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Cotton: Bridging Innovation, Sustainability, and Equity

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Editorial

Cotton: Bridging Innovation, Sustainability, and Equity

The global cotton sector is growing but faces serious challenges. Issues like unpredictable weather, scarce resources, and unequal opportunities need fresh solutions—not just small adjustments. Climate volatility, resource scarcity, market volatility, increasing competition from other fibers, and socio-economic inequities affecting smallholder farmers demand more than just incremental solutions — they call for a fundamental paradigm shift.

This issue of the ICAC Recorder brings together four articles that chart a potentially transformative course for the future of cotton, weaving together innovation, regenerative agriculture, and water stewardship in pursuit of a more competitive, sustainable, and equitable sector.

Dr Jodi Scheffler opens the issue with a compelling perspective in "Moving Cotton Forward by Combining Global Resources with New Technologies." Her article highlights a critical reality: The threats confronting cotton — be they verticillium wilt in Uzbekistan or Cotton Leaf Curl Disease in Pakistan — do not recognize borders. The success of the Cotton Productivity Enhancement Program (CPEP), uniting more than 70 scientists across 13 collaborative projects, illustrates that international partnerships are not optional — they are essential.

Yet, Prof. Scheffler's insights reach beyond the technical. She emphasizes the importance of listening to farmers and understanding their "backstories." In both Mississippi and Multan, prescriptive, top-down approaches fail when they overlook local realities. As digital tools proliferate in the post-Covid world, the challenge is to use them to amplify farmers' voices, not replace them.

The theme of equity is central to the next two articles: 1) A feature from Marcelo Paytas, Director of INTA in Argentina, on how regenerative agriculture can mitigate climate change in South America, and 2) An analysis of the challenges of regenerative cotton practices faced by India's smallholder farmers, by MV Venugopalan, Retd Principal Scientist at ICAR-Central Institute for Cotton Research, and ICAC Chief Scientist Dr Kranthi. Their articles emphasize that sustainability cannot be divorced from justice. In Argentina's Chaco region, regenerative practices such as zero-tillage, cover cropping, and precision irrigation have enabled large-scale farms to boost yields by up to 30% while simultaneously sequestering carbon. By contrast, smallholders in India's rainfed zones wrestle with labor shortages, limited mechanization, and insecure land tenure, even as they adopt ecologically sound practices like integrated nutrient management and the use of biopesticides.

This disparity reveals a stark truth: regenerative agriculture must not become a privilege of the well-resourced. It must be democratized through targeted financing mechanisms such as India's proposed Green Credit Scheme, gender-inclusive extension models like Pakistan's Women Open Schools (WOS), and harmonized policies for measuring soil carbon to unlock carbon markets.

Dr. Kranthi's global analysis of cotton's water footprint directly challenges the misleading perception of cotton as a "thirsty crop." The data reveal that 75% of the water used for cotton comes from rainfall, a resource completely beyond human control. While irrigation inefficiencies persist — especially with flood irrigation systems — drip systems are deployed in only 19% of irrigated cotton fields.

'This disparity reveals a stark truth: regenerative agriculture must not become a privilege of the well-resourced'

The real concern, as Kranthi argues, is not the total water consumed, but the inefficiency of its use. Irrigation water use remains disproportionately high in Egypt and across Asia's primary cotton belt, spanning the arid zones of North India, Pakistan, and Central Asia (Turkmenistan, Kazakhstan, Uzbekistan). Modernizing antiquated canal systems and inefficient flood irrigation practices in these regions could conserve billions of liters of water annually, while boosting crop resilience.

For instance, the Soviet-era canals in Central Asia lose over 40% of water to seepage and evaporation. Targeted upgrades — such as concrete lining, automated gates, and drip integration — could slash waste and align productivity with sustainability. In, India's Punjab region, switching from rice-cotton to maize-cotton rotations could reduce groundwater depletion by 30%. The conversation must evolve from "how much water cotton uses" to "how smartly we use water for cotton."

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Together, the articles in this issue outline three strategic imperatives for the cotton sector:

1. *Science must be collaborative. Germplasm exchange should be accelerated by minimizing bureaucratic obstacles, and investments in predictive tools that should be scaled as global public goods.*
2. *Equity must be non-negotiable. The mechanization gap, particularly in Africa where inefficient hand-hoeing results in an estimated 1.5 million tons of lost production annually, must be bridged through smallholder-friendly innovations like solar-powered weeders. Farmers should be compensated not just for lint but for ecosystem services such as carbon sequestration, following models like Brazil's ABC+ Carbon Program.*
3. *Water must be managed as a shared responsibility. Precision irrigation technologies should be prioritized in water-stressed regions, and watershed replenishment goals — like the "1.5x water return" metric in the Cotton 2040 initiative — should guide sustainability standards for cotton sourcing.*

As we move deeper into a technology-intensive era, cotton stands at a crossroads. The choice is stark: continue along a path defined by monocultures, high-input systems, and inequitable value chains — or embrace a regenerative future rooted in collaboration, innovation, and justice.

The conversation must evolve from "how much water cotton uses" to "how smartly we use water for cotton."

The second path requires boldness — the courage to share knowledge openly, to treat farmers as co-creators of solutions, and to measure success not just by productivity, but by the amount of carbon captured, livelihoods improved, and ecosystems restored.

As this issue goes to press, record heatwaves across Asia and devastating floods in East Africa are a sobering reminder that time is not on our side. Let these pages inspire not just discussion but determined action. Cotton's future must be forged in the language of economic, competitiveness, equity, resilience, and shared responsibility. In today's world, it has become imperative that we must rise to meet these challenges. Let cotton fields teach us resilience — where roots dig deep through drought and deluge, where every drop holds the weight of tomorrow, and every harvest whispers: "Begin again, with gratitude to the soil beneath."

– Keshav Kranthi

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Moving Cotton Forward by Combining Global Resources with New Technologies

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Dr Jodi Scheffler

Dr Jodi Scheffler is Lead Scientist of the cotton genetics research group at the USDA Crop Genetics Research Unit, Stoneville, Mississippi USA and adjunct Professor at Mississippi State University. She worked for 12 years in the United Kingdom and Germany, before joining USDA in 2000. At USDA, she has been instrumental in identifying, developing and making available molecular markers for use by the cotton community. Her research focuses on increasing cottonseed use and incorporating traits that will improve host plant resistance (HPR). Internationally, she has worked with a number of research partners developing ultra-early cotton with verticillium wilt resistance and producing cotton leaf curl disease resistant cotton along with diagnostic tests and best management practices to mitigate effects of the disease. More recently, cotton leaf roll dwarf virus (CLRDV) has emerged as a threat to U.S. growers. Using germplasm from many geographic sources, she identified resistant germplasm and developed putative DNA markers to facilitate transferring resistance into elite breeding lines. She has always sought to build teams and seek out collaborators globally who had complimentary expertise so together their research could

Throughout her career she has advised students and mentored the next generation of scientists. She believes in starting early with STEM outreach activities in the schools and job training for high school and undergraduate student interns. Of the 44 students that have worked in her group, 39 have obtained a B.S degree or higher. Dr. Scheffler is active in a number of professional organizations including ICAC and the International Cotton Researchers Association (ICRA).

Dr. Scheffler was the recipient of the 2014 National Cotton Genetics Research Award, co-recipient of the 2016 Federal Laboratory Consortium's Regional STEM Education Award, the 2016 Secretary of Agriculture's Abraham Lincoln Award and winner of the ICAC Researcher of the Year Award 2022.

Global Challenges in Cotton Production

The Today, there are many challenges facing cotton production and processing, and no single scientist or any individual country can overcome these challenges alone. Solving our challenges will take a coordinated global effort.

The first step is to find ways to join together with other research partners and identify resources that can be leveraged to solve problems common to all cotton-producing countries. Although there is no total replacement for in-person meetings and collaborations, there are ways that we can form and maintain meaningful partnerships using modern communication technologies and networking options. The Covid-19 pandemic forced us to find new and novel ways to communicate and maintain partnerships, and we can now use some of those skills to remain more connected globally and work together more effectively to solve threats to cotton production internationally.

Figure-1 The Climate Change Challenge

Importance of International Cooperation

The mission of the United States Department of Agriculture (USDA) is to solve problems for US growers — but to do this effectively, we need work together by forming international partnerships that successfully address threats and mitigate global production problems. It is also vital to be proactive. It can take five to 10 years to develop cotton varieties with resistance to pests or diseases, so we don't want to wait until the problem has already become a major threat.

My first international USDA project was in Uzbekistan, where the two countries had common goals and collaborated to find sources of resistance to a serious cotton disease called verticillium wilt. Together, we developed cotton that can mature in only 110 days rather than 160 days.

Figure-2 *Combating Verticillium Wilt in Uzbekistan*

This germplasm was important for cotton growers in the USA and Uzbekistan because verticillium wilt is a problem in both countries, and early-season frost can kill later-maturing cotton. Some valuable lessons learned from this partnership can be important more broadly for successful collaborative projects.

