT, a non-destructive, three-dimensional (3D) imaging technique that uses x-ray to produce high-resolution images of small objects or biological samples. High-resolution micro-CT technology allows for the three-dimensional analysis of seed morphology, revealing internal structures and providing new, quantitative metrics for evaluating seed quality that were previously impossible to measure (Li et al., 2023).

Hyperspectral imaging (HSI) offers a non-destructive and rapid method for assessing genetic purity by capturing detailed spectral information. By analysing the unique spectral signatures, HSI enables precise identification of genetic variations, making it a powerful tool for ensuring seed purity (Figure 2). Hyperspectral Imaging (HIS) can determine the chemical composition of seeds. In watermelon and maize, this technology was used for seed vigour assessment (Yasmin et al., 2022, Bai et al., 2020). The unique spectral signatures of different seed varieties of millets were used for seed level genetic purity testing (Ekramirad et al., 2024). Wang et al., (2023) predicted seed germination and vigour using Hyperspectral Imaging Information in sugar beet.

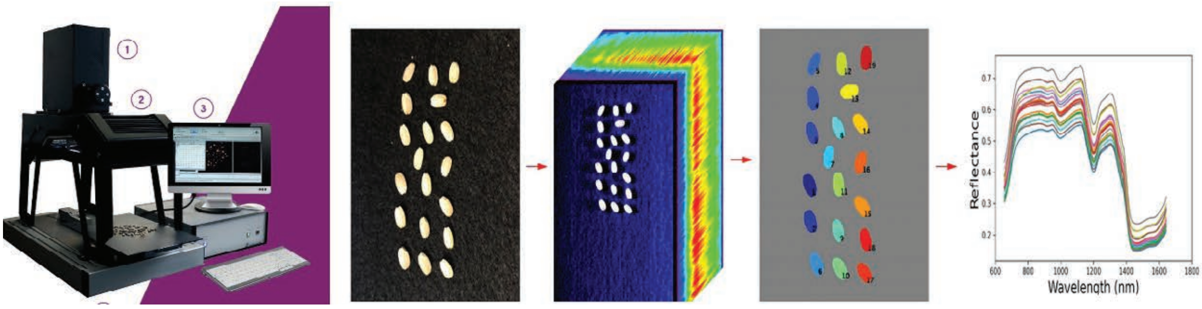


Figure 2: Flow chart representing seed quality assessment through Hyperspectral Imaging

IoT and Digital Platforms: The use of Internet of Things (IoT) sensors and digital platforms can monitor and control storage conditions (temperature and humidity) in real-time, preventing the deterioration of stored seeds. Blockchain technology provides a potential solution for creating a secure, transparent, and traceable supply chain, from the breeder to the farmer, to combat the sale of counterfeit seeds. Blockchain also offers a strong foundation for traceability by guaranteeing the validity and integrity of product-related data, from seed sources to end consumers. (Paul et al., 2024b) reported successful implementation possibilities for seed quality assurance through block chain enabled seed traceability system.

Policy and Regulatory Interventions

Strengthened Certification and Inspection: Robust seed certification programs with mandatory field and laboratory inspections are also important for assuring seed quality. This includes enforcing stricter standards for isolation distances and genetic purity for the crops in concern.

Promoting Use of Certified Seeds: Public-private partnerships and government schemes can encourage the use of certified seeds by providing subsidies or incentives. Educational campaigns can also help farmers understand the long-term economic benefits of planting quality seed.

Conclusion

The journey of a cotton seed from the breeder's plot to the farmer's field is a complex pathway, with numerous points where its quality can be compromised. The challenges are significant, ranging from environmental vulnerabilities and biological complexities to systemic issues like regulatory gaps and market inefficiencies. However, a new era of technological innovation, combined with a commitment to stronger policy frameworks and farmer education, presents a unique set of opportunities. Through leveraging technologies like hyperspectral imaging and deep learning for rapid quality testing, enhancing seeds with protective coatings and building transparent supply chains, we can assure better seed quality. In conclusion, focusing on ensuring genetically pure, physically sound and physiologically vigorous seeds is not just a matter of quality control; it is a fundamental pillar for securing sustainable and profitable cotton production.

References

Abdurakhmonov IY 2013. Role of genomic studies in boosting yield. Proceedings of International Cotton Advisory Board *(*ICAC*)* 20:7-22.

Aggarwal S, Mor VS, Paul D, Tanwar H, Malik A 2025. Green nanopriming: a comparative analysis of chemical and bioinspired approaches for sustainable agriculture. Seed Biology 4(1).

