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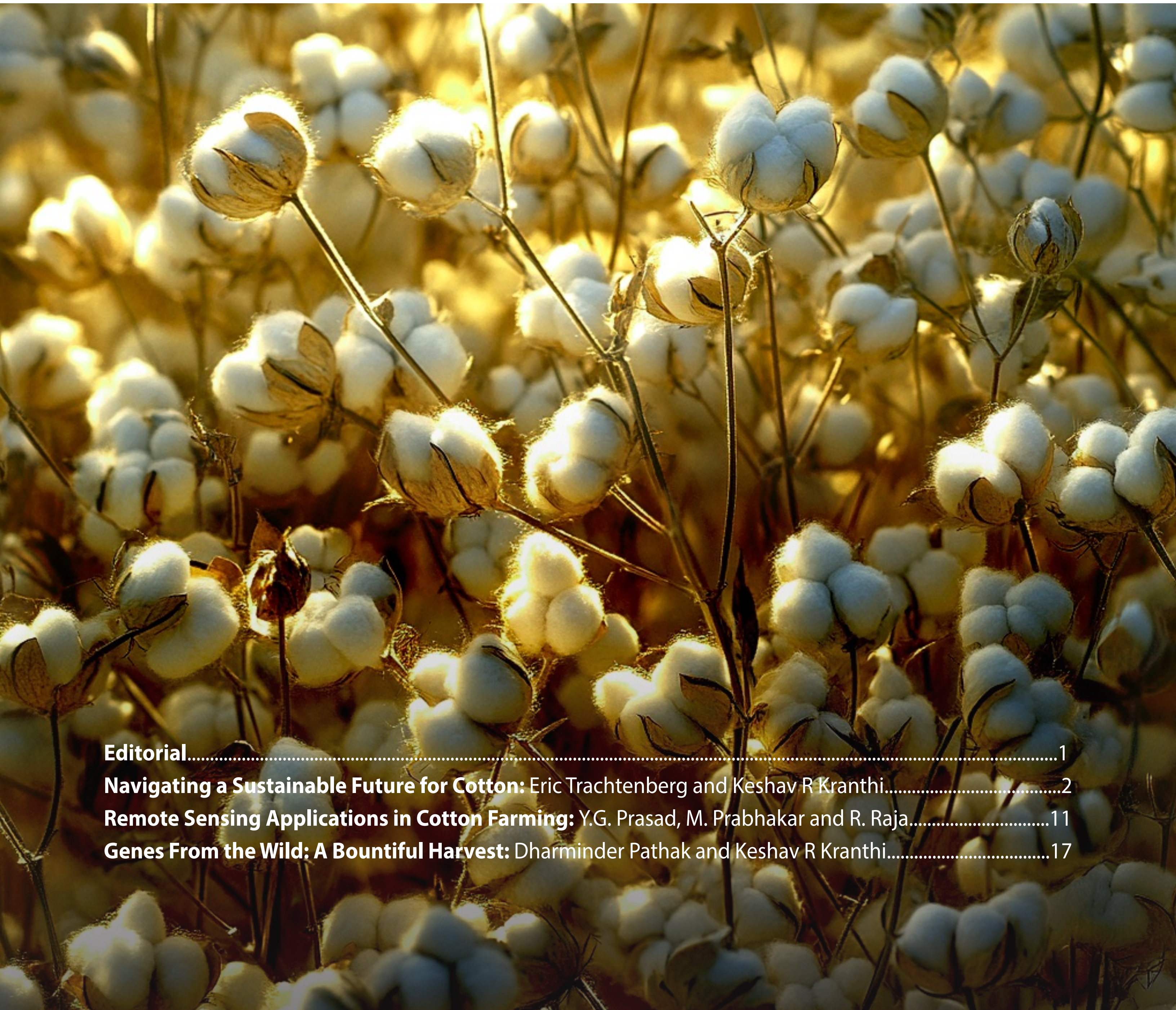
International Cotton Advisory Committee



Editorial

Cotton is far more than a crop; it is a lifeline for millions of farmers, particularly in dryland regions. Its resilience to harsh climates, its capacity to sequester carbon, and its ability to produce nature's finest fibers make it a cornerstone of livelihoods and global economies. Yet, the true challenge lies not merely in cultivating cotton but in ensuring that its production sustains livelihoods while safeguarding the planet. This dual responsibility—to support the present and protect the future—demands a concerted effort from all stakeholders in the cotton value chain.

Livelihood is not just about fulfilling basic needs like food, clothing, and shelter; it is about enabling better living and laying the foundations for a sustainable future for generations to come. As the Native American proverb reminds us, "We do not inherit the Earth from our ancestors; we borrow it from our children." This vision aligns with the Brundtland Commission's timeless definition of sustainability: "meeting the needs of the present without compromising the ability of future generations to meet their own needs."

The journey toward sustainable cotton begins in the farmer's field and extends to every thread in the value chain. Regenerative agriculture, precision farming, and innovative technologies provide pathways to achieve this sustainability. These approaches are not just about sustaining current practices; they are about reviving, healing, and replenishing soils, biodiversity, and farming systems. As Robert Swan aptly said, "The greatest threat to our planet is the belief that someone else will save it." Time is running out, and the responsibility to act falls on each of us.

The articles in this edition of the ICAC Recorder address the multifaceted challenges of achieving sustainability in cotton production.

In his article, "Navigating a Sustainable Future for Cotton," Eric Trachtenberg highlights key issues and opportunities for the global cotton sector. He discusses how regulatory changes, the environmental image of cotton, farmer incomes, and the growing demand for functional fabrics are reshaping the cotton industry. Importantly, Trachtenberg emphasizes that consumers are increasingly willing to pay a premium for products with credible sustainability claims. The article highlights how the global cotton sector can meet the emerging challenges. On the regulatory front, there are important economic, social, and environment arguments can make a difference in favor cotton and other natural fibers. The data demonstrates the environmental benefits of natural fibers like cotton, including biodegradability, carbon sequestration, and their role in supporting livelihoods, particularly in the Global South. In the developing world, improved production practices can boost farm income and generate quality work downstream in the textile sector. Innovations are essential to make cotton more competitive with synthetic alternatives, particularly in functional applications like sportswear and technical fabrics. With the right support, cotton can remain the fabric of choice while contributing to a healthier planet.

Technological advancements are playing a transformative role in cotton farming. Remote sensing technologies, as highlighted by Y.G. Prasad and colleagues, offer precise tools for crop monitoring, stress detection, and resource management. Ground-based systems, UAVs, and satellites provide invaluable data for yield prediction, nitrogen management, pest control, and disaster assessment. While satellite imagery is ideal for large-scale mapping, UAVs excel in high-resolution, localized monitoring, making them particularly useful for smallholder farmers. Challenges like cost and scalability remain, but innovations in hyperspectral imaging, artificial intelligence, and spectral indices promise to revolutionize precision farming. These technologies enable cotton farmers to optimize inputs, enhance productivity, and minimize environmental impact, ensuring a sustainable future for cotton agriculture.

In their article, "Genes From the Wild: A Bountiful Harvest," Dharminder Pathak and Keshav Kranthi emphasize the untapped potential of wild cotton species. Over the years, modern breeding practices have narrowed the genetic diversity of cultivated cotton, making it vulnerable to pests, diseases, and climate change. Wild cotton species harbor traits like drought tolerance, pest resistance, and superior fiber quality, which can significantly enhance the resilience of cultivated varieties. The authors advocate for introgressive hybridization to integrate these valuable traits into commercial cotton varieties. They also propose establishing a "Centre of Excellence on Pre-Breeding of Cotton" to systematically explore and utilize the genetic resources within the Gossypium genus. This initiative would not only improve cotton's resilience but also secure its sustainability for future generations.

As we reflect on the insights shared in this edition of the ICAC RECORDER, one message stands out: the path to a sustainable cotton future requires collective action, innovative solutions, and a deep commitment to stewardship of the land. Sustainability in cotton is not just a matter of individual efforts; it requires collaboration among farmers, researchers, policymakers, and the private sector. Regenerative agriculture is a key component of this journey. By restoring soil health, enhancing biodiversity, and sequestering carbon, it addresses both environmental and economic challenges. Similarly, precision farming technologies enable more efficient resource use, reducing the environmental footprint of cotton production.

Cotton's journey from field to fabric is a story of resilience, innovation, and opportunity. But the challenges ahead demand urgent action. Whether through adopting regenerative practices, leveraging cutting-edge technologies, or fostering global collaborations, the cotton sector must rise to the occasion. As Mahatma Gandhi once said, "The future depends on what we do in the present." Let us act decisively to ensure that cotton continues to be a source of livelihoods, sustainability, and hope for generations to come. The time to act is now, and together, we can weave a future where cotton thrives in harmony with the planet.

– Keshav Kranthi

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Navigating a Sustainable Future for Cotton

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INTRODUCTION

Cotton, often referred to as "white gold," has been used in clothing for millennia and has been a cornerstone of the modern textile industry for centuries. Its natural comfort, breathability, and versatility have made it an indispensable fabric in wardrobes around the world (Eagan, 2014). Cotton is also globally recognized as a poverty-reducing crop. Each ton of cotton produced generates full-time, year-round employment for five people throughout the cotton-textile value chain.

Despite its merits, the market has not always been favorable to cotton. As a result of a changing market, global textile fiber demand surged from 15 million to 107 million metric tons, growing at a 3.1% annually from 1960 to 2023. Synthetic fiber demand skyrocketed from 700 thousand tons in 1960 to 76 million metric tons in 2023.

Despite rapidly expanding demand for textiles, over the same period, cotton demand only rose at 1.3% annually from 10.4 million to 23.4 million metric tons. As a result, cotton's market share fell from 68% to about 22%, overtaken by the swift rise of synthetic fibers that have met the growing demands for functional clothing, a rising interest in fast fashion, and a more affluent global population.

These market conditions for cotton were driven by rapid technological change, rising market competition, and heightened environmental awareness that created both significant opportunities and formidable challenges for cotton. As the global cotton sector looks into the future, this article examines some of the most important strengths and obstacles associated with cotton, exploring the paths that could support or even eventually expand its prominence in the global market.