The most important lesson I learned is to never assume I know the best way to approach a research problem before observing and listening to the people I will be working with — and the people our research may be impacting. It is sometimes challenging, but we should always try to understand the reality of a situation for the people we serve. Even if we think they are not being as effective as they could be, there are often good reasons for their current cultivation techniques or seed selection.

Try to understand the "backstory" before charging forward. It is important to develop good relationships with government officials in the field in which you work. They should not dictate what you do, but their support is critical, especially for the long-term sustainability of any project. It is also necessary to fit your actions to the circumstances. For example, purchasing the most modern equipment for capacity building is no good if the country's current infrastructure cannot support it, or there is no way to obtain supplies for the equipment. Make sure what you are doing will actually help.

Successes in Weed and Disease Control

An example of a successful large international project was one started in 2009, with government officials from Pakistan and the United States meeting and identifying several agricultural problems of mutual interest.

One common threat identified was Cotton Leaf Curl Disease (CLCuD). From this meeting, the Cotton Productivity Enhancement Program (CPEP) was born. Many scientific institutions and governmental agencies worked together to make this project a success. During the 10 years of the initiative, CPEP included 13 projects and more than 70 scientists, post-docs, students, support staff, and farmer organizations that all played essential roles in making the project successful. To keep everything on track, online meetings were conducted regularly, with biennial in-person meetings held in Pakistan. Written reports and on-site visits were also part of keeping the projects coordinated and moving forward.

Figure-3 Cotton Leaf Curl Virus Disease (CLCuD)

The initial program needed to be organized quickly and this was possible because of previously established, good relationships developed between US and Pakistani scientists over many years. Through organizations such as the International Cotton Researchers Association (ICRA), we can continue to develop and maintain these international relationships among cotton researchers globally. Through CPEP, we identified genetic resistance to CLCuD and made seed freely available to breeders globally. Pakistani breeders used the resistance source and, in 2021, released the first commercial varieties for Pakistan. Diagnostic tests to detect, identify, and track the virus were also developed, as were best management practices to mitigate the effects of the disease.

Engagement and Adaptation

However, all this research is worthless unless these best management practices can actually be used by farmers to mitigate the effects of CLCuD and improve their productivity. A survey of Pakistani farmers revealed that there were approximately 1.2 million total farmers and most of the farms were less than 10 hectares. So, techniques used in the USA, where a farm is often 800 hectares or more, might not be practical.

Based on this information, we knew that the extension model commonly used in the United States definitely would not work — so what was the best way to engage and assist these smallholder farmers? As part of our project, we consulted Pakistani experts who were already working directly with domestic farmers and together developed effective methods to teach them. Part of our solution was to establish Farmer Field Schools (FFS). The FAO created the original FFS, then Pakistani scientists developed programs specific for Pakistan in cooperation with domestic farmer associations.

Figure-4 Agro-ecosystem Analysis (AESA)

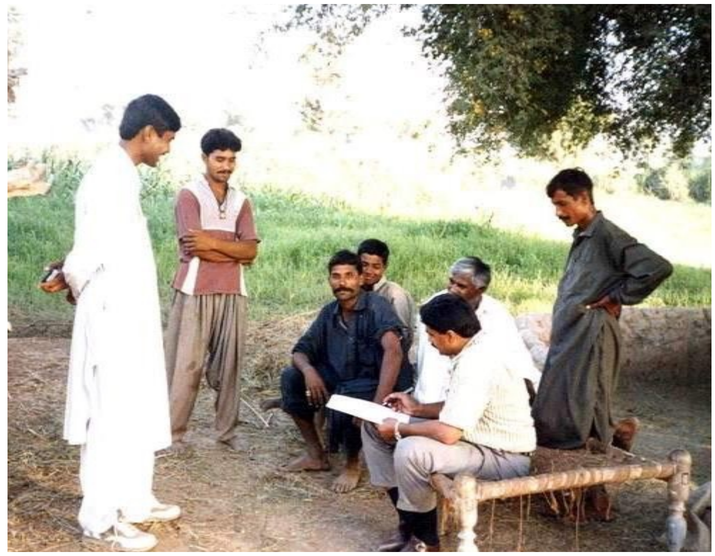

Figure-5 A Farmer Field School (FFS) in Progress.

Worldwide, women and children are often the farm workers. If women can earn money, they are more likely to use it to help the family unit. However, cultural norms may make it difficult for women to fully participate in mixed-gender groups. Wherever we do our research projects, we need to be aware of the local norms and traditions. Because of the situation in Pakistan, using Women Open Schools (WOS) gave the women in our outreach efforts their own participatory learning programs that taught skills to make their lives safer and economically more secure.

Figure-6 Women Open School (WOS)

Genetic Resources and Future Prospects

Commercial cotton production demands uniformity, but cotton as a genus is variable with many valuable traits that will help it adapt to the changing climate. A valuable USDA resource is their collection of cotton germplasm and obsolete cultivars. It is an important source of naturally occurring, novel traits that can improve cultivated cotton.

This genetic resource can help us find natural variation not only for disease and insect resistance or longer, stronger fiber, but also traits that will help cotton be more resilient and tolerate changing climatic conditions. Seed exchange with Pakistan was an important part of the success of the CPEP project and there are ways to facilitate international seed exchange.

However, navigating the logistics and politics of seed exchange can be difficult. Although cotton is not part of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), we can use the guidelines and protocols laid out in the treaty to guide seed exchanges between willing partners.

Figure-7 Diversity of Germplasm

Technology and Collaboration

Being able to share seed is an important part of successful cooperation, but it is not always possible. Fortunately, with many of our new technologies, the seed can stay in-country and DNA or dried tissue can be exchanged within a collaboration, especially for sequencing and genotyping projects and DNA marker-assisted selection (MAS).

Figure-8 Collaborative Networks

Genomics and Cotton Improvement

Just as with the human genome project — and subsequent additional sequences of human DNA have yielded valuable information about diseases and the underlying basis of those diseases — the same has been done with many plants, including cotton. This information has allowed us to identify specific genes that cause a particular trait and, using cutting-edge technologies such as CRISPR-Cas9, we can make very targeted modifications to develop a plant with a more desirable form of that trait.

Many of the desired forms already exist in nature but are found in wild relatives of cotton that are not adapted to agricultural systems and thus do not yield well. With CRISPR and other emerging technologies, we can modify adapted cotton varieties to have the same trait as the wild relative but with a high-yielding output.

Networking and Knowledge Sharing

While sharing seed and DNA is an important goal, we can still make progress by combining forces and sharing our information and research results. So, how do we find other partners and venues to exchange information? One way is by belonging to professional organizations such as the National Association of Plant Breeders (NAPB) and their partner, the African Plant Breeders Association (APBA). There are many similar organizations, and hopefully, we can find and network through more of them.

Fortunately, as cotton researchers, we have our own valuable organization, the International Cotton Researchers Association (ICRA). A good place to start finding out what is happening in cotton is the ICRA website, http://www.icracotton.org/.

Regenerative Cotton Practices: Climate Mitigation in South America

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University, Corrientes, Argentina, and obtained a PhD at the University of Queensland, Australia, in Cotton Physiology and Agronomy. He currently serves as Director of INTA (National Institute of Agricultural Research), Reconquista Santa Fe, Argentina.

A member of APPA (the Association for the Promotion of Cotton Production), which associates all representatives of the cotton chain of Santa Fe, Argentina. He also serves a coordinator of academic and technical agreements between INTA and other national and international organisations. A member of the ICAC's SEEP Committee and ICRA, Dr Paytas's main interest is to link and promote research and development together with the cotton industry through public and private interaction for sustainable production.

Sustainability in Cotton Production

Sustainability in cotton production is essential and encompasses three fundamental pillars: social, environmental, and economic aspects. Terms like regenerative agriculture, climate-smart agriculture, sustainable agriculture, and carbon farming are commonly used today to describe sustainable production systems that aim for climate change mitigation and adaptation. There is a natural overlap between these terms. It can be briefly mentioned that regenerative agriculture focuses on improving soil health and farm efficiency. Sustainable agriculture aims for stability and focuses on providing longevity for both the land and the business. Climate-smart agriculture has three main goals: increasing farm productivity and income, adapting to a changing climate by building resilience, and reducing greenhouse gas emissions (Paytas, 2023). This review assesses the potential of regenerative agriculture in cotton farming by limited-resource farmers and on large farms in South America to capture and store carbon, thereby mitigating climate change.

It is important to recognize the differences between regenerative agriculture practices and products labeled by specific programs as regenerative cotton. Many cotton farmers have already implemented regenerative approaches, reducing environmental impacts and sequestering carbon, even without participating in a specific program or becoming familiar with this concept.

The application of regenerative agricultural practices and technologies holds the potential to mitigate the adverse effects of climate change on cotton production, both at the farm level and within regional contexts. Nevertheless, adoption is contingent upon numerous factors, including institutional arrangements, landscape governance, resource availability, and the prevailing economic, social, and climatic conditions.

Therefore, the pursuit of this concept requires the active participation and collaboration of a diverse array of stakeholders, including farmers, researchers, representatives from the public and private sectors, and civil society (FAO, 2021).