Bai X, Zhang C, Xiao Q, He Y, Bao Y 2020. Application of near-infrared hyperspectral imaging to identify a variety of silage maize seeds and common maize seeds. RSC advances 10(20):11707-11715.

Chandraprakash R, Masilamani P, Rajkumar P, Geetha R, Albert VA, Eevera T 2019. Effect of specific gravity separation on seed germination and biochemical potential of castor hybrid YRCH1. Journal of Pharmacognosy and Phytochemistry 8(4): 2369-2373.

Chauhan JS, Waghmare VN, Singh KH, Choudhury PR, Mishra JP, Prakash AH, Singh RK 2023. Cotton crop in India: growth, varietal improvement and seed production. Journal of Cotton Research and

Development 37: 1-15.

Deho ZA, Laghari S, Abro S 2012. Effect of picking dates on seed germination, gin turn-out, seed index and staple length in Gossypium hirsutum L. Pakistan Journal of Botany 44(1): 135- 137.

Ekramirad, N, Doyle L, Loeb J, Santra D, Adedeji AA 2024. Hyperspectral imaging and machine learning as a nondestructive method for proso millet seed detection and classification. Foods 13(9): 1330.

Gade RM, Koche M, Wasule D, Haque Z 2021. Soybean seed and seedling blights, rots, bacterial spot and mosaic. Dis Natl Important F Crop Todays Tomorrow's Printers Publ New Delhi. Today & Tomorrow's Printers and Publishers, New Delhi, pp 421-34.

Genze N, Bharti R, Grieb M, Schultheiss SJ, Grimm DG 2020. Accurate machine learning-based germination detection, prediction and quality assessment of three grain crops. Plant methods 16(1): 157.

Gwathmey CO, Bange MP, Brodrick R 2016. Cotton crop maturity: A compendium of measures and predictors. Field Crops Research 191: 41-53.

Hegde RB, Kudva V, Nayak S 2025. Advanced techniques for seed quality assessment and germination monitoring. Discover Applied Sciences 7: 690. https://doi.org/10.1007/s42452-025-07284-8

Kranthi KR 2013. Testing seed quality of Bt cotton. CAI Weekly, Publication No. 29.

Kumar R, Paul D, Sain SK, Singh A, Chandra S, Singh S, Cheema RS, Prasad YG 2025. Pink Bollworm, Pectinophora gossypiella (Saunders) Infestation Escalates from Incipient to Serious Proportions in North Cotton Zone of India. Journal of Crop Health 77(1): 1.

Kumari S, Chakrabarty S, Paul D 2024. Influence of pre-harvest climatic variables and natural storage duration on seed physico-chemical profile in diverse maturity groups of rice (Oryza sativa) varieties. The Indian Journal of Agricultural Sciences 94(6): 600-605.

Li Y, Huang G, Lu X, Gu S. Zhang Y, Li D, Guo M, Zhang Y, Guo X 2023. Research on the evolutionary history of the morphological structure of cotton seeds: a new perspective based on high-resolution micro-CT technology. Frontiers in Plant Science 14: 1219476.

Maity A, Paul D, Lamichaney A, Sarkar A, Babbar N, Mandal N, Dutta S, Maity PP, Chakrabarty SK 2023. Climate change impacts on seed production and quality: current knowledge, implications, and mitigation strategies. Seed Science and Technology 51(1): 65-96.

Paul D, Bagri S, Jhajhriya S, Garai S, Dutta S 2024b. Blockchain enabled seed traceability for enhancing seed quality assurance. Journal of Agriculture and livestock Farming 4: 10-20.

Paul D, Dutta S, Nidhi, Sapna, Jha R, Biswas N, Bagri S, Kumar R 2025. Heterosis Breeding and Hybrid Seed Production in Cotton. In Hybrid Seed Production for Boosting Crop Yields: Applications, Challenges and Opportunities pp 225-246. Singapore: Springer Nature Singapore.

Paul D, Kumar R, Prasad YG 2024a. Blending procedure is crucial for BG-II cotton hybrids to adhere to the prescribed 'Refugia in Bag' standards. Current Science (00113891) 127(1).

Pereira Lima JJ, Buitink J, Lalanne D, Rossi RF, Pelletier S, Da Silva EAA, Leprince O 2017. Molecular characterization of the acquisition of longevity during seed maturation in soybean. Public Library of Science ONE 12: e0180282

Santhy V, Balasubramani G, Biswas A, Santosh HB, Puttawar M, Raut P, Waghmare VN, Prasad YG 2024. Determination of minimum sample size for testing proportion of non-Bt seeds under refuge-in-bag (RIB) for Bt cotton. Environment, Development and Sustainability 27(3): 7243-7253.