STRENGTHS OF COTTON

Natural Fiber and Biodegradability: Cotton's identity as a natural fiber is one of its most compelling advantages (Thomas et al., 2011). Unlike synthetic fibers derived from petrochemicals, cotton is biodegradable, decomposing naturally without leaving harmful residues. This characteristic reduces environmental waste and supports the circular economy because cotton does not persist in the environment long after disposal. In a world increasingly conscious of sustainability, cotton's ability to return to the earth gracefully positions it favorably among eco-friendly materials (Riello, 2015).

Global Popularity and Market Share: Commanding approximately 22% of the global fiber market (Textile Exchange, Materials Market Report, 2023), cotton is the most popular natural fiber and second only to polyester amongst all fibers. Its widespread acceptance is a testament to its desirable qualities—softness, durability, and versatility. Cotton's adaptability for different uses across various climates and cultures has solidified its role not just as a generic commodity but as a global staple in the textile sector.

Established Trade and Stable Market Environment: The cotton industry benefits from a long-standing, well-organized commodity trade system. Institutions like the Bremen Cotton Exchange and the International Cotton Association (ICA) provide a stable trading environment, ensuring transparency and reliability in transactions. At the international level, the International Cotton Advisory Committee (ICAC) is one of the world's oldest international commodity bodies. These organizations uphold industry standards, provide critical market data, facilitate dispute resolution, and maintain market integrity, all of which are crucial for fostering international trade, trust, and cooperation.

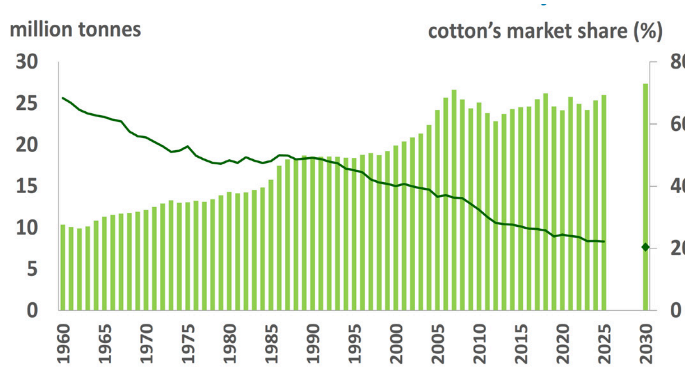
Commitment to Contract Sanctity and Research Networks: Cotton's global trade is underpinned by a strong adherence to contract sanctity. The industry boasts extensive expertise and robust research networks, such as ICAC's Commercial Standardization of Instrument Testing of Cotton (CSITC). These efforts promote uniform quality assessments and support contract integrity, enhancing confidence among stakeholders and reducing transactional risks.

Superior Consumer Appeal: Cotton offers a premium feel that resonates with consumers seeking comfort and quality. Its natural breathability and hypoallergenic properties make it ideal for sensitive skin (Vhanbatte et al., 2022; Islam et al., 2020). The tactile experience of cotton garments often surpasses that of synthetic alternatives, fostering consumer loyalty and preference for cotton-rich products.

CHALLENGES FACING COTTON

Declining Market Share: Despite its strengths, cotton has experienced a decline in market share due to the rise of synthetic fibers like polyester (Textile Exchange, Materials Market Report, 2023). Synthetics are often cheaper to produce, have less complicated supply chains because they come from mined rather than farmed sources, and can offer specific performance attributes. This can make them attractive to manufacturers and consumers focused on cost and functionality, which poses a significant challenge to cotton's dominance in the textile industry.

Fig-1 Declining market share of cotton



Environmental Reputation Concerns: Cotton has been criticized for its perceived high consumption of water, chemicals, and fertilizers (Naqvi et al., 2024). The narrative of cotton as a water-intensive and environmentally taxing crop has negatively impacted its reputation. In an age where sustainability influences consumer choices and regulatory policies, addressing these perceptions is critical for cotton's future.

Supply Variability Due to Natural Factors: As an agricultural product, cotton's supply is inherently linked to environmental conditions. Adverse weather events, such as droughts or floods, can significantly impact crop yields, leading to supply shortages and price fluctuations (Li et al., 2009; Moghaddam et al., 2024). Weather can also affect fiber quality. This dependency on nature adds an element of risk not typically associated with synthetic fiber production.

Higher Costs and Price Volatility: Cotton is generally more expensive than synthetic fibers due to labor-intensive cultivation and a long and often complex supply chain (Nayak et al., 2024). Additionally, its prices are subject to volatility influenced by factors such as weather conditions, pest outbreaks, quality variability, falling crop area in favor of other crops, and geopolitical events. This unpredictability can be a deterrent for manufacturers seeking stable input costs. However, it is worth noting that cotton is only deemed "expensive" compared to synthetics when the full spectrum of costs and benefits—including environmental and social impacts—is not fully considered.

WEAKNESSES, THREATS, OPPORTUNITIES, AND ACTIONS

CHALLENGE-1: REGULATORY CHANGES FAVORING SYNTHETICS

As the global textile industry grapples with sustainability challenges, a wave of new regulations and legislative proposals is emerging to promote environmentally friendly practices (Puglia et al., 2024). However, there is growing concern that these measures may inadvertently favor synthetic fibers over natural ones like cotton. The following points highlight how regulations, incomplete life cycle assessments, and overlooked environmental impacts could inadvertently disadvantage cotton producers and mislead consumers about the true sustainability of various textile materials.

Threats

Supply Chains and Agriculture: Current and proposed legislative proposals may impose stringent sustainability standards on natural fibers like cotton while overlooking the environmental impacts of synthetics (Monseau et al., 2024). One particularly important challenge arises from supply chain due diligence requirements that could significantly affect the market for cotton and other natural fibers. Since agricultural products such as cotton are often supplied through many small farmers via long supply chains, due diligence processes of these systems can be risky, expensive, complex, and difficult to implement. Without effective mitigation, these issues may make markets shift away from already poor smallholder farmers in favor of synthetics that have shorter value chains. This could disadvantage cotton producers and affect the livelihoods of millions without achieving meaningful sustainability goals.

Environmental Regulations Favoring Synthetics: Amid the changing landscape of global textile regulations, the Life Cycle Assessment (LCA) methods, especially those based on the Higg Materials Sustainability Index (MSI), may be causing a noticeable shift that may favor synthetic fibers over natural ones like cotton. While LCAs seek to provide a systematic analysis of environmental impact over the course of the entire life cycle of a product, these assessments have limitations. For example, they often leave out important environmental factors such as microplastics, plastic waste, the concept of circularity, and the potential for carbon sequestration by natural fibers. By ignoring these elements, the LCA provides an incomplete picture, which can make synthetic fibers appear more environmentally friendly than they truly are, while downplaying the benefits of natural fibers like cotton (Watson and Wiedemann, 2019). The danger lies in promoting materials that, while appearing sustainable in a limited scope of assessment, may impose greater harm on the environment over time.

Fig-2 Cotton is biodegradable, unlike synthetic fibres

Global Movement Towards Stricter Environmental Regulations: While the European Union is the most active region with more than 15 textile-related policies in various degrees of drafting and implementation connected to green claims, eco-design, due diligence, waste, and waste, similar rules are being developed elsewhere. The New York Fashion Act in the USA, Green Claims regulations in Canada, and the adoption of LCA-related standards in France all show a global move towards stricter environmental rules in the textile industry (Sammons, 2024; Alizadeh et al., 2024). However, if these regulations don't fully consider all environmental factors—including issues like microplastic pollution—they might unintentionally disadvantage natural fibers that are more environmentally friendly.

Opportunities and actions

Considering the above challenges, it is important for the cotton industry to actively engage with policymakers (Pires et al., 2024). By highlighting cotton's environmental benefits—such as its biodegradability, ability to sequester carbon, and support for sustainable practices—the industry can advocate for regulations that not only level the playing field for natural fibers but can improve environmental outcomes (Tao et al., 2024). This proactive approach can help ensure that policies truly reflect the environmental costs and benefits of all types of fibers. It is essential for all stakeholders to collaborate and take a comprehensive view of environmental impacts. By doing so, the textile industry can move towards a future where sustainability is genuinely achieved, benefiting both the planet and society.

ICAC Supports Initiatives to Enhance Cotton Sustainability: There are significant opportunities to enhance the sustainability and positive perception of cotton in the global textile industry. Firstly, the ICAC fully supports the environmental objectives of its member countries as they develop and implement regulations to support improved social and environmental performance in the textile sector. By aligning with these goals, the ICAC demonstrates its commitment to promoting sustainable practices within the cotton industry. These regulations aim to standardize how the environmental impacts of products are measured and communicated (Berning and Sotirov, 2024), ensuring transparency, and fostering a more sustainable market. The ICAC believes that adopting such frameworks is essential for advancing environmental stewardship and meeting the growing consumer demand for sustainable products.

Advocacy for Balanced Metrics and Policy Engagement: The cotton sector should actively participate in dialogues with governments and regulatory bodies to ensure that policies are fair and based on comprehensive environmental assessments. Active participation in policy discussions can promote regulations that recognize and support the positive attributes of cotton. Support the development and adoption of assessment tools that account for all environmental impacts, including microplastics, plastic waste, and end-of-life considerations. This governmental engagement can lead to more informed decisions that favor sustainable agricultural practices and natural fiber production.

Promoting Cotton's Environmental Benefits: The cotton sector should highlight cotton's biodegradability and role in carbon sequestration to policymakers and the public, reinforcing its position as a sustainable choice. It is vital to make a strong environmental, economic, and social case for cotton. Cotton textiles are biodegradable and support circularity, reducing long-term environmental impact (Wang and Salmon, 2022). The cultivation of cotton contributes to carbon sequestration and supports livelihoods, promoting economic development and social well-being (Tlatlaa et al., 2023), especially in the Global South. By emphasizing these benefits, the industry can reinforce cotton's position as a sustainable and responsible choice in the textile market.

CHALLENGE-2: ADDRESSING ENVIRONMENTAL MISCONCEPTIONS

Threats

The negative sustainability perception of cotton farming systems threatens the cotton industry. Consequently, cotton faces a significant threat due to its poor environmental reputation. There is a widespread perception that cotton is a water-intensive and environmentally harmful crop. For example, without citing any evidence, Sen and Dasgupta, (2022), claim that "Producing 1 kg of cotton consumes 22,500 liters of water. Thus, with the export of 7.5m bales of cotton in 2013, India also exported about 38bn cubic meters of virtual water." This negative image jeopardizes consumer acceptance and market competitiveness, potentially leading to reduced demand and increased regulatory pressures on cotton producers. Moreover, misconceptions about cotton's environmental footprint can influence consumer behavior and regulatory decisions, potentially reducing demand while also potentially triggering adverse regulatory action.