Regenerative Agricultural Practices

A variety of farming practices are promoted as components of regenerative agriculture in cotton production. Some practices have widespread applicability and are easily adopted. Crop rotation and the use of cover crops are pivotal practices. The main aims of regenerative farming are to minimize soil disturbance, maintain permanent soil cover, and cultivate diverse crops.

Figure-1 Conservation Tillage

Minimizing Soil Disturbance: This farming practice is known as reduced tillage, minimum tillage, or in some countries, zero tillage. Reducing the number of mechanized passes per year on the farm or combining operations in one pass minimizes soil disturbance. Organic matter in soils is directly affected by these practices. Adoption of reduced or zero tillage is substantial in Argentina, where farmers in about 91% of the total cultivable area for major extensive crops (wheat, soybeans, corn, sorghum, sunflower, and barley) use these methods. However, adoption among cotton farmers is significantly lower, varying by farm size and region.

Figure-2 A Cotton Field with Minimum Soil Disturbance

Maintaining Permanent Soil Cover: Local growing conditions and crop characteristics are crucial for designing a production plan that maintains permanent soil cover. In some temperate regions, double cropping cotton within a single year is rare, but growing three crops over two years is a common practice, as seen with most farmers in Argentina. Conversely, in tropical regions like northern Brazil, planting secondary crops within a year is common when rainfall or irrigation is sufficient.

Figure-3 A Field With a Permanent Soil Cover

Growing Diverse Crops: Crop rotation is prevalent on small family farms since soil nutrition benefits from a variety of crops such as corn, wheat, sunflower, and other intensive crops. Crop rotation is also strategic in the production planning of medium and large farms, offering benefits related to diversified farm incomes and agronomic advantages. Typically, crop rotation involves three crops within two calendar years. It is essential for carbon sequestration, adding fibrous roots and surface residue, effectively controlling weeds, and disrupting disease and insect pest cycles.

Cover cropping is another practice that introduces plant diversity to a field. Common cover crop species — which include grasses, legumes, and other pastures — bring diversity and additional benefits to the field.

Figure-4 Growing Diverse Crops

Potential of Regenerative Cotton Farming by Limited Resource Farmers and on Large Farms

The expansion of regenerative agriculture is feasible with the integration of local knowledge, research, extension services, and organizational support. In South America, particularly in Argentina, the scale of farming operations significantly influences the adoption of regenerative production strategies, as does the specific regional location of the farms.

Since the 1990s, farmers in Argentina and Brazil have embraced zero or minimum tillage techniques, which include innovative practices such as establishing cotton plants without a seedbed and controlling weeds without cultivation. Once these strategies are implemented, it is crucial to identify other key practices:

- **Machinery for Zero Tillage Systems:** These practices reduce soil disturbance, promote soil health, and enhance carbon sequestration.
- **Crop Rotation and Cover Crops:** Implementing crop rotation and cover cropping helps maintain soil fertility, reduce erosion, and improve overall soil structure (Mieres, 2022).
- **Soil Health Studies:** Routine soil analysis by producers and research programs is essential. These analyses inform nutrient management strategies, guiding decisions on nutrient dosages and critical application timings. In the 2018/19 season, surveys indicated that 87% of the total area was fertilized, the highest level recorded in 18 years (alongside the 2007/08 season) (Zorzon, 2019).

- **Service Crops and Rotations:** Incorporating service crops, grain crop rotations, and pastures within the agricultural system contributes to soil conservation (Mieres, 2017, 2021).

Moreover, developing comprehensive land management strategies is imperative. These strategies should include changes in crop and livestock placement, efficient drainage and rainwater management, flexible production shifts between livestock and crops, and tailored fertilizer and pesticide applications. Utilizing nutrient sources from the agro-industrial sector can further enhance sustainability.

These strategies may involve:

1. **Changes in Crop and Livestock Production Locations:** Assess opportunities for relocating crops and livestock production to optimize resource utilization and reduce environmental impact.
2. **Drainage and Rainfall Water Management:** Efficiently manage drainage and rainwater to prevent soil erosion and improve water-use efficiency.
3. **Crop Rotation and Shifting Production:** Rotate crops and shift production between livestock and crops to diversify the agricultural system and reduce soil degradation.
4. **Optimized Fertilizer and Pesticide Application:** Vary the intensity and timing of fertilizer and pesticide applications based on specific crop and soil requirements (Mieres, 2018).
5. **Use of Agro-Industrial Sector Resources:** Explore alternative nutrient sources from the agro-industrial sector to reduce reliance on synthetic fertilizers (Mieres, 2021).

This comprehensive approach ensures that regenerative agricultural practices not only sustain but also enhance the productivity and environmental resilience of cotton farming in South America.

Figure-5 A Community Approach for Regenerative Agriculture

Regenerative Agriculture Beyond Soil Health: Associated with the Concept of Smart Agriculture

Crop Management and Critical Periods: Selecting optimal sowing dates is a critical factor in achieving successful cotton cultivation within a crop rotation program. Ideally, sowing in Argentina should commence in October and conclude in November to ensure that the crucial flowering stage aligns with the most favorable environmental conditions, resulting in higher cotton yields and better-quality production (Winkler, 2018).

It is equally important to embrace the concept of integrated fiber management, which encompasses various physiological processes influenced by meteorological conditions (Scarpin, 2017, 2023). To mitigate the adverse effects of increased climate variations commonly observed in semi-arid tropics and arid regions worldwide, strategies may include adjusting sowing dates to capitalize on water availability and sunshine periods during critical stages while avoiding unfavorable weather events throughout the growing season.

Figure-6 Crop Management at Critical Periods is crucial

In addition to optimizing sowing dates, it is imperative to propose and evaluate a range of agronomic practices tailored to specific environmental limitations. These practices may include efficient fertilization at both sowing and pre-flowering stages, soil amendments, crop configuration, crop management techniques, and other innovative approaches to enhance overall crop production.

Environmental limitations for cotton production also affect various physiological processes. Water stress, commonly due to low water availability or drought, can affect the crop differentially depending on the phenological stage, its duration, and intensity (Paytas, 2023). Similar challenges arise with light stress (Paytas, 2016) and high temperatures (Colombo, 2018).

Integrated Pest Management Amidst Climate Change and Pesticide Reduction: Climate change, characterized by shifts in temperature and rainfall patterns, significantly impacts insect pests, weeds, and disease dynamics in cotton crops. To address these challenges, the adoption of Integrated Pest Management (IPM) is crucial, emphasizing a greater reliance on biological control and cultural practices (Vitti, 2023; Menapace and Szwarc, 2019; Lorenzini, 2019; Almada, 2017; Roeschlin, 2017). This approach should be complemented by the introduction of new cotton cultivars resistant to diseases and pests, along with the implementation of other crop protection measures.

Supporting farmers in developing a deeper understanding of IPM is essential to reduce their reliance on synthetic pesticides, which can have detrimental impacts on both the environment and the health of farming communities. Transitioning away from highly hazardous pesticides mitigates potential risks (Vitti, 2019). Additionally, the availability and adoption of alternative organic products are on the rise, providing sustainable alternatives to conventional pest control methods.

Figure-7 Integrated Pest Management

Social Benefits: Worker safety, education and training, living environments, profitability, and economic resilience to extreme weather events are key aspects to highlight under a sustainable framework.

Figure-8 Trained Women Farmers

Digital Tools for Prediction, Modelling, and Weather Monitoring: Crop modeling emerges as a valuable tool for managing agricultural risks. Modeling plays a pivotal role in developing techniques that provide crop management insights and yield forecasts. Simulation models significantly contribute to the improvement of crop development practices and offer practical recommendations for effective crop management.

Figure-9 Digital Tools for Weather Monitoring

Collecting meteorological information, including historical and daily data, is an indispensable task for effective agricultural planning. Investment in meteorological stations is essential to obtain accurate and real-time regional weather data. Weather forecasts and early warning systems are invaluable tools for mitigating potential risks associated with climate-related crop losses.

Precision application, as a farming management strategy, is based on observing, measuring, and responding to temporal and spatial variability to improve agricultural and livestock sustainability production.

Stakeholders and Farming Communities: Addressing this multifaceted challenge requires collaborative efforts from a diverse range of stakeholders, including producers, consumers, researchers, and the public-private sector. Together, they must implement strategies that enhance agricultural productivity and encourage climate change resilience. Organizations such as APPA (Association for the Promotion of Cotton Production from Santa Fe) and RAMA (Argentinean Network of Women in Cotton) are essential to implement these types of sustainable strategies (Feuillade, 2022). It is crucial to underscore that producers require comprehensive support, including training, technical guidance, financing, and investment throughout the entire cotton supply chain, especially in countries heavily reliant on agriculture for their economies. Public and private investment can play a pivotal role in incentivizing farmers or guiding access to funding for supporting these initiatives.

Figure-10 A Field Managed through Precision Practices

Conclusions

Cotton production worldwide faces significant challenges related to sustainability and offers opportunities for improvement. Assessing the potential of regenerative cotton farming by limited resource farmers and on large farms in South America to capture and store carbon, thereby mitigating climate change, is essential to explore and promote. Both farmers and consumers would benefit from the adoption of innovative and sustainable farming practices.