Santhy V, Verma P, Paul D, Dhakade P, Choudhary A, Waghmare VN 2025. Protein Composition of Cotton Seeds in Relation to Agro-Climatic Variation. Seed Research 53(1): 31-35.

Varier A, Vari AK, Dadlani M 2010. The subcellular basis of seed priming. Current Science 99: 450–456

Wang J, Sun L, Xing W, Feng G, Yang J, Li J, Li W 2023. Sugarbeet seed germination prediction using hyperspectral imaging information fusion. Applied Spectroscopy 77(7): 710-722.

Yasmin J, Ahmed MR, Wakholi C, Lohumi S, Mukasa P, Kim G, Kim J, Lee H, Cho BK 2022. Near-infrared hyperspectral imaging for online measurement of the viability detection of naturally aged watermelon seeds. Frontiers in Plant Science 13: 986754.

Zhao G, Quan L, Li H, Feng H, Li S, Zhang S, Liu R 2021. Real-time recognition system of soybean seeds full-surface defects based on deep learning. Computers and Electronics in Agriculture 187: 106230.

Advances in Seed Enhancement and Coating Technologies for Improved Germination and Vigor in Cotton *(Gossypium spp.)*

VIPIN CHANDRA JOSHI[1*], ABHISHEK PANDEY[2], RIYA SAHU[3] AND N BHAVANA STELLA[4]
[1]Associate Director, Seed Supply chain, AgroStar, Pune.
[2,3,4]Seed Quality Analyst Agrostar, Pune, AQAL

Lead Author

DR. VIPIN CHANDRA JOSHI

Associate Director
Seed Supply Chain
AgroStar, Pune

Dr. Vipin Joshi holds a Ph.D. in Seed Science and Technology from GBPUAT, Pantnagar, Uttarakhand. He has held various positions in seed companies across North, Central, and South India, specializing in seed quality assurance within field operations, processing plants, and seed testing laboratories. Dr. Joshi has authored over 7 research papers, 12 research articles, and three book chapters. He has also participated in more than 26 training sessions including International & national conferences, seminars, and workshops organized by various ICAR institutes and SAUs. With extensive experience in the seed supply chain, Dr. Joshi is currently serving as the Associate Director, Seed Supply Chain at AgroStar India Limited in Pune.

Abstract

Cotton production is fundamental to the global economy, but its initial establishment is vulnerable to both biotic (pest and disease) and abiotic (drought, salinity, and temperature extremes) stresses. Seed enhancement and coating technologies provide a crucial head start by improving germination rates, uniformity, and

overall seedling vigor. This article reviews modern advancements in cotton seed enhancement, including innovative priming techniques, multifunctional coating technologies, and the integration of novel materials like nanoparticles and beneficial microbes. It highlights how these strategies are being used to develop climate-resilient cotton varieties, ensuring robust crop stands and higher yields in the face of environmental challenges.

Introduction

Cotton (*Gossypium spp.*) is one of the most important fiber crops in the world, serving as the backbone of the textile industry and contributing significantly to agricultural economies in countries like India, China, USA, and Brazil. The productivity of cotton is highly dependent on the **quality of seeds**, which directly affects **germination rate, seedling vigor, and uniform crop establishment**.

Traditionally, cotton seeds were sown without much treatment, relying on natural germination processes. However, environmental stresses, soil-borne pathogens, and seed dormancy often resulted in **low and uneven emergence**, reducing overall yield.