Opportunities and Actions

Present Accurate Data to Counter Misinformation: Enhancing cotton's environmental reputation requires presenting accurate data to counter negative stereotypes. Contrary to common misconceptions, cotton's environmental impact is relatively low. According to the ICAC, cotton occupies only 2.38% of global cropland and uses just 1.7% of global irrigation water. It accounts for 4.8% by value and 4.3% by volume of global pesticide use, utilizes merely 2.8% of global fertilizers, and emits less than 2 kg of CO_2 per kilogram of fiber compared to around 5 kg for polyester. By promoting these facts, the cotton industry can correct misunderstandings and highlight cotton as a sustainable choice.

Leverage Cotton's Resilience in Arid Climates: Cotton's resilience in arid climates further showcases its adaptability and sustainability. As a semi-xerophyte plant (Sonone et al., 2020; Valu, 2021), it thrives in arid regions like the Sahel and Texas, where other crops cannot grow. Its cultivation in such areas means it doesn't compete with food crops for prime agricultural land or water, reducing competition for resources. In some regions such as the Sahel, it provides better cash returns than other crops.

Capitalize on Rising Interest in Sustainability: The rising global interest in sustainability presents an opportunity to engage governments, donors, and the private sector in investing in sustainable cotton practices (Milder et al., 2010). Not only do these approaches boost yields and support the social license for cotton, but they may provide the opportunity for farmers to obtain a price premium.

Collaborate with Environmental Civil Society Groups: Collaborating with various stakeholders can drive advancements in sustainable cotton production and attract funding for research and development. Partnering with environmental civil society groups can also enhance credibility and foster the adoption of eco-friendly methods in cotton farming, benefiting both the environment and the industry's reputation. In the future, it may be possible to partner with civil society to communicate the truth about cotton.

Advance Sustainable Technologies and Carbon Sequestration: Advancing sustainable technologies like biochar and bokashi composting can significantly improve soil health and carbon capture. Biochar, produced from cotton stalks, is stable for more than 100 years (Cross and Sohi, 2013; Leng et al, 2019) and enriches soil carbon content, while bokashi composting enhances soil fertility and reduces waste (Quiroz and Céspedes, 2019). Implementing these production improvements demonstrates the industry's commitment to sustainability and contributes to carbon sequestration.

Implement Regenerative Agriculture Practices: Utilizing insights from the ICAC Expert Panel on the Social, Environmental, and Economic Performance of Cotton Production (SEEP) report (Kater Hake, 2024) on regenerative agriculture can help adopt feasible regenerative farming practices suitable for diverse farming systems ranging from smallholder to large farms. Adopting these practices in ways best suited to diverse farm systems can lead to higher yields, increased farm income, more sustainable production, and improved environmental outcomes.

Explore Long-Term Financial Incentives: Since cotton can sequester carbon, it is possible to develop carbon markets and Payment for Ecosystem Services (PES) to support farmers (Milder et al., 2010; White et al., 2022). Creating financial mechanisms like carbon credits can incentivize cotton farmers to adopt sustainable practices by providing additional income streams, aligning economic and environmental benefits (Sangha et al., 2024).

Increase Public Awareness and Positive Messaging: Finally, increasing public awareness through proactive media engagement and public campaigns is essential to reshaping public perceptions. By actively sharing accurate information, the industry can highlight cotton's sustainability and counteract misinformation. Focusing on these opportunities and taking strategic actions will enhance cotton's environmental reputation and promote sustainable practices that benefit both producers and the planet.

CHALLENGE-3: FARMER AND GENERAL POVERTY IN AFRICA AND INDIA

Threat

The cotton industry faces a significant challenge with farmer and general poverty, particularly in regions like Africa and India. The 15 to 20 million smallholder farmers in these regions often struggle with low incomes, limited access to resources, and economic instability. These problems hamper the overall growth and sustainability of the cotton sector in these areas by reducing production and undermining the financial health of producers.

Opportunities and Actions

Generating Employment and Income Through the Supply Chain: Leverage the cotton supply chain to create jobs and increase income levels. The cotton supply chain has the potential to generate substantial employment opportunities and income for local communities. By investing in all stages of the supply chain — from cultivation and harvesting to processing and distribution — the industry can create jobs, stimulate economic activity, and improve living standards for farmers and others who work off the farm.

Diversifying the Value Chain and Sourcing Agricultural Products: Promote a diverse value chain and sourcing strategies for agricultural products. Diversifying the cotton value chain enhances economic resilience and opens new market opportunities. By encouraging the development of aligned products and services related to cotton, such as regenerative cotton, fair trade products, and cotton by-products, producers can tap into different market segments (Radhakrishnan, 2022). This diversification not only adds value but also reduces dependency on a single income source, thereby mitigating risks associated with market fluctuations.

Expanding International Development Activities to Boost Yields: Implement international development programs aimed at increasing cotton yields. Expanding activities in international development is crucial for boosting cotton yields in poverty-stricken regions. This includes providing farmers with access to better seeds, modern farming techniques, and education on sustainable practices. International partnerships can facilitate the transfer of technology and knowledge, leading to higher productivity and improved crop quality. Finally, where there is country interest and support, policy and institutional reform can significantly enhance the enabling environment for cotton production. These measures often include input sector reform, revised technology regulations, and improved international trade measures.

Adding Value in Producing Countries: Invest in textile production within cotton-producing countries to add value locally. By developing textile industries within cotton-producing countries, these nations can retain more value from their raw materials. Exporting finished textiles rather than raw cotton allows countries to benefit from higher profit margins, create skilled employment opportunities, and generate foreign exchange. Supporting economic growth can help ease political pressures on governments that support political stability against violent extremism. For example, programs like the African Growth and Opportunity Act (AGOA) and Economic Partnership Agreements (EPA) enable African countries to export textiles to rich countries with favorable terms (Lu, 2024). AGOA was passed by the U.S. Congress in May 2000 with the goal of supporting the economic development of sub-Saharan African countries and strengthen economic ties between the region and the United States.

Fig-3 A Cotton Textile Mill in Africa

Impact of Increased Cotton Returns on Crop Competition: Enhance cotton profitability to reduce competition with other crops for arable land. If the financial returns from cotton cultivation increase, farmers are more likely to allocate land to cotton rather than competing food crops (Raha et al., 1986; Chaudhry, et al., 2009; Baig et al., 2023). Since farmers aim to maximize net returns, making cotton more profitable can ensure cotton cultivation supports food security because farmers will have increased financial resources to purchase food.

The Cost of Certification: Who Pays for Sustainability and Traceability? Address the financial responsibility for sustainability certifications and traceability systems (Chkanikova and Kogg, 2018). A key question is who should bear the costs associated with sustainability certifications and traceability measures. Implementing these systems is essential for meeting international standards and consumer demands for ethical products. However, the financial burden can be significant for smallholder farmers. Stakeholders must collaborate to develop funding mechanisms, possibly involving governments, NGOs, and private companies, to ensure that the costs do not disproportionately affect the most vulnerable participants in the supply chain (Sneyd, 2014).

By addressing these challenges with targeted actions, the cotton industry can play a pivotal role in alleviating poverty among farmers in Africa and India. Enhancing employment opportunities, diversifying value chains, boosting yields through international development, adding value locally, focusing on key regions, balancing crop competition, and resolving certification cost issues are essential steps toward a more sustainable and equitable cotton sector.

CHALLENGE-4: COTTON'S LIMITATIONS IN FUNCTIONAL USES

Threat

Cotton traditionally faces challenges in certain functional applications where synthetic fibers dominate. For example, cotton may not meet the specific technical requirements of certain applications where synthetics excel, such as moisture-wicking in activewear. However, new technologies are emerging to enhance cotton's performance characteristics.

Opportunities and Actions

Innovating to Improve Performance Characteristics: Innovations like Cotton Incorporated's STORM COTTON™ improve moisture-wicking abilities and offer better weather resistance while its PUREPRESS™ cotton reduces wrinkles. By adopting such technologies, the cotton industry can make its products more competitive in markets that demand high-performance functional materials.

Showcasing Innovations Through the ICAC Cotton Innovation Platform (CIP): ICAC's new Cotton Innovation Platform (CIP) serves as a hub for highlighting technological advancements in cotton. By promoting innovative solutions and fostering collaboration, CIP will help accelerate the adoption of new technologies that can overcome cotton's technical limitations and boost its market share. Stakeholders interested in contributing technologies that help cotton compete are encouraged to participate in the CIP.

Contributions from Industry Leaders and Academic Institutions: The CIP will include organizations like Cotton Incorporated, Texas Tech University, and others that are at the forefront of research and development aimed at enhancing cotton's properties. Their work includes developing new finishes, hybrid fabrics, and treatment processes that extend cotton's usability into technical and high-performance applications.

Expanding Markets by Enhancing Cotton's Competitiveness: Making cotton more competitive through technological innovation opens new market opportunities. By improving characteristics such as durability, moisture management, and weather resistance, cotton can expand into sectors traditionally dominated by synthetic fibers. This not only increases market share but also offers consumers a natural and sustainable alternative in technical textiles.

CHALLENGE-5: MARKET DYNAMICS AND CONSUMER WILLINGNESS TO PAY

Threat

Price Sensitivity: Brands and retailers may be reluctant to pay a premium for cotton products, especially when synthetic alternatives offer significant cost advantages. Consequently, cotton probably cannot compete with the lowest end of the market since polyester costs a fraction of cotton. Synthetics are often cheaper to produce due to lower raw material costs and more straightforward manufacturing processes. This price sensitivity poses a significant threat to the cotton industry, as businesses might opt for more affordable synthetics to reduce costs and increase profit margins.

Opportunities

Consumer Willingness to Pay and Capitalizing on Sustainability Trends.