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Challenges of Regenerative Cotton Practices in India's Smallholder Farms

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Introduction

Carbon sequestration is one of the important ecosystem services provided by soil. Regenerative agriculture (RA), through its interventions focused on the rejuvenation of soil health, aims to sequester carbon, improve farm productivity and efficiency, and simultaneously mitigate climate change (Babaniyi *et al.*, 2024; Ghosh *et al.*, 2024; Vamshi *et al.*, 2024). Cotton researchers in India have standardized several regenerative cotton farming practices directed toward one or more core principles of RA. These practices, outlined below, are being packaged into location-specific technology modules and promoted.

In India, a number of regenerative cotton farming techniques are recommended:

Minimizing Soil Disturbance: Practices include reduced tillage, bed planting, broad bed furrow, intercropping, poly-mulching, using herbicides to minimize intercultures, restricting deep ploughing in summer, sowing across slopes, and reducing interculture activities. These methods help to reduce the physical disruption of the soil (Pahlow *et al.*, 2014) and loss of soil organic carbon.

Keeping the Soil Surface Covered: Techniques such as crop residue or organic mulching, inter and cover cropping, multitier cropping, and poly-mulching are employed to protect the soil surface, helping to maintain moisture levels and prevent erosion (Pahlow *et al.*, 2014).

Adding Carbon Sources and Closing Nutrient Cycles: This involves the addition of organic manures such as farmyard manure (FYM), vermicompost, and other composts, in-situ or ex-situ green manuring, biochar, sheep or goat penning, and the use of biofertilizers and bio-stimulants to enhance soil fertility and structure (Rahman *et al.*, 2020; Rani, 2022; Baruah, 2024).

Water Conservation and Management: Strategies include broad bed furrow and ridge or furrow planting, ridges after the second interculture, drip irrigation, alternate furrow irrigation, rainwater collection and recycling, mulching (organic and poly-mulch), water quality testing, and the conjunctive use of rain, surface, and groundwater. These practices aim to optimize water usage and reduce wastage (Kumar *et al.*, 2008; Bhattacharyya *et al.*, 2023).

Maximizing Biodiversity: The practices of incorporating mixed or inter-cropping, trap cropping, border cropping, planting refugia in Bt cotton, microbial inoculation (seed and soil), and the inundated release of bio-agents (parasites and predators) enhance biodiversity (Josephrajkumar *et al.*, 2022). An integrated farming system, including agroforestry, also contributes to increased biodiversity (Coyne *et al.*, 2009).

Reducing Agrochemicals: Integrated nutrient management and pest management, using biorationals, botanicals, microbial consortia, mass trapping, mating disruption techniques, ETL-based spray scheduling, yellow sticky traps, mechanical de-topping, high-density planting with short duration compact genotypes, integrated weed management, and avoiding cocktails or tank mixtures (Khangura *et al.*, 2023; Samal *et al.*, 2024). Recommendations for fertilizers are based on soil tests.

Integrating Livestock: Involves sheep or goat penning, an integrated farming system, rearing milch and draught cattle, and using bullock (animal) power for farm operations, thereby linking animal husbandry with crop production to create a more sustainable farming ecosystem (LaCanne and Lundgren, 2018; Venugopalan *et al*. 2021; Nielsen *et al*., 2024).

Maintaining Living Roots: Practices such as double cropping (cotton with wheat, paddy, chickpea, maize, etc.), alley cropping, and cover cropping are employed to ensure that living roots are present in the soil to sustain biological activity, as much as possible, which in turn helps to improve soil health (White, 2020).

Figure-1 Minimizing Soil Disturbance

Figure-2 Adding Biochar (carbon) to the Soil

Figure-3 Water Conservation and Management

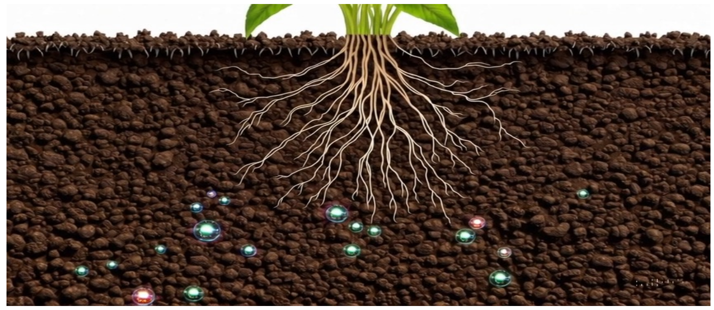

Figure-4 Maintaining Living Roots

Efforts to Enhance Regenerative Farming Adoption

Traditionally, Indian farmers are well-versed in natural farming production systems such as organic cotton farming, biodynamic cotton farming, and zero budget natural farming, which form part of the general indigenous technical knowledge (ITK) systems in vogue (Charyulu and Biswas, 2011). These systems are now being integrated with science-based regenerative cotton production systems and are patronized as strategies to combat climate change. All these regenerative cotton production practices have the potential to capture and store carbon while simultaneously improving soil health, crop productivity, and mitigating the effects of climate change.

In recent years, efforts have been intensified by public sector institutions, NGOs, CSOs, and other organizations in the cotton value chain, including brands, to promote regenerative cotton farming (Venugopalan and Satish, 2024). Training programs, the distribution, display, and dissemination of ICT materials, demonstrations on farmers' fields, Farmer Field Schools, and input/financial incentives are being offered to cotton farmers to adopt RA practices (Mishra *et al*., 2022). Despite the best efforts, the adoption rates of regenerative cotton farming across diverse cotton-growing landscapes have been mixed.

Based on the extent of adoption among farmers (using quick reconnaissance survey), some regenerative cotton farming practices have been classified into low, medium, and high adoption.

Low Adoption Practices

Several regenerative cotton farming practices are still seeing low adoption rates among farmers. These include:

Alley Cropping: Alley cropping involves planting rows of trees or shrubs at wide spacings with a companion crop grown in the alleyways between the rows. This practice enhances biodiversity, improves water infiltration, reduces soil erosion and can increase soil organic matter (McCauley and Barlow, 2023). However, it requires significant land and long-term commitment, which may be barriers to widespread adoption.

Avoiding Cocktails/Tank Mixtures: This practice refers to not mixing multiple pesticides or fertilizers in a single application to avoid toxicity to the soil microbial community and soil functioning (Steffani., 2022). This strategy reduces the risk of chemical interactions that can diminish effectiveness or increase toxicity. Cocktails/tank mixtures are still prevalent due to the perceived convenience, lower water requirements, and cost-effectiveness of tank mixes. Farmers are also not aware of the incompatibility of some molecules.

Broad Bed Furrow (BBF): The BBF systems involve creating raised beds with furrows that improve water drainage and root development (Sayre and Hobbs, 2004). BBF is particularly effective in waterlogged areas but requires initial investment in machinery and a learning curve for optimal implementation, limiting its adoption.

Cover Cropping: Cover cropping, especially effective where irrigation is available, involves growing crops to cover the soil rather than for harvest. Cover crops improve soil health by preventing erosion, enhancing soil organic content, and suppressing weeds (Adetunji *et al.*, 2020). However, its adoption varies depending on water availability and the additional management required.

Economic Threshold Level (ETL) based Spray: ETL based practices involve applying pesticides only when pest populations reach a predefined economic threshold level, minimizing pesticide use (Lala and Das, 2022). While economically and environmentally beneficial, the need for regular monitoring, pest identification, cumbersomeness of the counting methods and ETL calculation expertise hinders its adoption (Rathod *et al.*, 2018).

Figure-5 ETL based sprays

Green Manuring: The practice of green manuring involves growing specific crops that are subsequently ploughed under to enhance soil fertility and organic matter (Kumar *et al.*, 2020). Although this method significantly benefits soil health, shortage of land and the delay in economic returns can deter farmers who prioritize immediate financial gains (Verma *et al.*, 2023).

Figure-6 Green Manure Applied in a Cotton Field

Agroforestry in Integrated Farming Systems (IFS): IFS combines agriculture and forestry technologies to create more integrated, diverse, and productive land-use systems (Rathore *et al.*, 2019). This complex setup requires careful planning and long-term investment, which can be a barrier to its widespread adoption (Tanwar and Tewari, 2017)

Release of bio-agents: Biological control of pests involves introducing natural predators or parasites to regulate pest populations in an environmentally friendly manner. However, its broader application is constrained by the need for detailed knowledge of the bio-agent lifecycle and pest interactions, the timely availability of sufficient quantities of biocontrol agents, affordable market access, convenient application methods, and compatibility with other Integrated Pest Management (IPM) tools such as pesticides (Giles *et al.*, 2019).

Mass trapping and mating disruption: Semiochemicals are generally used to reduce pest populations through traps or pheromone disruptors (El-Ghany, 2019). While effective, these methods can be costly and labor-intensive, leading to lower adoption rates (Kumar and Bajpai, 2007: Pringal *et al.*, 2024). Moreover, these techniques work better on an area-wide basis rather than in individual small land holdings.

Organic mulching: The application of plant residues or other organic materials to the soil surface helps conserve moisture, improve soil health, and suppress weeds. However, the availability of suitable mulching materials and the need for additional labor generally restrict its use (Schonbeck, 1999), leading to lower adoption rates in India.