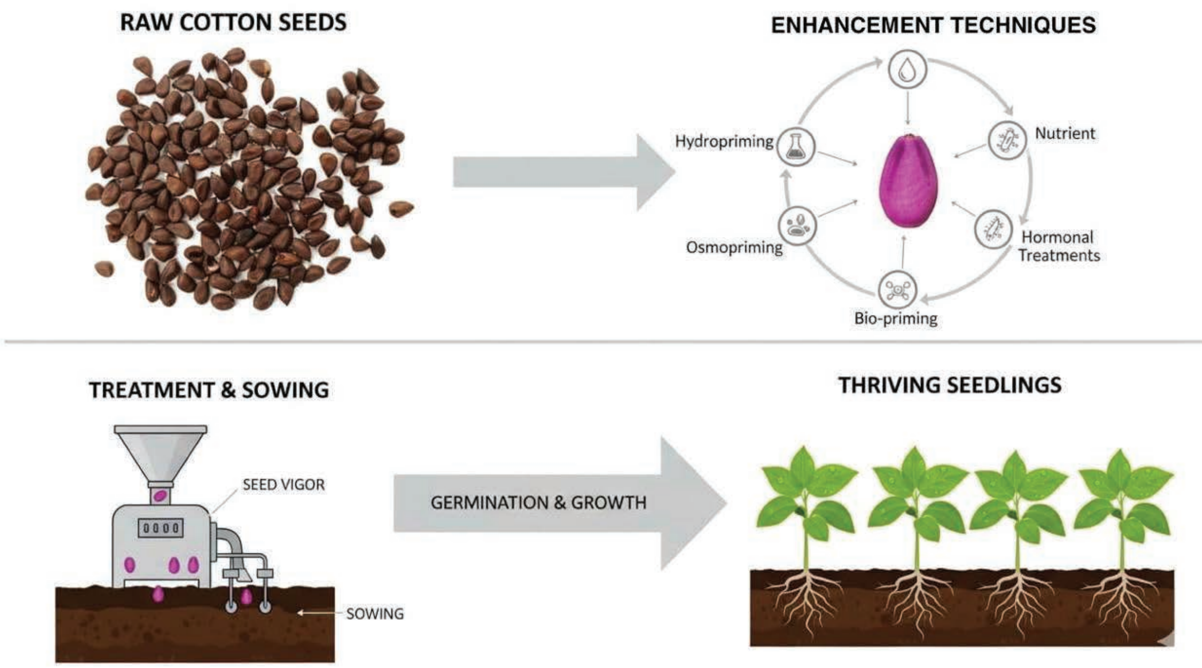
To overcome these challenges, modern **seed enhancement and coating technologies** have been developed. These innovations aim to:

- Improve seed metabolic activity for faster and uniform germination
- Protect seeds from biotic (disease and pest) and abiotic (drought, heat, salinity) stresses
- Enhance early seedling vigor, ensuring robust crop establishment

- Reduce chemical inputs by integrating biological treatments and controlled-release nutrients

Seed enhancement and coating technologies are now considered an essential component of precision agriculture, aligning with sustainability goals and improving resource-use efficiency.

Concept of Seed Enhancement



Seed enhancement refers to pre-sowing treatments that improve seed performance without altering its genetic makeup. These treatments target the physiological and biochemical properties of the seed, preparing it for optimal germination and growth.

In cotton, early-stage vigor is crucial because **delayed or weak seedling establishment can drastically reduce yield**. Seed enhancement techniques help overcome seed dormancy, improve water uptake, activate enzymes, and enhance stress tolerance.

Key Seed Enhancement Techniques

Seed Priming

Seed coating involves applying exogenous materials—such as chemicals, plant growth hormones, or microbial agents—onto seeds to improve germination, seedling vigour, and protection against pathogens. For cotton, this is crucial for improving seedling emergence, especially under challenging environmental conditions.