PwC's 2024 Voice of the Consumer Survey: A recent global survey by PwC (2024), encompassing over 20,000 consumers from 31 countries, underscores a significant consumer shift towards sustainability, with nearly 80% of buyers willing to pay a premium for sustainably produced or sourced goods. On average, consumers are prepared to spend 9.7% more on products that meet environmental criteria like local sourcing, recycled materials, or lower carbon footprints. This strong willingness to pay more for sustainability highlights an essential opportunity for the private sector to respond by offering sustainable options. By aligning with consumer preferences and investing in environmentally friendly practices, businesses can meet market demand and contribute to positive environmental impact, reinforcing the necessity for increased private sector engagement in sustainability initiatives.

Bain & Company Consumer survey: Recent research from Bain & Company in 2023, surveying 23,000 consumers worldwide, also reveals a significant consumer willingness to pay more for sustainable products—an average premium of 12% globally. In fast-growing markets like India, Indonesia, Brazil, and China, consumers are even willing to pay between 15% and 20% more. Despite this readiness, over 60% of businesses are off track to meet their sustainability goals. This disconnect underscores the urgent need for greater private sector investment in sustainability initiatives.

As consumers across generations and political spectrums express high levels of environmental concern—64% reporting heightened worries intensified by extreme weather events—they are seeking products that minimize environmental impact. However, with sustainable products often priced higher than the premium consumers are willing to pay (e.g., a 28% average premium in the U.S. against an 11% willingness to pay), there is a clear opportunity for businesses to align pricing and offerings with consumer expectations. By recognizing and responding to this consumer willingness to pay, the private sector can drive meaningful progress toward sustainability goals while meeting market demand.

Harvard Business Review Research on Consumer Patterns: Recent research (Reichheld et al., 2023) suggests we are on the brink of a significant shift in consumer behavior, where sustainability becomes a baseline requirement of social license rather than a mere "nice to have" bonus. Trust has been identified as a crucial driver of this change, profoundly impacting business outcomes. Studies involving hundreds of thousands of consumers and employees across more than 500 brands reveal that highly trusted companies can outperform others by up to 400% in market value. Notably, a one-point increase in a company's trust score (e.g., from 30 to 31) can lead to a 3% rise in expected stock returns, escalating to 6% when moving from 60 to 61.

Sustainability fosters trust among younger generations in particular. When Gen Z and Millennial consumers believe a brand cares about its impact on people and the planet, they are 27% more likely to purchase from it than older generations. Moreover, if they rate a brand highly on humanity, they are 15% more likely to spend more money and choose it over competitors; with high transparency ratings, these percentages increase to 30% and 20%, respectively. This is crucial as Millennials and Gen Z are projected to surpass Boomers in purchasing power around 2030, with up to $68 trillion transferring to them by decade's end.

An example illustrating these trends is Publix, a supermarket chain that ranks first in customer trust among 11 peer brands. Publix's humanity and transparency scores are 75% and 47% higher than its closest competitor, leading trusting customers to be 54% more likely to purchase from them — and this likelihood soars to 162% among Gen Z and Millennials. Publix's commitment to employees (who own 80% of the company), low voluntary turnover rate of 5% compared to the industry's 65%, and environmental initiatives like eliminating over 360,000 pounds of plastic waste annually exemplify how genuine investment in sustainability and transparency can build trust and secure future consumer loyalty.

Consumer Education: Continue focusing on sustainability and other issues such as durability, waste reduction, livelihoods, and other issues. Raising awareness about the environmental and social benefits of cotton has the potential to encourage consumers to make informed choices. Educating consumers about the advantages of cotton over synthetic fibers can influence purchasing decisions, especially if the price premium for cotton is modest. By highlighting cotton's natural, biodegradable properties and its lower environmental impact compared to synthetics, consumers may be more willing to choose cotton products if the cost is not excessive and trust is sufficient. Awareness campaigns and informative labeling can emphasize how cotton farming supports rural economies and promotes sustainable agricultural practices.

Fig-4 Consumer education

Building Trust and Transparency: Enhance transparency in the supply chain to build consumer trust and foster brand loyalty. Brands that demonstrate a genuine commitment to sustainability — through certifications, transparent sourcing, and ethical labor practices — can attract consumers who prioritize ethical consumption. This approach is especially effective among younger consumers who are more likely to support brands that align with their values on environmental and social responsibility.

Bridging the Intention-Action Gap: Address barriers that prevent consumers from acting on their sustainable intentions by offering competitive pricing and wider availability. While many consumers express a desire to purchase sustainable products, factors like higher prices and limited accessibility can hinder actual purchases. By offering cotton products at competitive prices and ensuring they are widely available, the industry can bridge this intention-action gap. Strategies may include optimizing production efficiencies, collaborating with retailers to feature cotton products prominently, and developing affordable cotton lines that meet both environmental standards and consumer budgets.

By addressing price sensitivity through consumer education and capitalizing on sustainability trends, the cotton industry can enhance consumer willingness to pay for cotton products. Building trust through transparency and making sustainable options accessible can further strengthen market position, allowing cotton to compete effectively against synthetic alternatives.

Transitioning from Fast Fashion to a Circular and Sustainable Model: The fashion industry's current reliance on fast fashion has led to significant environmental concerns, including waste generation and resource depletion. To support cotton and reclaim market share, there is an urgent need to transition from this model to a circular and sustainable one. This shift involves reimagining the entire lifecycle of cotton products—from design and production to consumption and recycling.

By making a compelling sustainability case for cotton, emphasizing its natural properties, biodegradability (Li et al., 2010), and lower environmental impact compared to synthetics (Zambrano, et al. 2018), the industry can attract environmentally conscious consumers. If the premium price for sustainably produced cotton remains reasonable, it becomes more accessible, encouraging both brands and consumers to choose cotton over less sustainable alternatives. This approach not only supports cotton farmers but also contributes to a more sustainable fashion industry overall.

ICAC's Role in Convening Stakeholders and Sharing Experiences: ICAC plays a pivotal role in uniting stakeholders across the cotton value chain to address common challenges and share best practices. Through the Private Sector Advisory Council (PSAC) — which includes cotton producers and ginners, spinners, weavers, machinery manufacturers, merchants and traders, brands, and retailers — the ICAC facilitates open dialogue on pressing issues affecting the industry. Additionally, the newly established Global Cotton Leaders Roundtable provides a high-level forum for discussion among industry leaders.

Scheduled to convene during the 82nd ICAC Plenary Meeting in Tashkent from 30 September to 3 October 2024, this group aims to foster collaboration and develop strategies to enhance the sustainability and competitiveness of cotton. By bringing together diverse perspectives, the ICAC helps coordinate efforts to promote sustainable practices and address market challenges collectively.

Building Stronger Connections Through the Cotton Value Chain: To transform sustainability intentions into a tangible market reality, strengthening connections throughout the cotton value chain is essential.

The ICAC seeks to build these connections by engaging with trade groups and facilitating partnerships among stakeholders at all levels — from farmers and manufacturers to brands and retailers.

By fostering better understanding and collaboration, the industry can align on sustainability goals and effectively implement practices that meet consumer demands. This collective effort enables the development of strategies that not only improve the sustainability of cotton production but also enhance its market appeal.

Through coordinated actions and shared commitment, the cotton industry can create a robust market for sustainable cotton products, ensuring long-term viability and success in an increasingly competitive global market.

CONCLUSION

Cotton stands at a crossroads where its rich heritage meets the demands of a modern, sustainability-focused world that is also price sensitive. By acknowledging its challenges and strategically leveraging its strengths, the cotton industry can chart a course toward a even more prosperous future.

Collaboration is key. Stakeholders across the supply chain — from farmers and traders to manufacturers and retailers — must work together to innovate and promote sustainable practices. By investing in research, engaging with policymakers, and fostering transparent relationships with consumers, the industry can enhance cotton's value proposition.

Cotton's journey is not just about maintaining market share; it's about reaffirming its place as a fiber that embodies quality, sustainability, and social responsibility. As global consciousness shifts towards more sustainable living, cotton has the opportunity to not only adapt but to lead the way in defining what a truly sustainable textile industry can look like.

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Remote Sensing Applications in Cotton Farming

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INTRODUCTION

Remote sensing (RS) is a technique that involves capturing and analyzing electromagnetic radiation from target objects or surfaces. This can be done using ground-based, airborne, or satellite technologies, depending on the required spatial and spectral resolutions for a specific application.

Handheld Remote Sensing Instruments Handheld remote sensing devices are highly effective for small-scale, field-level monitoring of both biotic and abiotic stress factors, as highlighted by Jackson in 1986. These instruments offer superior temporal, spectral, and spatial resolutions when compared to their airborne and satellite counterparts. However, a significant limitation is the time needed to assess small areas. Despite this, handheld spectroradiometers are commonly used in agriculture for various purposes, including yield forecasting, assessing nutritional needs, pest damage detection, water demand evaluation, and weed control.

Transition to Unmanned Aerial Vehicles (UAVs) Traditionally, airborne remote sensing was conducted using piloted aircraft, but this has largely been supplanted by Unmanned Aerial Vehicles (UAVs), controlled from ground stations. UAVs, which are cost-effective, lightweight, and capable of flying at low speeds, come in two main types: fixed-wing and rotary-wing. The choice between these types depends on the required flight speed, duration, and specific features such as vertical takeoff/landing and hovering capabilities. UAVs can carry a variety of sensors to collect high-resolution imagery, making them ideal for observing individual plants or patches within a field. This facilitates detailed assessments of crop health and field variability. Additionally, UAVs offer the flexibility of quick and repeated deployments at varying heights as per the user's convenience.

Satellite Imagery in Agriculture Historically, satellite imagery was used primarily for mapping crop types, assessing general crop conditions over large areas, and estimating crop acreage, despite its limited spatial resolution. Recent advancements in satellite sensor technology have improved resolution, enabling more precise assessments within individual fields, such as identifying areas affected by drought, flooding, or hail damage. However, satellite images are still constrained by their resolution limits and susceptibility to weather conditions. The effectiveness of satellite imagery for specific locations also depends on the frequency of satellite revisits.

Overall, the selection of a remote sensing method is driven by the scale of the area to be monitored, the detail required in the data, and the specific agricultural challenges being addressed.

KEY APPLICATIONS OF REMOTE SENSING IN AGRICULTURE

Remote sensing technology has significantly impacted agricultural management and monitoring since its initial application in the 1960s. A detailed overview of how remote sensing is utilized in agriculture is presented below:

Crop Identification and Cropland Mapping: Remote sensing aids in distinguishing between different crop types and mapping the extent of croplands. This is crucial for effective agricultural planning and management.