Multitier cropping: Inspired by the layering methods used in permaculture, multitier cropping involves growing different types of crops at varying heights to maximize space utilization. This practice not only increases biodiversity and productivity but also requires detailed knowledge of crop compatibilities and precise management to be effective (Khan *et al*., 2024).

Poly-mulching: Synthetic materials like plastic sheets are used to cover the soil, helping with temperature regulation, weed management, and moisture conservation (Nalayini *et al*., 2009, Iqbal *et al*., 2020). While beneficial, concerns about plastic waste and the cost of materials can hinder adoption (Bahadur *et al*., 2018).

Figure-7 Polymulching

Rainwater collection and recycling: Rainwater collection and recycling is a sustainable practice particularly vital for smallholder farmers in India, where water scarcity can significantly impact agricultural productivity (de Sá Silva *et al*., 2022). By capturing and storing rainwater, farmers can irrigate crops during dry periods or take a second crop using recycled rainwater, thus enhancing water security and reducing dependence on unpredictable rainfall.

Figure-8 Rainwater Harvesting in a Farm Pond

This method not only conserves water but also helps in maintaining soil health by reducing soil erosion and nutrient runoff. Despite these benefits and several supportive policies from the Indian government, the adoption of rainwater harvesting remains low among smallholder farmers. Challenges include the high initial costs of setting up systems, lack of awareness about efficient techniques, and the need for significant management and maintenance (Kahinda and Taigbenu, 2011). Additionally, the variability in rainfall patterns due to climate change makes it difficult to rely solely on harvested rainwater, further complicating its widespread adoption (Goyal., 2020).

Reduced primary tillage and zero tillage: Minimum tillage and no-till practices effectively minimize soil disturbance, thus preserving soil structure and organic matter (Jacobs *et al*., 2010). These practices enhance soil fertility and reduce labor requirements. Although they offer significant benefits for soil health and erosion control, the transition from traditional plowing practices can be slow due to deeply entrenched farming habits (Somasundaram *et al*., 2020). Additionally, despite the advantages of zero-tillage, the shift from conventional tillage methods and an initial increase in weed pressure and increased weed management cost discourages its adoption (Kumar *et al*., 2020).

Avoidance of deep ploughing in summer: Deep ploughing in summer has been a longstanding practice in India, historically supported by scientific recommendations aimed at destroying diapausing insects (Ghanghas *et al*., 2018).

However, avoiding deep ploughing can help preserve soil organic carbon, soil moisture and structure during the dry season. Despite these benefits, changing traditional ploughing practices requires significant adjustments in farming techniques and is often met with resistance from farmers.

Medium Adoption Practices

The following practices are more widely adopted but still not universally implemented:

Alternate Furrow Irrigation: Alternate furrow irrigation involves irrigating one furrow while leaving the adjacent one dry during each watering cycle.

This method can significantly reduce water usage. The adoption level is relatively less because it requires farmers to adjust traditional irrigation practices and invest time in learning new irrigation scheduling, which can be challenging without adequate support and training (Feder and Umali, 1993).

Bed Planting: The method involves raising seedbeds above the normal field level to enhance water drainage and root development. This technique has only moderate adoption because it is time consuming, requires specific machinery or additional labor, which might be out of reach for smallholder farmers with limited resources (Kumar *et al*., 2021).

Bio-stimulants: Bio-stimulants, which include various substances and microorganisms, are applied to plants to promote growth, increase stress tolerance, and improve crop quality, without serving as nutrients, soil improvers, or pesticides. Their adoption is at a medium level primarily because their effectiveness can be inconsistent, and farmers often require additional information and persuasion regarding their benefits and correct application methods (Yakhin *et al*., 2017).

Cleaning of Irrigation Channels: Regular maintenance and cleaning of irrigation channels ensure unobstructed water flow and efficient irrigation. Irrigation channels are also a main source of weed infiltration in cotton fields. Although beneficial, the task is labor-intensive, expensive, and often neglected, resulting in only medium adoption (Huppert *et al*., 2003; Jain *et al*., 2019).

Double Cropping: Double cropping involves growing two consecutive crops in the same field within a single year, dependent on water availability and using short-duration genotypes. Cotton-wheat/paddy/maize/mustard/chickpea are the dominant double cropping system in irrigated regions. However, in the 60% of the area where cotton is rainfed, this technology is not feasible.

Drip Irrigation: Drip irrigation delivers water directly to the soil at the base of the plant, which significantly reduces water wastage. The initial cost of installation and maintenance of drip systems can be high, deterring widespread adoption among smallholders (Moin and Kamil, 2018).

Figure-9 Drip Irrigation

High Density Planting Systems (HDPS): High density planting involves planting crops closer together than usual to increase yield per unit area. While potentially increasing yields, it demands more precise soil, nutrient, and crop canopy management and necessitates changes in conventional agronomic practices. These requirements make it less appealing to risk-averse farmers (Ranapanga *et al*., 2023).

Figure-10 High Density Spacing

Figure-11 High Density Crop

Figure-12 Inter/Mixed Cropping

Inter/Mixed Cropping: This practice involves growing two or more crop species together to promote biodiversity, enhance productivity, and reduce pest and disease incidence. While Indian farmers are familiar with inter-cropping, the complexity of managing the differing needs of multiple crops simultaneously and the higher profits often associated with monocropping *Bt*-cotton hybrids, compared to inter-cropping with lower-value crops, can deter some farmers, thus leading to only a medium level of adoption (Keller *et al*., 2024).

Organic Manures: Organic manures, derived from animal or plant waste, are used to improve soil fertility. While they offer significant benefits for soil health, the physical labour required for their application (Harshita *et al.*, 2021). Further, a dwindling cattle population is restricting the availability of FYM.

Figure-13 Organic Manures

Penning (Sheep/Goat): Penning involves confining livestock in a specific area so that their waste directly contributes to soil fertility. This practice requires additional management of livestock, and often, the limited availability of animals in the region can pose a challenge for crop-focused farmers, thereby reducing its adoption (Sudeepkumar *et al.*, 2024).

Figure-14 Penning of Goats

Post-Emergence Herbicides: Herbicides applied after crop and weed emergence help control existing weed populations, decrease the need for secondary tillage operations, enabling the crop to utilize nutrients and water more effectively. However, adoption can be hindered by the limited availability of selective herbicides that effectively control all types of weeds while minimizing harm to the main crop. Additionally, the absence of herbicide-tolerant varieties for many broad-spectrum herbicides further complicates widespread adoption (Kumar *et al.*, 2014).

Biochar Application: Biochar is a carbon-rich product obtained from organic materials heated in a controlled environment, used to improve soil properties. Despite its soil health benefits, the production and application processes, limited awareness of its benefits, and high initial costs can be barriers (Shackley *et al.*, 2015).

Figure-15 Biochar Application

Minimizing Secondary Tillage: This practice involves reducing the frequency and intensity of tillage to preserve soil structure. The transition from traditional intensive tillage practices can be slow, as farmers evaluate the long-term benefits against short-term changes in soil behavior (Somasundaram *et al.*, 2020).

Border Cropping: Border cropping involves planting specific crops around the perimeter of the cotton crop to act as a barrier against pests and diseases. The method requires additional planning and space, understanding of the cotton ecosystem, which might not always be available or seen as immediately beneficial by smallholder farmers.

Each of these practices holds potential benefits for sustainability and productivity but faces specific challenges in broader adoption, particularly among smallholders who may lack resources or face risks that make transitioning to new agricultural methods daunting.

High Adoption Practices

The following practices have high adoption levels due to their direct perceptible benefits in increasing productivity, enhancing sustainability, and reducing farming risks, aligning well with the needs and goals of smallholder Indian cotton farmers. These practices are now commonly seen in regenerative farming systems:

Conjunctive Use of Rain/Surface and Ground Water: This practice involves the integrated use of rainwater along with surface and groundwater to optimize water resources for irrigation. The quality of irrigation water too is improved in areas where groundwater is saline. The necessity to maximize water efficiency due to fluctuating rainfall and limited water resources drives high adoption among smallholder farmers, making this an essential practice for sustaining crop growth during dry spells (Upadhyaya *et al.*, 2013).

Early Maturing Genotypes: These are crop varieties developed to mature faster, thereby reducing the crop's exposure to risks such as drought and pests. Early maturing genotypes allow farmers to avoid adverse weather conditions and late-season infestation of pink boll worm as well as facilitate double cropping, making them attractive for regions with short growing seasons or where a supplementary irrigation source is available, thus encouraging their demand and widespread use (Raj and Patil., 2023).

Integrated Nutrient Management: Combining organic manures with inorganic fertilizers provides a balanced nutrient profile that enhances soil fertility and crop yield. This integrated approach to fertilization is popular for its ability to improve soil health while providing immediate nutrient benefits, appealing to farmers looking for sustainable yet effective practices (Vats *et al.*, 2001).