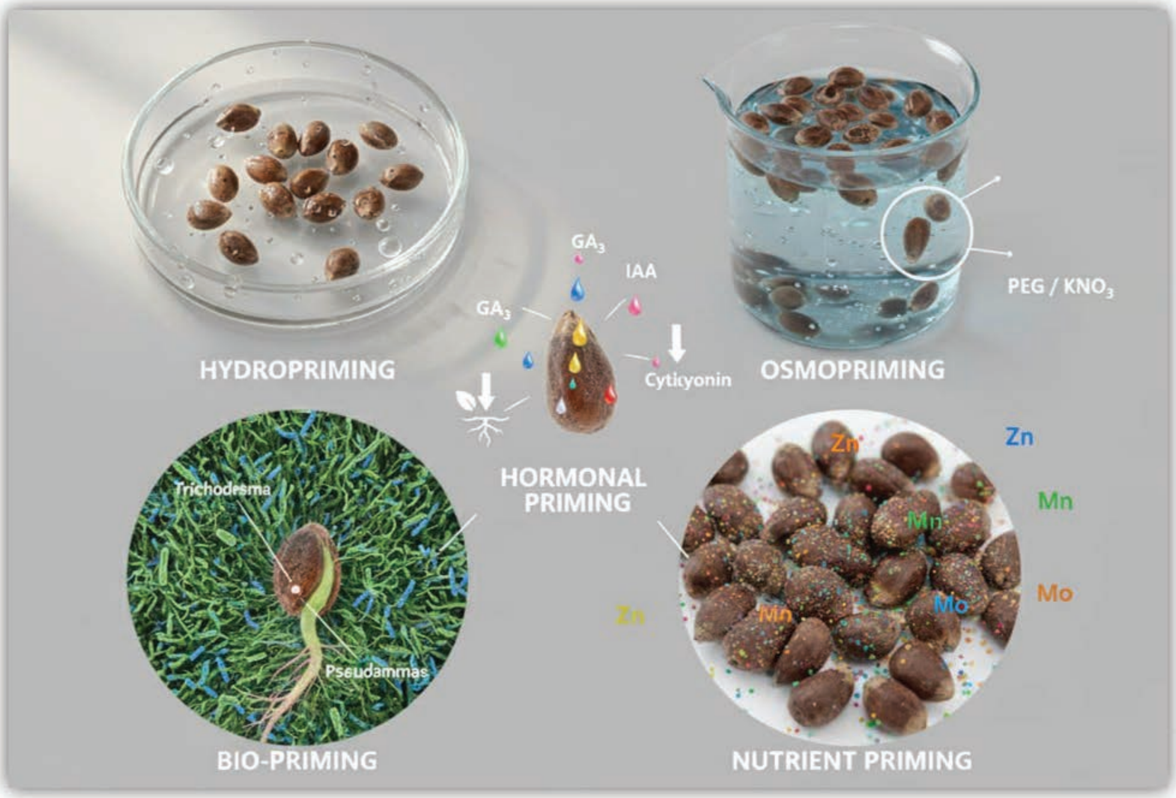
1. Hydropriming

A simple and low-cost technique where cotton seeds are soaked in **clean water for a specific duration (e.g., 8–10 hours)** and then re-dried before sowing.

This method activates essential **enzymes such as amylase and protease**, improving energy availability and accelerating seed germination.

Example: Hydroprimed cotton seeds can show **10–15% faster emergence** and stronger seedlings compared to untreated seeds.

2. Osmopriming



Seeds are soaked in **osmotic solutions** such as **polyethylene glycol (PEG)** or **mannitol**. This regulates water absorption, avoiding premature radicle emergence while activating seed metabolism.

Osmopriming is highly effective for improving **drought and heat tolerance**, ensuring uniform seedling establishment even under adverse environmental conditions.

3. Bio-priming

Seeds are inoculated with beneficial microorganisms like Trichoderma spp., Pseudomonas fluorescens, **or** Plant Growth-Promoting Rhizobacteria (PGPR)**.**

These microbes colonize the seed surface, promoting disease resistance, enhanced nutrient uptake, and robust root development.

It also provides early protection against soil-borne pathogens**.**

4. Nutrient Priming

- Seeds are enriched with micronutrients (Zn, Mn, Mo, B) to support initial root-shoot development.
- Particularly important in nutrient-deficient soils.

5. Hormonal Priming

Seeds are primed with plant growth regulators (PGRs) like gibberellic acid (GA_3)**,** indole-3-acetic acid (IAA), cytokinins, **or** brassinosteroids (BRs)**.**

Hormosnal priming enhances germination rate, root elongation, and seedling vigor**,** even under suboptimal temperature or water-stress conditions.

Notably, brassinosteroid priming can counteract the inhibitory effects of abscisic acid (ABA)**,** promoting germination under salinity and heat stress.

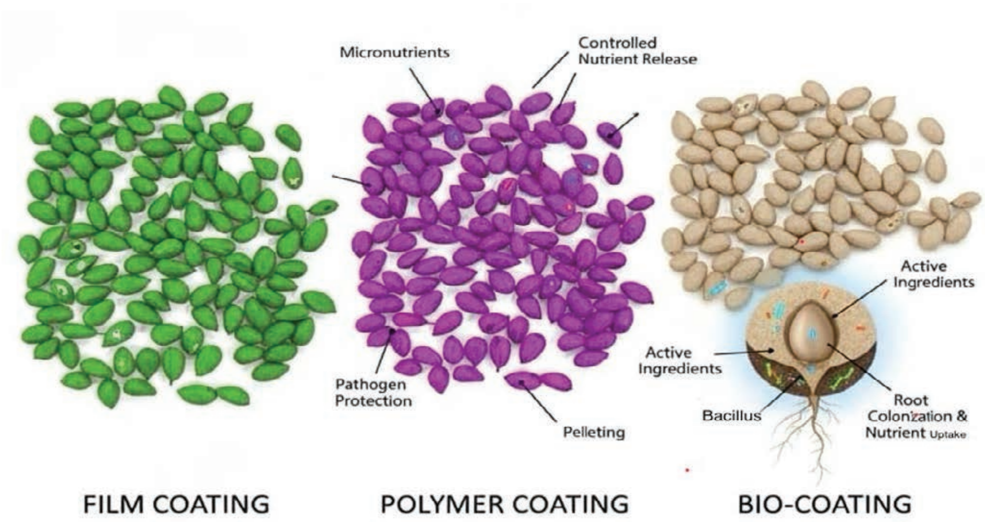
These techniques collectively improve germination percentage, uniformity of emergence, and seedling vigor, which ultimately impacts the crop yield and fiber quality.