Crop Growth Monitoring and Yield Estimation/Prediction: Sensors mounted on various platforms enable the continuous observation of crop growth stages and health. This data is instrumental in estimating and predicting yields, helping farmers and stakeholders make informed decisions.

Investigation of Biophysical, Biochemical, and Environmental Parameters: Remote sensing is used to gather detailed information on a range of parameters including soil types, soil moisture levels, and crop health indicators like chlorophyll content. This data is vital for assessing crop vitality and planning resource allocation.

Crop Damage/Disaster Monitoring: This application involves monitoring crops for damage from pests, diseases, or weather-related disasters such as floods and droughts. Timely data from remote sensing allows for quick response to mitigate losses.

Precision Farming: Remote sensing technology supports precision farming practices by providing detailed data that helps in applying the right amounts of inputs (like water, fertilizers, and pesticides) at the right time and place to enhance crop productivity and sustainability.

Table 1. Sensitive wavebands used in remote sensing for monitoring crop growth and development

Waveband	Wavelength Range (nm)	Application	Reference
Blue	450-495	Early vegetation detection, chlorophyll absorption	Carter (1993)
Green	495-570	Chlorophyll content, plant health	Gitelson et al (1996)
Red	620-750	Vegetation health, biomass estimation, stress detection	Tucker (1979)
Near Infrared (NIR)	750-900	Biomass estimation, canopy structure, water content	Rouse et al (1974).
Red Edge	690-740	Chlorophyll concentration, stress detection	Barnes et al (2003)
Shortwave Infrared (SWIR)	1000-2500	Moisture content, plant water stress, lignin, and cellulose content	Key and Benson (2006)
Thermal Infrared (TIR)	8000-14000	Plant water stress, evapotranspiration	Jackson et al (1981)

Note: The specific bands and their associated wavelengths may vary based on the sensor and platform used.

Remote sensing continues to evolve with advancements in technology, providing increasingly detailed and timely data to support agricultural productivity and sustainability. The integration of these technologies into daily agricultural practices enables more precise and efficient management of resources, ultimately leading to enhanced crop yields and reduced environmental impact.

Crop stress conditions, such as those caused by drought, nutrient deficiencies, or disease, can be more effectively monitored through spectral vegetation indices rather than relying solely on individual spectral bands. These indices are calculated using data from multiple bands to enhance the contrast of specific vegetation characteristics, making it easier to identify and quantify changes in crop health.

Table 2. Multispectral and hyperspectral imaging-based vegetation indices used in crop monitoring

Vegetation Index	Formula	Application	Reference
Normalized Difference Vegetation Index (NDVI)	(NIR - Red) / (NIR + Red)	General vegetation health, nitrogen status	Rouse et al (1974)
Green Normalized Differ-ence Vegetation Index (GNDVI)	(NIR - Green) / (NIR + Green)	Chlorophyll content, ni-trogen status	Gitelson et al (1996)
Soil-Adjusted Vegetation Index (SAVI)	(NIR - Red) / (NIR + Red + L) * (1 + L)	Reduces soil back-ground influence, useful for low vegetation cover	Huete (1988)
Ratio Vegetation Index (RVI)	NIR / Red	Indicates vegetation densi-ty and health	Pearson and Miller (1972)
Normalized Difference Red Edge Index (NDRE)	(NIR - RedEdge) / (NIR + RedEdge)	Sensitive to chlorophyll content, nitrogen status	Barnes et al (2003)
Chlorophyll Index (CI)	NIR / Green - 1	Assesses chlorophyll con-tent, useful for nitrogen management	Gitelson et al (1996)
Red Edge Chlorophyll Index (CIred-edge)	(NIR / RedEdge) - 1	Sensitive to chlorophyll and nitrogen content	Gitelson et al (2008)

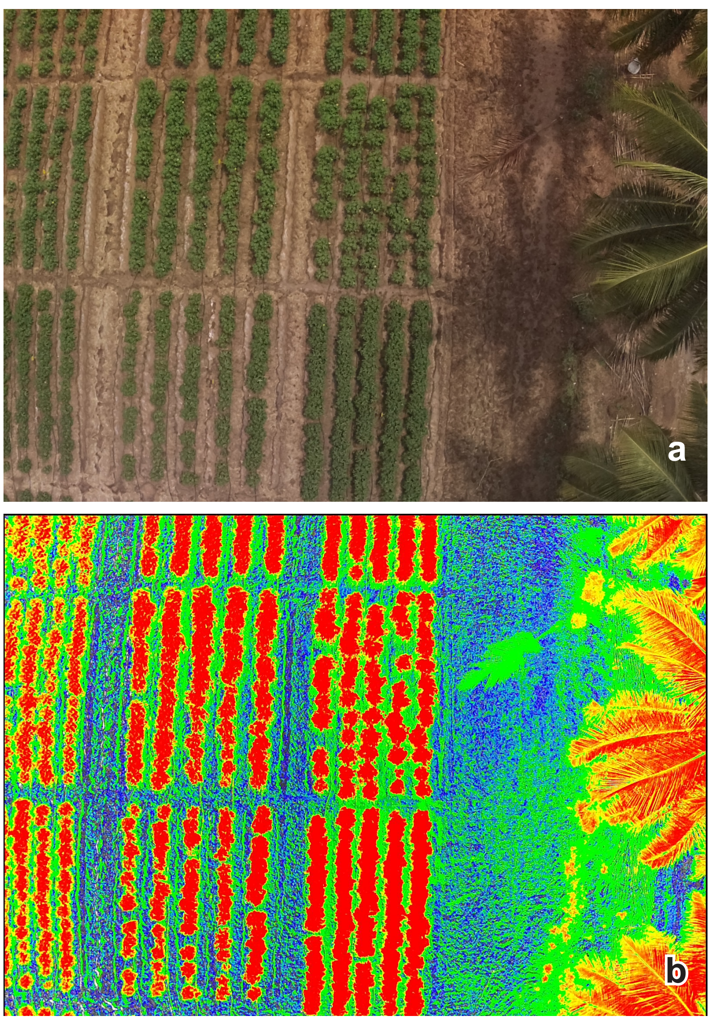
Remote Sensing Application in Agriculture: Remote sensing technology offers a variety of specific applications in agriculture that significantly enhance farm management and crop monitoring. These applications include sensing soil properties, which involves assessing soil texture, structure, physical condition, soil moisture, and nutrient levels. Crop sensing is another vital application, focusing on evaluating plant population, crop stress, pest and disease monitoring, and the nutrient status of crops. Additionally, yield monitoring systems utilize remote sensing to track crop yield, harvest swath width, and crop moisture content. Variable Rate Technology (VRT) systems also play a crucial role, regulating the flow of fertilizers, detecting weeds, and monitoring pressure sensors to optimize agricultural inputs and improve crop management practices. These technologies collectively contribute to more precise and efficient agricultural operations.

REMOTE SENSING AND COTTON FARMING

Cotton Area and Production Estimation: Cotton, a major global cash crop, benefits significantly from remote sensing technologies, which facilitate the efficient and timely estimation of cotton acreage, particularly in remote areas. These technologies also help in predicting production, assessing crop area loss due to natural disasters, and gathering other relevant statistics in a cost-effective and less labor-intensive manner. For large-scale monitoring, satellite data is predominantly used due to its extensive coverage and ability to capture broad geographic data quickly. On the other hand, Unmanned Aerial Vehicles (UAVs) are employed for more detailed, small-scale monitoring. A crucial aspect of precision agriculture is the accurate identification of cotton crops from remotely sensed imagery. Currently, the identification of the extent of crop areas is primarily achieved through supervised classification techniques, which depend on a considerable amount of training data and the use of advanced, optimized models, including neural networks, to enhance accuracy, as noted by Li Haolu and colleagues in 2021.

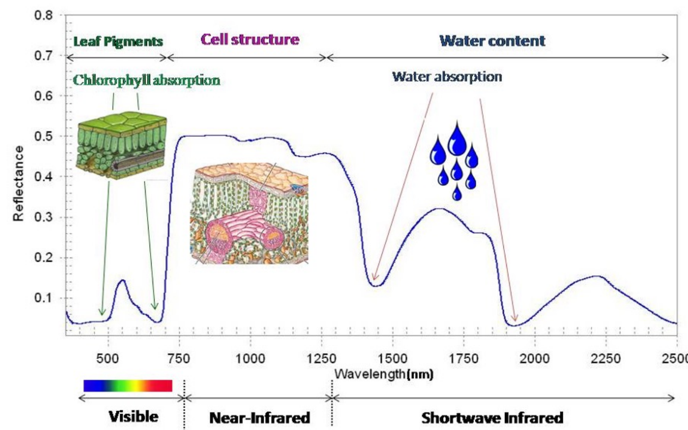
Figure 1. Cotton crop growth monitoring using DJI Phantom 4 multispectral imaging drone

Figure 2. Cotton crop growth observed through multispectral drone based (a) RGB image (b) Normalized Difference Vegetation Index image.



Monitoring crop stress in cotton: Monitoring crop stress in cotton is effectively conducted through the measurement of spectral reflectance, which is the reflectance of light from a target surface or object across different wavelengths. This is graphically represented as a spectral reflectance curve.

Figure 3. Typical spectra reflectance curve showing regions of electromagnetic spectrum and major absorption features (Source: Prabhakar et al., 2012)



Plant stress typically manifests as an increase in visible reflectance due to a reduction in chlorophyll content, which leads to decreased absorption of visible light, and a decrease in near-infrared (NIR) reflectance, which results from changes in the internal structure of the leaves (Hatfield and Pinter, 1993). The use of remote sensing techniques for detecting crop pests and diseases hinges on the assumption that the stress they induce interferes with both photosynthesis and the physical structure of the plant. This interference affects the plant's absorption and utilization of light energy, thereby altering its reflectance spectrum (Riley, 1989; Hatfield and Pinter, 1993; Moran et al., 1997). Such changes in the reflectance spectrum provide a means for remote detection and monitoring of plant health.