Bio-rationals/Botanicals: Bio-rationals and botanicals comprise natural or derived substances that serve as alternatives to synthetic chemicals for pest control. Traditionally and historically, Indian farmers are well-acquainted with botanical pesticides, valuing these products for their safety in terms of environmental and crop impact. This preference positions bio-rationals and botanicals favourably among farmers committed to sustainable agriculture and those catering to organic markets (Abrol, 2017; Kapoor and Sharma, 2020).

Microbial Consortia: This practice involves the application of beneficial microorganisms to enhance soil fertility and plant health. Microbial consortia improve nutrient uptake and disease resistance, attracting farmers who benefit from healthier crops and reduced chemical inputs (Maiyappan *et al.*, 2010; Sarma, *et al.*, 2015). Several state/CSO/NGOs sponsored initiatives have accelerated their adoption.

Integrated Weed Management (IWM): IWM is a comprehensive approach that combines mechanical, biological, and chemical methods to manage weed populations effectively. Its versatility and effectiveness in reducing crop competition, preventing herbicide resistance in weeds and increasing yields make this an attractive option for farmers dealing with diverse weed challenges (Das *et al.*, 2012; Das *et al.*, 2021)

Planting Refugia (now RIB): Refugia involves planting non-Bt cotton or other crops that are hosts of bollworms, among Bt cotton to prevent the buildup of resistant bollworm pests. This strategy is crucial for maintaining the effectiveness of Bt crops against the target insect pests. With the introduction of the refuge-in-bag strategy, the adoption rates of planting refugia have significantly increased. This approach embeds non-*Bt* seeds within the *Bt* crop bags, in a particular ratio, ensuring compliance by farmers who previously might have chosen to avoid planting non-*Bt* seeds when they were supplied separately for planting in border rows. This mandatory integration leaves farmers with no option but to implement refugia, thereby enhancing the overall effectiveness of pest management strategies in *Bt* cotton cultivation (Mohan *et al.*, 2019).

Integrating Cattle/Goat/Poultry: This practice involves incorporating livestock farming with crop production, using animals to provide manure and control weeds and pests naturally. The dual benefits of additional income from livestock and improved crop production through natural fertilization and pest control make this a favorable choice particularly among small and medium sized cotton farms.

Figure-16 Integrating Cattle/Goat/Poultry

Ridges after Second Interculture: This practice involves forming ridges in the field after the second cultivation to improve water management and root development. Effective in areas prone to waterlogging and for better nutrient placement, this method is commonly adopted for its agronomic benefits (Venugopalan *et al.*, 2012) and simplicity.

Figure-17 De-topping

Mechanical De-topping: Mechanical de-topping involves cutting the top of the apical growing tips of the plant at the cut-off stage to prevent the formation of new branches and fruiting parts.

This minimizes competition from new bolls, ensuring that existing bolls receive adequate nutrients and water, which leads to better boll formation, bigger bolls, and increased yields. This practice is favored for its ability to enhance cotton yield and quality, making it particularly attractive in highly competitive market conditions (Alam *et al.*, 2024).

Soil Testing for Nutrient Application: Regular soil testing enables farmers to apply precise amounts of nutrients tailored to the specific needs of their soil, optimizing fertilizer use and enhancing crop growth. As awareness of sustainable practices increases, more farmers are adopting soil testing to reduce costs and boost crop yield efficiency. This uptake is further encouraged by various government policies in India and agricultural extension services that promote this practice, supporting farmers in their transition to more efficient and sustainable agricultural methods (Singh *et al.*, 2017).

Figure-18 Soil Testing Laboratory

Challenges for Adoption of Regenerative Cotton Farming Practices

The overview below highlights the multifaceted challenges faced in advancing regenerative cotton farming practices across different stakeholders in the agricultural sector. Adopting regenerative cotton farming practices presents multiple challenges that can be categorized from the perspectives of farmers, extension officials, and researchers. Each group faces unique obstacles that impact the adoption rates of these sustainable practices.

Farmers' Perspective

Farmers face several practical and logistical challenges that hinder the adoption of regenerative practices. Key issues include:

Weed Management: Weed management is the primary deterrent preventing the adoption of practices such as minimum tillage, cover cropping, intercropping, or high-density planting using early maturing genotypes. Additionally, the non-availability of herbicide-tolerant (*HT*) cotton limits the ability to apply herbicides over the top, which is a significant constraint. These issues complicate effective weed control, making it challenging for farmers to adopt these regenerative farming practices that could otherwise enhance soil health and productivity (Ramprakash *et al.*, 2024).

Water Availability: Water availability is another significant constraint for rainfed farmers, particularly when it comes to planting cover crops after cotton and maintaining living roots throughout the year. This limitation restricts the ability to implement practices that could improve soil health and water retention, posing a challenge for sustainable agricultural development in areas dependent on natural rainfall patterns (James *et al.*, 2024).

Figure-19 Manual Weeding

Figure-20 Bullock tillage

Labor Intensity and Cost: Most regenerative cotton farming practices are labor-intensive, and the dual challenges of limited labour availability and high labor wages pose significant impediments to their adoption.

These factors make it difficult for farmers to implement such practices on a large scale, especially in regions where labor shortages or high costs add to the financial burden on smallholder farmers (Ramasundaram and Gajbhiye, 2001; Tausif *et al.*, 2018).

Farm Machinery: Appropriate farm machinery for planting, land shaping, and shredding cotton stalks is either not available or not affordable for many farmers. This lack of access to suitable and economically feasible equipment hinders the implementation of efficient farming practices that could significantly enhance productivity and sustainability in agricultural operations (Himshikha *et al.*, 2024).

Figure-21 Farm Machinery

Certification and Bookkeeping: Diverse certification standards and cumbersome bookkeeping requirements for certification act as significant disincentives for farmers. These complexities make it challenging for smallholders to comply with the necessary documentation and processes.

Moreover, outreach teams established by various cotton identity programs often lack the capacity to provide adequate support to farmers, further hindering their ability to transition to regenerative practices and obtain certification (Ward and Mishra, 2019).

Community-Level Practices: Practices like mass trapping and mating disruption for managing bollworms are not feasible for individual small farmers to implement effectively. These methods require coordinated efforts and support at the community level, covering large, contiguous areas to achieve significant pest control.

Without such collective action and infrastructure, the adoption of these practices remains limited among smallholder farmers (Geedi and Reddy, 2023).

Owner cultivators and tenant/leased land farmers: A fair amount of leased land is cultivated by growers on small and medium farms.

Security of tenure is an important factor influencing the farmer's decisions on investment and adoption of regenerative practices. Owner-cultivators are more likely to invest in regenerative farming practices than tenant farmers who are under lease agreements (Akram *et al.*, 2019).

Technology Adoption Challenges

Extension officials identify several educational and psychological barriers that need to be addressed to enhance adoption:

Convincing Farmers: Farmers are often not easily convinced of the benefits of regenerative cotton farming, making a change in mindset essential to improve adoption rates. Bringing about this attitudinal change represents a major challenge (Rizzo, 2024). Overcoming skepticism and resistance requires effective communication, education, and demonstrable success stories that clearly illustrate the long-term advantages such as enhanced soil health, increased biodiversity, and potential economic gains. Engaging farmers through participatory approaches and demonstrating the tangible benefits on fields can help shift perceptions and encourage a more sustainable approach to agriculture.

Skill Gaps: Addressing the knowledge and skill gaps in regenerative cotton farming necessitates substantial long-term investment, which often proves challenging to secure. Furthermore, the skill development of well-trained delivery personnel, who play a critical role in imparting knowledge directly to farmers, requires considerable time and suitable incentives (Pathania *et al.* 2024). These investments are crucial to ensure that the workforce is adequately equipped to support farmers effectively and sustainably. However, securing the necessary resources and commitment can be challenging tasks. This deficiency impedes the widespread adoption and successful implementation of regenerative practices, thereby highlighting the need to prioritize and strengthen these educational and support mechanisms (Dahri *et al.*, 2023).

Figure-22 Extension Activities

Reluctance to Change: Reluctance to change the existing production system, coupled with inadequate resources such as finance, farm power/machinery, and labor, as well as limited market access to inputs and diversified farm produce, are significant reasons for the non or partial adoption of new practices. These challenges create substantial barriers for farmers who might otherwise be interested in transitioning to more sustainable methods. The existing constraints not only hinder immediate adoption but also affect the long-term sustainability and scalability of innovative farming practices (Rao *et al.*, 2018).

Technical Inadequacies: Often, there are technical inadequacies in research recommendations, as they tend to be too generic and require refinement to fit specific production systems. For instance, the choice of border, inter, or trap crops, the most compatible varieties for intercropping, rotation, or border planting, and the planting patterns must be tailored to integrate seamlessly with the available farm equipment that farmers already possess. This customization ensures that the recommendations are practical and applicable, thereby enhancing their usability and adoption (Rao *et al.*, 2015).

Figure-23 Straw Mulch

Research and Policy Perspectives

Researchers and policymakers face a range of challenges that impact the promotion and implementation of regenerative practices:

Limited Evidence: Although the benefits of individual regenerative practices have been clearly documented, there is limited scientific evidence from cotton-based production systems in India to effectively counter the skepticism surrounding the benefits of the whole regenerative cotton farming package, and the timeframe required to realize these benefits under diverse agroclimatic conditions.