Seed Coating Technologies

Seed coating involves applying a protective or nutrient-enriched layer over the seed surface. Coating improves handling, sowing uniformity, and seedling establishment while delivering nutrients or bioactive compounds.

Types of Seed Coatings

1. **Film Coating**
    - A thin polymer layer applied to the seed.
    - Can contain fungicides, micronutrients, and growth regulators.
    - Minimal increase in seed size, making it suitable for small-seeded crops like cotton.
2. **Polymer Coating**
    - Provides controlled release of nutrients and protects seeds from pathogens.
    - Enhances electrical conductivity and vigor index in seeds.
    - Recent studies show polymer-coated cotton seeds exhibit higher germination rates and early seedling vigor.
3. **Pelleting:** The most extensive coating method, pelleting transforms the irregular cotton seed into a uniform, spherical shape. This provides a highly accurate delivery system for active ingredients and is ideal for precision planting.
4. **Bio-Coating**
    - Incorporates beneficial microbes into the coating matrix.
    - Promotes root colonization, enhances nutrient uptake, and suppresses soil-borne pathogens.

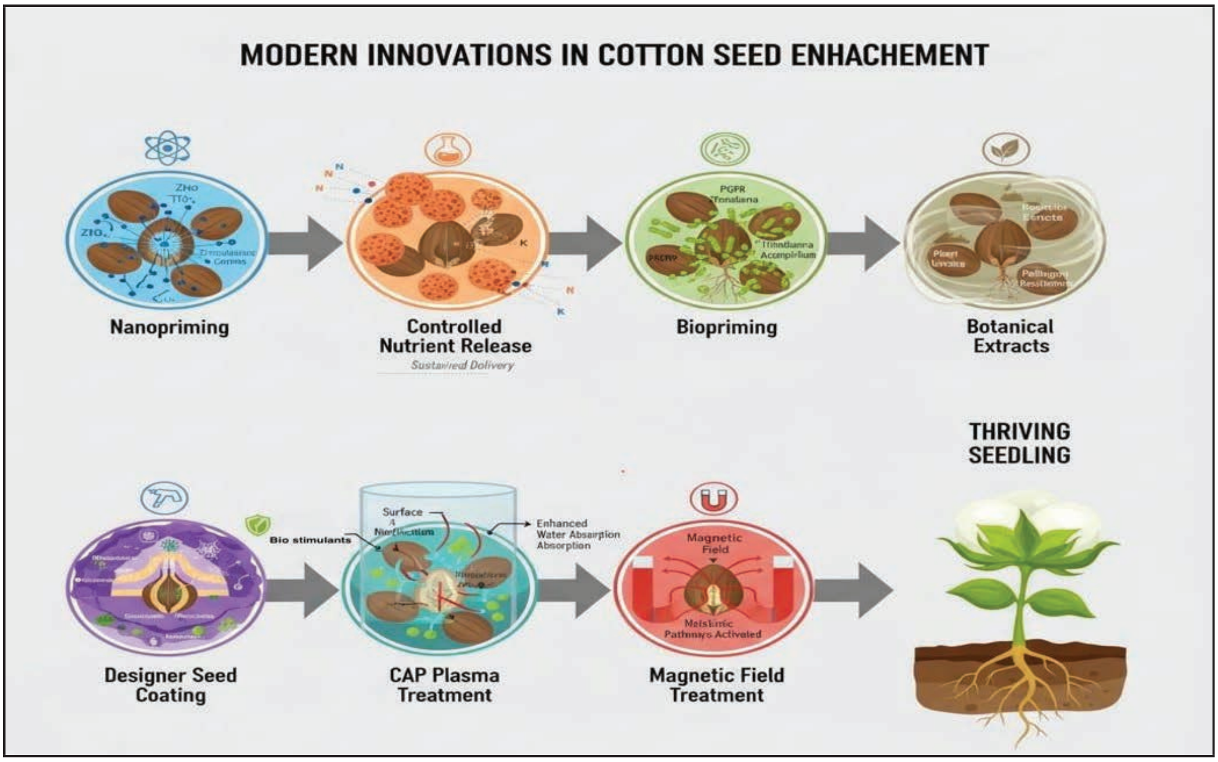


Modern Innovations and Integrated Technologies

1. Nanotechnology

Nanoparticles are revolutionizing seed enhancement by operating at the molecular level to improve seed resilience.