The induction of stress modifies the physiological behavior of the plant, creating distinct reflectance patterns that can be used for remote sensing diagnosis of vegetation stress. Additionally, natural growth processes such as biomass increase, development, maturation, senescence, changes in plant architecture, and fluctuations in hydraulic properties, along with biochemical changes like variations in chlorophyll and other pigment concentrations, influence how much solar energy is reflected, absorbed, and transmitted by the plants (Carter 1993; Lillesand et al., 2004; Ustin et al., 2002). Therefore, research into vegetative spectral reflectance provides valuable insights into the physiological, chemical, and physical processes of plants, facilitating the early detection of plant stress and enabling timely corrective measures.

Remote sensing for weed management: Remote sensing is increasingly popular for weed management in various crops, utilizing drones, spot sprayers, and satellite imagery. This approach is chosen based on several factors including capital expenditure requirements, scalability, costs, the ability to cover large areas quickly, and the need for trained operators. In scenarios where weeds affect only a small portion of a field, targeted spraying is employed to minimize chemical use, cost, and time. The effectiveness of using satellite imagery to identify weeds through custom algorithms has proven to be cost-effective. It not only reduces herbicide usage by 70-80% but also cuts down greenhouse gas emissions by 60kg CO_2e per hectare, showcasing significant environmental benefits (Neale, 2024).

Monitoring nutrition and precision nitrogen management in cotton: Monitoring nutrition and managing precision nitrogen application in cotton farming has been greatly enhanced through the use of hyperspectral monitoring. Research conducted by Lulu et al. (2022) established a theoretical framework using modeling methods to identify stable hyperspectral vegetation indices that are effective across different growth stages of cotton. As an indeterminate crop, the variability in soil fertility and nutrient management significantly influences cotton's growth patterns and eventual yield. Nitrogen (N) status, critical for plant health, can vary significantly within a single field. Traditional ground-based data collection methods for detecting this variability often face challenges related to spatial resolution. Recently, remote sensing has emerged as a promising alternative for assessing in-season nitrogen status in cotton. This shift has been facilitated by the integration of reliable, low-cost unmanned aerial vehicles (UAVs), high-resolution multi-spectral sensors, and sophisticated image processing software.

Figure 4. Graded level nitrogen field experiment for developing variable rate nitrogen application technology in cotton.

The application of these technologies allows for the precision delivery of nitrogenous fertilizers based on Variable Rate Technology (VRT). This approach not only enhances nitrogen use efficiency but also significantly reduces the overall quantity of nitrogen fertilizer applied, thereby mitigating environmental pollution. These advanced remote sensing techniques, could enable cotton farmers to optimize nutrient management, ensuring sustainable production and environmental conservation.

Recent advancements in remote sensing technologies have significantly improved nitrogen management in cotton farming across various global regions. In India, Sharma and Kumar (2023) utilized satellite imagery based NDVI (Normalized Difference Vegetation Index) to detect spatial variability in nitrogen requirements, while Patel and Singh (2022) integrated machine learning with NDVI for precision nitrogen recommendations.

In the Texas High Plains, Liu et al. (2019) employed UAV-based multispectral imaging, demonstrating that NDVI-based management enhances nitrogen efficiency and reduces costs without compromising yield. Similarly, Wang et al. (2023) in China optimized nitrogen application rates using UAV-based multispectral imagery, improving both yield and nitrogen use efficiency. Zhang et al. (2020) monitored cotton nitrogen status via hyperspectral imaging from satellite platforms, finding that hyperspectral indices correlate strongly with leaf nitrogen content, providing a reliable method for large-scale precision nitrogen management.

In Spain, Gonzalez and Perez (2021) used the NDRE (Normalized Difference Red Edge) index from UAV-based hyperspectral imaging for accurate nitrogen status assessments, and in a similar vein, Smith and White (2021) applied NDVI and SAVI (Soil Adjusted Vegetation Index) indices to enhance nitrogen management and cotton yield.

Remote sensing for pest monitoring and early warning in cotton: Accurate quantification of early symptoms is important from a pest management perspective, and efforts to remotely detect plant stress due to disease or insect activity utilize principles of biophysical remote sensing (Jensen, 1983). Prabhakar et al. (2011) demonstrated the capability of remote sensing techniques for detecting leafhopper (LH) severity stress on cotton. Cotton plants with varying levels of LH severity were selected from three major cotton-growing regions in India, with about 57-58 plants chosen from each location, each exhibiting different levels of LH damage symptoms.

Reflectance measurement in the spectral range of 350–2500 nm was recorded from these plants using a hyperspectral radiometer. In addition to spectral reflectance, chlorophyll (Chl) and relative water content (RWC) were also recorded. Reflectance from healthy and leafhopper-infested plants showed significant differences in the VIS and NIR regions.

The decrease in Chl a pigment was more significant than in Chl b in the infested plants, and the ratio of Chl a/b showed a decreasing trend with an increase in LH severity. Regression analysis revealed a significant linear relationship between LH severity and Chl (r^2 = 0.505), and a similar fit was also observed for RWC (r^2 = 0.402). Plotting linear intensity curves between reflectance at each waveband with infestation grade resulted in six sensitive bands that exhibited maximum correlation at different regions of the electromagnetic spectrum (376, 496, 691, 761, 1124, and 1457 nm).

Figure 5. Reflectance measurements of pest infestation using handheld hyperspectral radiometer.

Regression analysis of several ratio indices formulated with two or more of these sensitive bands led to the identification of new leafhopper indices (LHI) with the potential to detect leafhopper severity. These new indices, along with 20 other stress-related hyperspectral indices compiled from the literature, were further tested for their ability to detect LH severity. Two novel indices, LHI 2 and LHI 4, proposed in this study showed significantly high coefficients of determination across locations (r^2 range 0.521 to 0.825) and have potential use for detecting leafhopper severity in cotton.

Prabhakar et al. (2013) conducted a study to characterize the reflectance spectra of cotton plants affected by varying levels of mealybug infestation, categorized from grade-0 (healthy) to grade-4 (severe). Using a hyperspectral radiometer, reflectance measurements were taken across the spectral range of 350–2500 nm. They observed significant differences in the green, near infrared, and short wave infrared spectral regions for plants in the early stages of *P. solenopsis* infestation, with these differences becoming more pronounced across almost all regions, except blue, for plants with higher infestation levels. The study also noted a significant reduction in total chlorophyll content, ranging from 12.83% to 35.83%, and in relative water content, ranging from 1.93% to 23.49%, in the infested plants.

A reflectance sensitivity analysis of the hyperspectral data pinpointed wavelengths at 492, 550, 674, 768, and 1454 nm as being most sensitive to mealybug damage. Based on these findings, Mealybug Stress Indices (MSIs) were developed using two or three of these wavelengths and were then tested using multinomial logistic regression (MLR) analysis. These indices proved superior to other spectral vegetation indices, achieving an r^2 value of 0.82. The effectiveness of the MSIs was further validated using two independent field data sets, with overall correct classification rates for different severities of mealybug damage ranging between 38.3% and 54.9%. Notably, the high classification accuracy for a 'grade-1-damage' of 81.8%, demonstrated the models' capability for early detection of mealybug damage in cotton plants.

In 2021, Weicheng et al. developed a sophisticated cotton yield estimation model utilizing time-series data from Unmanned Aerial Vehicles (UAVs). The model employs the U-Net semantic segmentation network to identify and isolate boll opening pixels in high-resolution visible images, calculating the boll opening pixel percentage (BOP) based on these extracted results. This data is then integrated with multispectral images covering the cotton bolls, and a Bayesian regularization back propagation (BP) neural network is utilized to predict cotton yields.

To streamline the model's input parameters, a stepwise sensitivity analysis method was applied to remove redundant variables and optimize the input feature set. The model achieved a robust R^2 value of 0.853 at a spatial scale of 0.81 m^2. This approach not only fulfills the dual needs of large-area and small-scale yield forecasting but also introduces innovative techniques for measuring cotton yield and advancing breeding screening processes.

CONCLUSION

Remote sensing offers precise and reliable data crucial for managing the health of various crops, including cotton. Ground-based radiometric studies are vital for analysing spectral interactions between healthy and stressed vegetation, providing essential ground-truth data to interpret observations from airborne and satellite remote sensing. While satellite remote sensing is valuable for large-scale studies, it faces limitations such as temporal and spatial resolution issues and cloud cover interference. In contrast, airborne systems accord higher resolution and greater temporal flexibility, allowing for timely dissemination of crop protection advisories.

Hyperspectral remote sensing, with its ability to detect narrow band wavelengths, precisely measures the characteristic absorption peaks of plant pigments, enhancing the assessment of plant health.

However, there is a pressing need for further research to identify hyperspectral bands and spectral vegetation indices that are specific to certain stressors. Additionally, integrating IoT, artificial intelligence (AI), and big data analytics with remote sensing technologies could significantly enhance the real-time monitoring of spatial variability in cotton crops, thereby supporting more informed decision-making processes.

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Genes From the Wild: A Bountiful Harvest

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Dr. Dharminder Pathak earned his Master's Degree and Ph.D. in Plant Breeding from Punjab Agricultural University, Ludhiana, India. He is currently serving as Principal Cotton Breeder (Professor) in the Department of Plant Breeding and Genetics at Punjab Agricultural University, Ludhiana. He has developed 25 cotton cultivars of Upland cotton and desi cotton (*G. arboreum*), as well as one variety of celery. Dr. Pathak has been instrumental in initiating and strengthening wide hybridization research in cotton at Punjab Agricultural University, which led to the successful introgression and mapping of cotton leaf curl disease (CLCuD) resistance from the diploid wild cotton species *G. armourianum* to Upland cotton. He has also developed pre-breeding lines with resistance to whitefly using a 'Synthetic Cotton Polyploid.' Other traits of interest include resistance to leafhopper, thrips, pink bollworm, and drought tolerance. Dr. Pathak teaches courses in genetics and plant breeding to undergraduate and postgraduate students. He has successfully guided 11 M.S. and two Ph.D. students as Major Advisor. He has handled several competitive projects as Principal Investigator. He has published in high-impact journals and edited a book, Cotton: Some Insights. He was a Visiting Scientist in the laboratory of Dr. Jonathan Wendel at Iowa State University, USA. For his contributions to cotton breeding, Dr. Pathak was awarded the "Appreciation Certificate" (2019) by Punjab Agricultural University and the "Rao Bahadur V. Ramanatha Iyer Award" (2023) by the Indian Society for Cotton Improvement, Mumbai.