This scarcity of data makes it challenging to convincingly demonstrate the long-term advantages of regenerative practices — such as improved soil health, increased biodiversity, and enhanced ecosystem services — to stakeholders who may be hesitant to adopt or promote new agricultural methods without clear, immediate returns (Pathania *et al.*, 2024).

Communication Gap: The inability to effectively translate research results and convince extension personnel and farmers about the benefits of regenerative cotton farming—particularly in terms of carbon capture, carbon storage, greenhouse gas (GHG) emissions reduction, and climate change mitigation—poses a significant challenge. These benefits, while crucial for long-term environmental sustainability, do not align closely with the immediate priorities of farmers, who are often more concerned with short-term yields and profits. This disconnect can hinder the adoption of regenerative practices, as the immediate advantages may not be apparent or compelling enough to motivate change (Jin *et al.*, 2022).

Standards and Measurement: The lack of a uniform set of standards to measure, compare, and quantify the benefits of regenerative cotton farming presents a significant barrier. Establishing these standards is crucial for fostering consumer trust and sensitizing partners along the value chain to the advantages of adopting regenerative practices. Without such metrics, it is difficult to create a compelling and quantifiable case for the economic, environmental, and social benefits of regenerative agriculture, making it challenging to promote widespread adoption and support among stakeholders (James *et al.*, 2024).

Long-Term Benefits: The benefits of Regenerative Agriculture (RA) practices, such as improved soil health parameters and enhanced farm profits, are typically realized only over the long term. This delayed gratification can make it challenging to keep farmers motivated during the extensive transition period required to implement these practices fully. Without adequate financial incentives to support them through this period, maintaining commitment and enthusiasm among farmers for adopting and continuing sustainable farming methods becomes significantly more difficult (Sneha *et al.*, 2021).

Local Adaptation Needs: Regenerative cotton farming practices are inherently local and context-dependent, requiring iterative adjustments before they can be effectively adopted. These practices often need several modifications to suit specific environmental and agricultural conditions. However, resources such as finance, land, and skilled staff are frequently inadequate for conducting the necessary micro-level validation and refinement. This lack of resources hampers the ability to fine-tune these practices for wider adoption, limiting the potential for regenerative methods to be implemented broadly across different regions (James *et al.*, 2024).

Carbon Credits: Carbon credits could serve as a significant incentive for farmers to adopt regenerative cotton farming practices. There is an urgent need for integrated technological solutions that are credible, accurate, affordable, and reproducible to facilitate the measurement, reporting, and verification (MRV) of carbon sequestration. Establishing such systems is essential to ensure that farmers are rewarded for their sustainable practices, making it financially viable for them to invest in methods that improve carbon capture and contribute to environmental sustainability (Cariappa and Krishna., 2024).

Conclusion

In conclusion, the adoption of regenerative cotton farming practices in India holds tremendous potential to improve soil health, enhance productivity, sequester atmospheric carbon, impart climate resilience, and contribute significantly to environmental sustainability. Farmers are realizing the need to adopt regenerative farming practices. However, several challenges persist, including farmers' reluctance to change traditional practices, limited resources, technical gaps, and inadequate institutional support. Overcoming these barriers will require a coordinated approach involving financial incentives, customized solutions, effective training programs, and community-driven initiatives. Strengthening research and ensuring it is localized to suit diverse agroclimatic conditions, along with policies that offer tangible benefits like carbon credits, will play a critical role. Collaboration among farmers, extension workers, researchers, and policymakers is essential to making regenerative cotton farming a reality. With concerted efforts, India can lead the way in building a sustainable and resilient cotton sector that not only supports livelihoods but also secures the environment for future generations.

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WATER FOOTPRINT IN COTTON 2020-2024: A GLOBAL ANALYSIS

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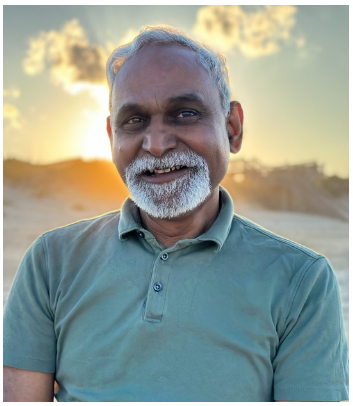

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Dr. Keshav R. Kranthi, Ph.D is the Chief Scientist at the International Cotton Advisory Committee (ICAC), Washington, DC. Before joining the ICAC, he served as the Director of the Central Institute for Cotton Research (CICR) in Nagpur, India, from 2008 to 2017. Dr. Kranthi has thirty-five years of experience as a cotton scientist. He received a gold medal in his Ph.D. in 1991 and has been honored with more than a dozen awards, including the Best CPP Program Award for Research Leadership by the Renewable Natural Resources Research International, UK; the ICAC Researcher of the Year Award in 2009; the Vasantrao Naik Smruti Pratisthan Award in 2004; the ICAR National Award for Leader of Best Team Research in 2006; Fellow of the National Academy of Agricultural Sciences in 2009; the ISCI Recognition Award in 2010; Krishi Gaurav Award in 2010; Bhumi Nirman Award in 2011; ISCI Fellow in 2017; the Plant Protection Recognition Award in 2016 by the National Academy of Agricultural Sciences; Suresh Kotak Global Cotton Award in 2023 and Life Time Achievement Award in 2024 by the Cotton Research and Development Association, India. Dr. Kranthi has four patents granted in South Africa, Mexico, China, and Uzbekistan, and six patent applications in India. He has published more than 100 peer-reviewed research papers, 15 books/handbooks/manuals, 17 book chapters, and more than 50 popular articles. Dr. Kranthi has presented invited talks, and conducted training sessions in more than 35 countries. His research citations exceeded 5,966 as on 20 June 2025. As the chief principal investigator, he coordinated and led more than 30 externally funded research projects.

Introduction

Water is a vital resource for agriculture, and its efficient use is critical for sustainable crop production. Cotton, like any other crop, has specific water requirements that vary depending on climatic conditions, soil properties, and growth stages. Adequate soil moisture is particularly crucial during critical growth stages, such as flowering and boll formation, when water deficits can severely reduce yields (Pettigrew, 2004).

Rainwater is the main source of water for crops, but its availability is often erratic, leading to soil moisture deficits that necessitate supplemental irrigation. In arid and semi-arid regions, where rainfall is insufficient to meet crop needs, irrigation becomes indispensable. However, even in regions with seemingly adequate rainfall, mismatches between crop water requirements and soil moisture availability can occur due to poor soil conditions, runoff, or seepage. Conversely, excessive rainfall during the crop season, especially under poor drainage conditions, can lead to waterlogging and yield losses (Bange *et al.*, 2004).

A critical challenge in cotton production is the excessive use of irrigation water; farmers often apply more than the crop requires, resulting in inefficiencies and waste. This study evaluates daily weather parameters to calculate crop evapotranspiration (ETc), crop water requirements, effective rainfall, and irrigation water applied, aiming to identify opportunities for optimizing irrigation water use. Because rainfall is a natural resource beyond human control, the focus should be on practical, water-saving irrigation strategies that are within human control. Emphasis should be placed on harvesting and conserving rainwater while enhancing irrigation efficiency through precision technologies to support sustainable cotton production.

Methodology

This study analyzed water usage data from 271 cotton-growing states or provinces across 38 major cotton-producing countries from 2020–2024.

The analysis focused on key parameters such as irrigated area, yield, effective precipitation (Pe), ETc, soil water balance (St), critical moisture threshold (S_{crit}), irrigation water requirements (IWR), irrigation water applied, excess irrigation, irrigation water footprint (WR_{irri}), rainwater footprint (WF_{rain}) and the total water footprint (WF_{total}).

Daily weather data for the 271 locations was obtained from the World Weather Online API (https://www.worldweatheronline.com).

ETc was calculated at daily intervals and subsequently aggregated to monthly values, while other parameters — including effective precipitation (Pe), soil water balance (St), critical moisture threshold (S_{crit}), and irrigation water requirements (IWR) — were computed directly at monthly intervals, using CROPWAT 8.0 (FAO) and the methodologies outlined in FAO Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998).

National data on water withdrawals was sourced from the AQUASTAT-FAO database. The total amount of water withdrawals for agriculture was calculated for 2020 and 2021, and projections were made for 2022-2024 using data from 2018-2021 on "total water withdrawals" and "agricultural water withdrawal as a percentage of total water withdrawal." Data on cotton area, irrigated area under cotton, cotton production, types of irrigation methods, and irrigation water applied were collected from official government websites and records, supplemented by insights from interviews with subject matter experts, researchers, and government representatives.

Data on irrigation water withdrawals for cotton cultivation was provided by a few countries based via official estimates. Some countries provided detailed information on the number of irrigations applied per season, approximate quantity of water used per irrigation, and the methods used (flood, furrow, sprinkler, and drip), which helped estimate the amount of water applied. Where such data was unavailable, it was assumed that the amount of irrigation water applied exceeded the cotton crop irrigation water requirement (*IWR*) by a factor of 1 to 1.2 times, depending on the method of application, accounting for potential losses due to application methods, runoff, and seepage. This assumption accounts for potential inefficiencies in water application, particularly in systems using less precise irrigation methods such as spate/flood or furrow systems. The amount of water applied through flood irrigation was estimated to be 1.2 times the calculated crop irrigation water requirement (*IWR*), while furrow irrigation applied approximately 1.15 times the required amount. In contrast, sprinkler and drip irrigation systems were assumed to apply water precisely aligned with the crop water requirements, reflecting their higher efficiency and precision.