- **Nanopriming:** Nanoparticles, particularly zinc oxide (ZnO) and titanium dioxide (TiO_2cap Ti cap O sub 2 TiO_2), can be used to prime cotton seeds. Their small size allows them to penetrate the seed coat, activating antioxidant enzymes and up-regulating stress-responsive genes to boost germination and vigor, especially in aged seeds.



Controlled Release: Nanoscale carriers can provide a sustained and controlled release of nutrients, mitigating the need for excessive field applications and reducing environmental impact.

2. Biologicals and Biostimulants

The move toward sustainable agriculture has increased the use of biological agents in cotton seed treatment.

- **Biopriming:** Combines seed priming with beneficial microorganisms like plant growth-promoting rhizobacteria (PGPR), *Trichoderma*, and *Azospirillum*. These agents can enhance nutrient uptake (including nitrogen fixation and phosphorus mobilization) and induce systemic resistance against pathogens.

- **Designer Seeds:** An integrated approach involves coating seeds with a combination of fortifying nutrients, biostimulants, and protectants. Field studies have shown that potassium K+cap K raised to the positive power□+) fortification combined with a polymer coating containing fungicide, insecticide, and beneficial microbes results in higher field emergence, fewer pest and disease incidents, and increased yields.

- **Botanical Extracts:** Natural plant extracts, such as from *Rauvolfia serpentina*, are being explored as potential biopesticides for seed treatments.

3. Physical and Smart Technologies

- **Plasma Treatment:** Cold atmospheric pressure (CAP) plasma treatment has shown promise in enhancing cotton seed germination, water absorption, and chilling tolerance by modifying the seed surface.

- **Magnetic Treatments:** Exposure to magnetic fields during priming or irrigation has been demonstrated to activate metabolic pathways in cotton seeds, leading to enhanced germination and seedling vigor.

4. Benefits of Seed Enhancement and Coating in Cotton

Benefit	Details
Higher Germination Rate	Faster and uniform sprouting under optimal and suboptimal conditions.
Enhanced Seedling Vigor	Improved root and shoot growth ensures better field establishment.
Stress Resistance	Seeds tolerate drought, heat, and salinity more effectively.
Disease & Pest Protection	Fungicidal coatings and bio-agents reduce early infections.
Uniform Stand & Planting Efficiency	Mechanical sowing becomes easier due to uniform seed size and weight.
Improved Yield & Fiber Quality	Healthy seedlings produce more bolls and better fiber quality.

5. Chemicals and Bioagents in Seed Treatments

Category	Examples	Purpose
Fungicides	Thiram, Carbendazim, Metalaxyl	Protect against fungal pathogens
Insecticides	Imidacloprid, Thiamethoxam	Protect against early-stage pests
Micronutrients	$ZnSO_4$, $MnSO_4$, $FeSO_4$	Support root and shoot development
Growth Regulators	GA_3, IAA, Cytokinin	Stimulate germination and vigor
Bioagents	*Trichoderma*, *Azospirillum*, *Pseudomonas fluorescens*	Biological protection and growth stimulation

6. Challenges and Limitations

Despite their promise, several challenges hinder the widespread adoption of advanced seed enhancement technologies:

- **Cost and Scalability:** The high costs of nanomaterials, specialized polymers, and plasma equipment can limit accessibility, particularly for smallholder farmers.
- **Storage Stability:** Maintaining the viability of embedded biological agents over extended storage periods is a persistent issue.
- **Seed–Coating Interaction:** Coatings must not impede crucial physiological processes such as gas exchange, seed expansion, or respiration.
- **Environmental Safety:** The potential leaching and accumulation of nanomaterials or synthetic chemicals necessitates rigorous safety assessments; biodegradable alternatives are preferred.
- **Regulatory Hurdles:** Seeds coated with bioactives or nanomaterials are subject to varying degrees of regulatory scrutiny across regions. evaluation.