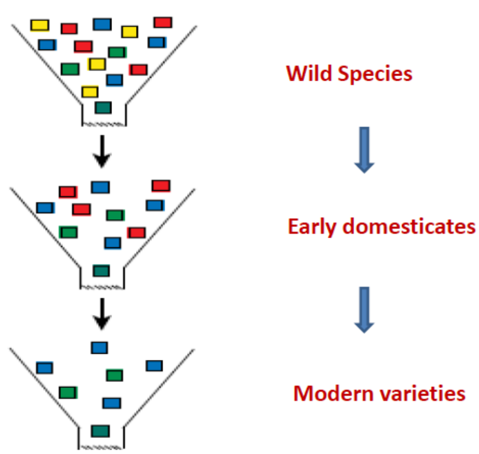
ORIGINS OF CROP DOMESTICATION

Crops were first domesticated about 10,000 years ago when early humans selectively cultivated plants that were most suitable to their needs from the vast genetic diversity found in the wild. At the time, these early agriculturalists were completely unaware of the underlying genetic variations that made domestication possible. The systematic manipulation of genes for crop improvement began much later, only after the rediscovery of Mendel's principles of inheritance in the last century. This led to significant enhancements in the yield of various crop plants such as wheat, corn, rice, and cotton. While genetic resources from primarily domesticated species have played a crucial role in these advancements, certain crops like sugarcane and tomato have seen substantial improvements, thanks to their wild relatives.

THE IMPACT OF MODERN BREEDING PRACTICES

The process of domestication followed by modern plant breeding has resulted in a significant narrowing of the genetic base for many crops, including cotton, wheat and soybean. The historical Southern corn leaf blight epidemic of 1970, which led to a significant drop in maize yields across the United States, exemplifies the dangers of genetic uniformity. The susceptibility to this disease was linked to the widespread use of a single cytoplasmic male sterility source. This example underscores the risks associated with genetic uniformity and highlight the urgent need to widen the genetic base by introducing novel alleles from related wild species, geographically un-adapted germplasm, and landraces. Plant breeders often focus on hybridizing genetically similar, high-yielding genotypes to create new cultivars, adhering to the philosophy of crossing the best with the best — and then hoping for the best. Unfortunately, this approach typically excludes genetically diverse but lower-yielding wild relatives from the breeder's selection, limiting the genetic diversity available.

Figure 1. Loss of genetic variation. Source: Tanksley, S. D and McCouch S (1997) Science277: 1063 DOI: 10.1126/science.277.5329.1063.

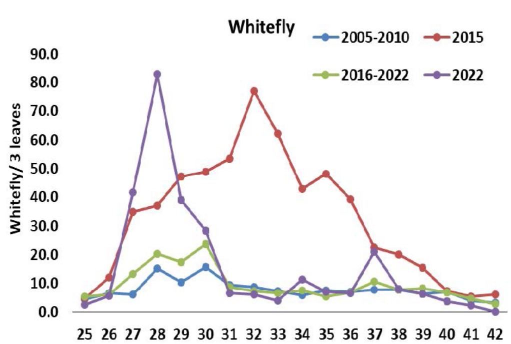


Domestication and intensive breeding have led to a significant reduction in the genetic diversity of the cultivated allotetraploid cotton species, *Gossypium hirsutum* and *G. barbadense* (Dubey et al., 2024), thereby narrowing the genetic base available for cotton varietal improvement. This limited genetic pool makes crops less capable of resisting major losses from insect and disease epidemics, as seen with the whitefly epidemic that devastated approximately 1.5 million hectares of cotton in the north Indian states of Punjab, Haryana, and Rajasthan in 2015. This epidemic drastically reduced cotton productivity in Punjab from a five-year average of 573 kg lint ha^{-1} to just 197 kg lint ha^{-1} (Kumar et al. 2020).

Figure 1. Cotton field devastated due to whitefly epidemic in 2015

Figure 2. Whiteflies on a CLCuD infected cotton leaf

Figure 3. Whitefly epidemics in Punjab, India.



HARNESSING GENETIC DIVERSITY FROM WILD COTTON RELATIVES

While most commercial cotton varieties derive from *G. hirsutum* and *G. barbadense*, the *Gossypium* genus comprises around 50 recognized species, many of which are wild. These wild species are treasure troves of genetic diversity, harboring genes that confer resistance to pests and diseases, tolerance to abiotic stresses such as drought and heat, and improved fiber qualities. Utilizing this genetic reservoir can lead to the development of robust high yielding cotton varieties that are better equipped to handle changing climate conditions and meet the demands of the textile industry.

Wild relatives of crop species consistently offer a rich reservoir of beneficial genetic diversity (Atwell et al., 2014). Wild species of cotton possess unique traits and alleles that are invaluable in cotton breeding programs. These traits can enhance genetic variability, facilitate the creation of pre-breeding genetic material, and aid in the development of new varieties that are climate-resilient, with improved fiber traits and increased productivity (Dempewolf et al., 2017; Scafaro et al., 2018; Bohra et al., 2022). The genetic resources of wild crop relatives, thriving in diverse environmental conditions, are essential for their wide range of genetic traits that can combat both abiotic and biotic stresses (Vincent et al., 2013). Due to their evolution in varied and challenging environments, these wild relatives are likely carriers of alleles that confer resilience to a variety of environmental stresses, including temperature extremes, drought, and salinity (Mammadov et al., 2018). Wild cotton species, found in diverse ecosystems from arid zones to tropical regions, exhibit a wide range of adaptive traits. For instance, *G. tomentosum* from Hawaii shows promising drought tolerance, while *G. aridum* from Mexico is known for its heat tolerance. These species have evolved over millennia to withstand specific environmental stresses, making them invaluable for enhancing the genetic makeup of cultivated cotton. The diverse traits identified in various wild *Gossypium* species offer substantial benefits for enhancing commercial cotton varieties. Additionally, recent research has shown that *Gossypium* wild relatives contribute to novel disease resistance mechanisms that could protect against emerging pathogens and pests, thereby ensuring sustainable cotton production under the threat of global climate change and increasing pest pressures.

G. tomentosum is known for its heat tolerance and the nectariless trait, which provides resistance against tarnished plant bugs, leafhoppers, boll rot, and bollworms, making it a valuable resource for improving cotton resilience and quality (Saha et al., 2006). Additionally, it resists jassids and thrips and is recognized for its superior fiber qualities such as length and fineness (Hulse-Kemp et al., 2014; Zhang et al., 2011).

G. mustelinum and *G. darwinii* are known for their finer fibers and drought tolerance, along with their resistance to Fusarium and Verticillium wilt, traits crucial in regions prone to these diseases (Chen et al., 2015; Wang et al., 2016;

Wendel et al., 1994). Similarly, *G. africanum* enhances cotton breeding programs with its high fiber strength, essential for improving the mechanical properties of cotton fibers (Chiavegato et al., 1985).

Figure 4. Wild species *G. mustelinum* and *G. darwinii*

et al., 1992; Miyazaki et al., 2012). *G. anomalum* stands out for its resistance to cotton wilt, angular leaf spot, and aphids, and is also recognized for its drought tolerance and high fiber quality (Wang et al., 2016).

Among other notable species, *G. capitis-viridis* and *G. sturtianum* offer high fiber quality and resistance to diseases like Fusarium wilt, which are valuable for breeding robust cotton varieties (Chen et al., 2015; Bi et al., 1998; Becerra Lopez-Lavalle et al., 2007). *G. thurberi* is adaptable to cooler climates,

Figure 5. *Gossypium arboreum*

G. herbaceum L., and *G. arboreum* L., both show resistance to common pests such as hoppers, white flies, thrips, aphids, and the leaf curl virus, with *G. arboreum* L. also exhibiting drought tolerance and resistance to black root rot, reniform nematodes, and spider-mites (Kulkarni et al., 2009; Stanton showing tolerance to mild frost and high resistance to *Verticillium dahliae* (Zhao et al., 2012; Wendel and Grover, 2015).

The salinity tolerance exhibited by *G. davidsonii, G. klotzschianum,* and *G. aridum* is critical for cultivation in saline environments, with *G. aridum* also showing resistance to the reniform nematode, enhancing its adaptability to various soil types (Zhang et al., 2016; Wei et al., 2017; Xu et al., 2013; Sacks and Robinson, 2009).

Additionally, species like *G. harknessii, G. gossypioides,* and *G. lobatum* contribute crucial traits such as cytoplasmic male sterility for hybrid breeding, resistance to cotton leaf curl disease for disease management, and strong resistance to Verticillium wilt, respectively (Meyer, 1975; Azhar et al., 2013; Peggy and Brady, 2002). *G. trilobum, G. stocksii,* and *G. somalense* further enhance cotton's resistance to various pests and diseases while improving fiber strength and tolerance to environmental stresses (Yu et al., 2012; Nazeer et al., 2014; Yik and Birchfield, 1984; Zhou et al., 2004).

Figure 6. Wild species *G. gossypioides* and *G. armourianum*

Finally, *G. longicalyx, G. bickii*, and *G. australe* are notable for their specific pest resistances and glandless-seed traits, which are particularly beneficial for producing hypoallergenic cotton products and developing resilient cotton varieties capable of thriving under challenging environmental conditions (Dighe et al., 2009; Zhu et al., 2005; Schuster et al., 1972; Chen et al., 2014).

These diverse and beneficial traits from wild *Gossypium* species underscore their significant potential in genetic improvement programs aimed at enhancing the resilience, quality, and environmental adaptability of cultivated cotton.

COMBATING CLIMATE CHANGE THROUGH INTROGRESSIVE HYBRIDIZATION

Crop productivity is increasingly affected by the consequences of climate change. Climate models predict a global mean temperature increase of at least 3°C over the next three decades, accompanied by more unpredictable and catastrophic weather events, including intense heatwaves (Calvin et al. 2023). These environmental stresses, particularly heatwaves, are recognized as increasing threats to agricultural productivity, including cotton, which is typically irrigated to mitigate drought yet remains vulnerable at both vegetative and reproductive stages (Hatfield et al. 2011; Reddy et al. 1992a,b; Singh et al. 2007; Masoomi-Aladizgeh et al. 2021). Higher temperatures may result in reduced water use efficiency and considerable fruit drop in cotton, thereby lowering yield and altering fiber quality (Bange and Broughton 2023). Temperatures above the optimal requirement for cotton disrupt critical reproductive processes, especially pollen viability and therefore fruiting (Reddy et al. 1992a; Masoomi-Aladizgeh et al. 2021, 2022), apart from impairing physiological processes in cotton leaves, thereby affecting multiple plant processes and overall plant performance (Reddy et al. 1992b; Najeeb et al. 2017; Zafar et al. 2018; Masoomi-Aladizgeh et al. 2022). These complex interactions under supra-optimal temperatures highlight the urgent need for breeding heat-tolerant cotton varieties to sustain productivity in warmer climates.