7. Future Directions and Recommendations

The future of cotton seed enhancement involves developing integrated, multi-functional, and cost-effective designer seed systems. By combining superior genetics with cutting-edge seed technologies, the agricultural sector can produce climate-resilient cotton, improve resource use efficiency, and foster long-term environmental sustainability.

Cold atmospheric-pressure plasma (CAP) treatment

This technology is arguably the most unique because it uses an ionized gas rather than chemicals or excessive water to improve seed quality.

How it works:

1. Cotton seeds are placed in a chamber and exposed to an ionized gas (plasma) generated by an electric field.
2. The plasma creates a cocktail of reactive oxygen and nitrogen species (RONS), charged particles, and UV photons that interact with the seed's surface.
3. This interaction causes micro-etching and modifies the seed coat, making it more hydrophilic (water-loving).
4. This increased hydrophilicity allows the seeds to absorb water more efficiently, accelerating and synchronizing germination.

Why it's unique:

- **Non-invasive:** Unlike chemical or mechanical treatments, plasma doesn't damage the seed's genetic material.
- **Eco-friendly:** It is a chemical-free and low-energy process, aligning with sustainability goals.
- **Addresses specific issues:** It effectively improves germination under suboptimal conditions, such as cold or limited moisture, making it highly valuable for climate-resilient agriculture.
- **Stable effects:** The beneficial effects of the treatment, such as improved water absorption and germination rates, have been shown to last for months after application, allowing for large-scale industrial treatment well in advance of planting.

Nanopriming

Nanopriming is a unique type of seed priming that leverages the properties of nanoparticles to reinforce seeds at the molecular level.

How it works:

1. **Controlled delivery:** Nanoparticles of materials like Zinc Oxide (ZnO) or Titanium Dioxide (TiO_2cap Ti cap O sub2 TiO_2) are used to create a priming solution.

2. **Penetration at the nanoscale:** The tiny size of these nanoparticles allows them to penetrate the seed coat and cell membranes more effectively than conventional treatments.

3. **Metabolic regulation:** Once inside, the nanoparticles can activate antioxidant enzymes, up-regulate stress-responsive genes, and regulate hormonal pathways to boost germination and vigor.

4. **Creating "nanopores":** Some nanoparticles can create tiny pores in the seed coat, which enhances water uptake and enzyme activity, directly addressing issues related to the cotton seed's hard outer layer.

Why it's unique:

- **Molecular-level precision:** It offers a level of precision that older methods can't match, as it operates at the nanoscale to reinforce the seed's biology from within.

- **Enhanced resilience:** Nanopriming significantly increases the seed's resistance to abiotic stresses like drought and salinity by activating key stress-response pathways.

- **Increased storage longevity:** Studies on cotton have shown that nanopriming can extend seed viability and vigor for over a year, a key advantage for seed suppliers.

- **Controlled release:** Nanomaterials can also be used in coatings to provide a steady, controlled release of nutrients or biostimulants during critical growth stages.

Conclusion

Seed enhancement and coating technologies represent a pivotal advancement in cotton cultivation. By improving germination, seedling vigor, and stress tolerance, these methods ensure robust crop establishment and higher yields. The future lies in **eco-friendly, smart, and precision-enabled seed coatings**, which will further enhance cotton productivity while supporting sustainable agricultural practices.

References

Basra, S.M.A., Farooq, M., & Tabassum, R. (2003). *Seed priming for improved germination and seedling growth in cotton (Gossypium hirsutum L.).* Seed Science and Technology, 31(3), 419–425.

Taylor, A.G., & Harman, G.E. (1990). *Concepts and technologies of seed coating and film coating.* Seed Science and Technology, 18, 605–620.

Halmer, P. (2008). *Seed technology and coating advances in horticultural crops.* Acta Horticulturae, 782, 45–58.

Farooq, M., Basra, S.M.A., Wahid, A., Ahmad, N., & Saleem, B.A. (2011). *Seed priming improves germination and early seedling growth under drought stress.* Journal of Agronomy and Crop Science, 197(3), 193–204.

Gogoi, N., Baruah, M., & Das, P. (2018). *Seed enhancement techniques for cotton: A review.* Indian Journal of Agricultural Sciences, 88(7), 1095–1102.

ICAR (2020). *Handbook on Seed Technology for Field Crops.* Indian Council of Agricultural Research, New Delhi.

National Seed Association of India

The National Seed Association of India

909, Surya Kiran Building,
19 Kasturba Gandhi Marg, New Delhi - 110001 (INDIA)

Ph.: 011-43553241-43, Fax.: 011-43533248
Email: info@nsai.co.in | Web: www.nsai.co.in