Wild cotton species often possess traits that can help cultivated varieties adapt to extreme weather patterns. For instance, genes responsible for deeper root systems in some wild species can be introduced into cultivated varieties to enhance water-use efficiency and drought tolerance. Saline soils significantly restrict cotton yields, particularly under changing climate conditions. D-genome wild cotton species namely, *G. davidsonii* , *G. klotzschianum* and *G. aridum* have been reported to exhibit tolerance to salinity stress (Xu, et al., 2013; Shim et. al., 2018). Improving fiber traits is another critical goal of cotton breeding in a changing climate that threatens fibre quality. Wild species such as *G. longicalyx* and *G. armourianum* exhibit unique fiber properties that, if integrated into commercial lines, could lead to the production of finer and stronger fibers, thus enhancing the economic value of cotton.

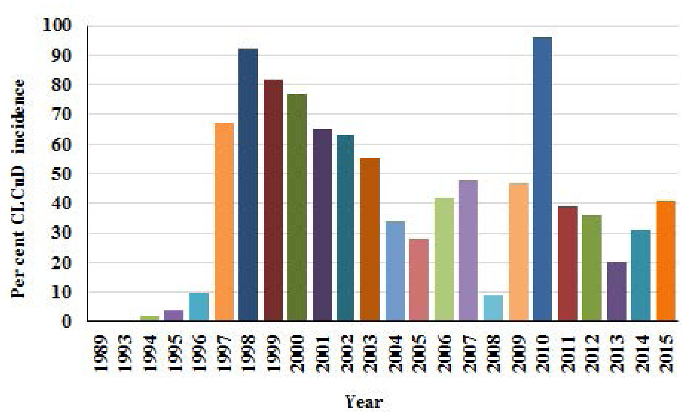
COMBATING COTTON LEAF CURL DISEASE (CLCUD) THROUGH INTROGRESSIVE HYBRIDIZATION

Among various biotic stresses, cotton leaf curl disease (CLCuD) poses a significant threat to *G. hirsutum* cultivation in north-western India and Pakistan. Enormous economic losses, estimated at US$ 5 billion from 1992-1997 in Pakistan (Briddon and Markham 2000), and a roughly 40% drop in cotton yield in India (Bhattacharyya et al. 2017), underscore the severity of the impact. This disease has also spread to China, affecting three countries that collectively produce nearly 49 percent of the global cotton and account for 84.5 percent of the world's cotton farmers (Kranthi 2022). Managing this disease is crucial for sustainable global cotton pro-

Figure 7. Cotton Leaf Curl Viral Disease (CLCuD)

Figure 8. Cotton Leaf infected with CLCuD

Figure 9. CLCuD incidence in India



duction. Unfortunately, resistance to CLCuD in *G. hirsutum* has diminished due to the emergence of new viral strains that break existing resistances.

Several related cotton species such as *G. thurberi, G. anomalum, G. arboreum* (Akhtar et al. 2010); *G. herbaceum, G. gossypoides* (Azhar et al. 2013); *G. armourianum* (Pathak et al. 2016); *G. robinsonii* (Azhar et al. 2011); *G. stocksii* (Nazeer et al. 2014) are known to possess resistance to CLCuD. However, transferring these genes or traits from related species to *G. hirsutum* presents significant challenges due to various genetic barriers.

Working with related or wild species is challenging and often frustrating, yet it remains a highly rewarding exercise. For example, a staggering 15,898 flowers of the interspecific hybrid (*G. hirsutum/G. armourianum*) had to be pollinated with *G. hirsutum* to achieve only four successful backcross plants. Through numerous backcrosses and rounds of self-fertilization, we have developed an advanced CLCuD resistant and named it, PAU Armour.

A major gene introgressed from *G. armourianum*, conferring resistance to CLCuD, has been successfully mapped (Pathak et al. 2024). Another significant source of CLCuD resistance is Mac 7, an introgression line of *G. hirsutum* (Zaidi et al. 2020). Several quantitative trait loci (QTL) associated with CLCuD resistance have been identified on chromosomes 3, 5, and 16 in Mac 7 (Schoonmaker et al. 2023). Utilizing Mac 7, an upland cotton variety namely IR-NIBGE-11has been released in Pakistan.

Figure 10. Advanced CLCuD resistant line 'PAU Armour'

COMBATING INSECT PESTS THROUGH INTROGRESSIVE HYBRIDIZATION

Bollworms have historically inflicted heavy losses on the cotton crop in India. The development and commercialization of transgenic *Bt* cotton provided significant relief from bollworm infestation. However, *Bt* cotton hybrids grown in India are highly susceptible to sap-feeding insect pests (Kranthi and Stone 2020), resulting in a shift in pest profile from bollworms to sap suckers. Climate change plays a crucial role in the dynamics of these insect pests.

Studies on the population dynamics of key pests in the Indian Punjab show that thrip incidence is increasing and remains high throughout the cotton season. Similarly, the leafhopper scenario has changed over the last decade, with higher populations persisting throughout the crop season. Pushpam and Raveendran (2006) successfully developed interspecific hybrids between *G. hirsutum* and jassid resistant wild species *G. raimondii* and *G. armourianum* for leaf hopper tolerance.

Figure 11. Progressive increase in thrips incidence

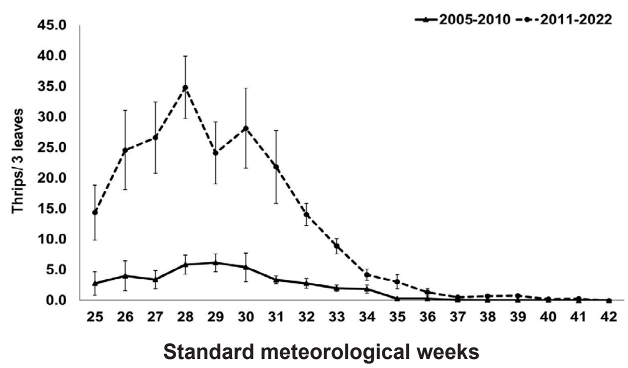
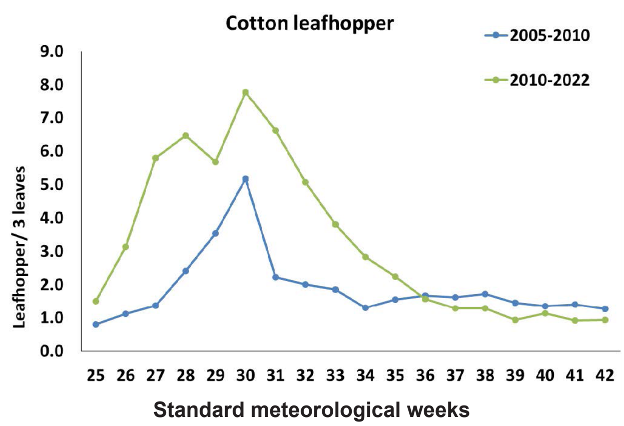


Figure 12. Progressive increase in leafhopper incidence



Whiteflies remain a significant challenge, as demonstrated by the devastating whitefly epidemics in 2015, which destroyed cotton crops across 1.5 million hectares in North India. Resistance or tolerance to these sap-sucking pests is present in related species; for instance, *G. arboreum*, one of the two cultivated diploid cotton species, shows strong resistance to leafhoppers (Sidhu and Dhawan 1980; Nibouche et al. 2008). Using bulked segregant analysis in an interspecific population derived from *G. hirsutum* × *G. arboreum* crosses, we have tagged two SSR markers (NAU 922 and BNL 1705) located on chromosomes A5 and A11 respectively, associated with leafhopper tolerance (Jindal et al. 2022).

Additionally, Mac 7, an introgression line developed by the United States Department of Agriculture, exhibits tolerance to whiteflies. We have identified two genomic regions associated with whitefly tolerance in Mac 7. In another study, we found that *G. arboreum* species was more tolerant to thrips as compared to *G. hirsutum*. Similarly, we have elucidated bases of tolerance to whitefly in a synthetic cotton polyploid and its derivatives (Kaur et al. 2024) and *G. armourianum* (Suther et al. 2022). After the breakdown of resistant against pink bollworm (*Pectinophora gossypiella*) in transgenic *Bt* cotton, this pest has become very serious. An earlier report by Mehetre et al. (2009) has shown that resistance to pink bollworm is available in a wild diploid D-genome cotton species – *G. thurberi*.

Figure 13. Mac 7 line, developed by the USDA

MISLEADING PHENOTYPES IN CROP IMPROVEMENT

It is often said that seeing is believing, yet phenotypes can sometimes be misleading. For example, fruits of *Lycopersicon hirsutum*, a wild tomato species, do not change color even after ripening and remain green. However, genes for enhanced red pigment (lycopene) have been successfully introgressed from this species into cultivated tomatoes (c.f. Tanksley and McCouch 1997). Similarly, genes for increased fruit weight have been introduced into cultivated tomatoes from *L. pimpinellifolium*, which has very small-sized fruits (Tanksley et al. 1996). *G. hirsutum* and Pima cotton are products of a hybridization event that occurred about 1-2 million years ago, involving progenitor species resembling today's *G. herbaceum* (AA) and *G. raimondii* (DD). Molecular genetic studies have shown that many genes conferring better fiber properties are located on the D-genome. Interestingly, the D-genome donor itself is lintless.

CALL FOR COLLABORATIVE EFFORTS

There is a vast ocean of genetic resources available within the 52 recognized species of the *Gossypium* genus, of which only four are currently cultivated for fiber. This untapped potential calls for collaborative efforts to explore and utilize these resources effectively. The establishment of a "Centre of Excellence on Pre-Breeding of Cotton" could spearhead these efforts, enhancing cotton genetics for future generations. Let us embrace collaboration over competition to harness the full potential of genes from the wild for crop improvement.

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