Reference Crop Evapotranspiration (*ETo*)

ETo was calculated using the FAO Penman-Monteith equation, representing the evapotranspiration from a hypothetical reference crop. It integrates meteorological data to estimate water loss due to evaporation and transpiration.

FAO Penman-Monteith equation:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{900}{T+273}\gamma U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

Where:

ETo = reference evapotranspiration [mm day^{-1}],
Rn = net radiation at the crop surface [MJ m^{-2} day^{-1}],
G = soil heat flux density [MJ m^{-2} day-1],
T = mean daily air temperature at 2 m height [°C] = (Tmax + Tmin) / 2
U_2 = wind speed at 2 m height [m s-1],
es = saturation vapor pressure [kPa] = [e^0(Tmax) + e^0(Tmin)] / 2
e^0(T) = 0.6108 * exp(17.27 * T / (T + 237.3))
ea = actual vapor pressure [kPa] = es * (RH / 100)
es - ea = saturation vapor pressure deficit [kPa],
D = slope vapor pressure curve [kPa °C-1] = 4098 * es / (T + 237.3)2
g = psychrometric constant [kPa °C-1] = (cp * P) / (ε * λ)
cp = 1.013 × 10^{-3} MJ/kg/°C, ε = 0.622 and λ = 2.45 MJ/kg

Potential Crop Evapotranspiration (*ETc*)

Potential crop evapotranspiration (*ETc*) for cotton was calculated using the FAO-56 methodology (Allen *et al.*, 1998).

The crop coefficient (*Kc*) represents specific cotton crop coefficient values based on growth stages: 0.35 for the seedling stage (0–30 days), 0.58 for peak squaring stage (30–60 days), 0.89 for peak flowering stage (60–90 days), 1.11 for peak green boll stage (90–120 days), 0.54 for maturation stage (120–150 days), and 0.20 for harvest stage (150–180 days).

These values were multiplied by the reference evapotranspiration (*ETo*), computed using the FAO Penman-Monteith equation, to obtain *ETc* as follows:

ETc = *Kc* x *ETo*

Effective Precipitation (*Pe*)

Effective precipitation (*Pe*) was calculated using the FAO-56 methodology (Allen *et al.*, 1998), accounting for soil water retention and drainage losses of rainwater within the cotton season, computed by *Kp* coefficient values.

Kp is the coefficient for effective precipitation, influenced by soil type, ground cover, crop stage, and climatic conditions.

The *Kp* values applied for different soil types were as follows: clay (0.45), clay loam (0.60), silt loam (0.70), loam (0.78), loamy sand (0.80), sandy loam (0.85), and coarse sand (0.90), with other soil types ranging between 0.70 and 0.85.

Effective precipitation (*Pe*) was then calculated as:

Pe = *P* x *Kp*

Where:

Pe = Effective precipitation (mm)
P = Total monthly rainfall (mm) within the cotton season
Kp = Coefficient for effective precipitation

Irrigation Water Requirement (*IWR*)

The irrigation water requirement (*IWR*) was calculated using a soil depletion approach following FAO-56 guidelines, incorporating a dynamic water stress coefficient (*Ks*) to account for crop water stress under varying soil moisture conditions.

Readily Available Water (*RAW*)

The threshold for irrigation triggering, was calculated as follows:

RAW = *p* × *TAW*

Where:

p = crop-stage-specific depletion factor set at 0.45 for the seedling stage, 0.50 for squaring stage, 0.55 for flowering stage, 0.60 for green boll stage, 0.65 for maturation, and 0.70 for harvest.

TAW = Total Available Water -equivalent to the field capacity (*FC*) for a 1.0 m root zone -was defined for each soil type (e.g., clay loam (400 mm), clay (350 mm), coarse sand (100 mm), loam (200 mm), loamy sand (100 mm), sandy loam (150 mm), silt loam (250 mm), and silty clay (350 mm)).

Root Zone Depletion (*Dr*)

$Dr = TAW - St$

Where:

St = soil moisture storage

St was updated daily via water balance as follows:

$St = St{-}1 + Pe + I - ETa$

Where:

St = Soil moisture storage (mm)
ETc = Potential crop ET (mm)
ETa = Actual ET adjusted for stress (mm)
Pe = Effective precipitation (mm)
I = Irrigation applied (mm)

Stress Coefficient (*Ks*)

$$K_s = \begin{cases} 1 & \text{if } D_r \leq \text{RAW} \quad \text{(no stress)} \\ \frac{\text{TAW}-D_r}{(1-p)\times\text{TAW}} & \text{if } D_r > \text{RAW} \quad \text{(stress)} \end{cases}$$

Actual ET (*ETa*) adjusted for stress (mm)

$ETa = Ks \times ETc$

$$\text{IWR} = \begin{cases} \max(0, ET_c - P_e) & \text{if } D_r > \text{RAW} \\ 0 & \text{otherwise} \end{cases}$$

Water Footprints

Potential crop evapotranspiration (*ETc*) theoretically represents the total volume of water consumed by the crop during its growth cycle, commonly referred to as Crop Water Use (*CWU*).

This water is derived from two primary sources: the Irrigation Water Requirement (*IWR*) and the Effective Rainfall (*Pe*) received during the crop season.

For each location, the relative contributions of *IWR* and *Pe* were quantified as components of the seasonal *ETc*. These proportions form the basis for calculating the water footprint, which is a theoretical estimate of the volume of water—whether from irrigation or rainfall—used to produce one kilogram of lint.

The water footprint components were calculated using the methodology proposed by Hoekstra (2009). Specifically, the consumptive water footprint from irrigation ($WF_{IWR\text{-}ETc}$), the consumptive water footprint from effective precipitation ($WF_{Pe\text{-}ETc}$), and the total consumptive water use footprint ($WF_{total\text{-}ETc}$) were computed, all expressed in liters per kilogram of lint (L/kg lint). These calculations are based on crop evapotranspiration (*ETc*) reflecting consumptive water use rather than total irrigation withdrawals.

The following formulas (Hoekstra, 2009) were used to compute the water footprints for the consumptive irrigation water footprint ($WF_{IWR\text{-}ETc}$) component and the consumptive effective precipitation ($WF_{Pe\text{-}ETc}$) component of *ETc* and the total consumptive water use footprint ($WF_{total\text{-}ETc}$) expressed in L/Kg lint:

$WF_{IWR\text{-}ETc} = IWR\text{-}ETc / Y$
$WF_{Pe\text{-}ETc} = Pe\text{-}ETc / Y$
$WF_{total\text{-}ETc} = Total\text{-}ETc / Y$

The water footprint of irrigation water applied (WF_{irri}), expressed in liters of irrigation water per kilogram of lint yield (L/kg), was calculated as:

$WF_{irri} = Iw / Y$

Where:

Y = Yield of cotton lint (kg/ha).
IWR-ETc = *IWR* component of *ETc* (L/ha).
Pe-ETc = *Pe* component of *ETc* (L/ha).
Total-ETc = *IWR-ETc* + *Pe-ETc* (L/ha)
Iw = Total irrigation water applied (L/ha).

The *IWR* component of *ETc, Pe* component of *ETc*, total irrigation water applied (I) and the *ETc* values were converted from mm to L/ha using the conversion factor 1 mm = 10 m^3/ha.

Results

Summary results from the data analysis of 273 locations across 38 major cotton-growing countries over five years from 2020 to 2024 are presented in Table 1.

The data indicate that the average global cotton area was 30.98 million hectares, with 44.0% (13.61 million hectares) under irrigation. The global average cotton lint production over the five-year period was 25.54 million tonnes, with an average yield of 786 Kg/ha. Cotton occupies 2.21% of the arable land under arable crops, which totaled 1,397 million hectares (FAOSTAT).

Table-1: Summary of the Data on Area, Production, Rainfall, Evapotranspiration, Irrigation and Water Footprints from 271 Locations Across 38 Cotton-growing Countries. Data presented as Average Values over Five Years (2020–2024) with Standard Error of the Mean.

Area, Production & Irrigation	**Value** (Mean ± SE)
Total Cotton Area (Million Ha)	30.98 ± 0.4
Lint Yield (Kg/ha)	786 ± 8
Lint Production (Million Tonnes)	24.54 ± 0.24
Irrigated Area (Million Ha)	13.61 ± 0.2
% Irrigated Area	44% ± 0.5
Rainfall	
Effective Precipitation (mm/ha)	508 ± 6
Effective Rainwater in Cotton Farms (Trillion L)	157.4 ± 2.8
Evapotranspiration (mm/ha)	
Potential Crop Evapotranspiration (*ETc*)	565 ± 4
Adjusted Evapotranspiration (ET_{adj})	512 ± 5
Consumptive ET-green	370 ± 8
Consumptive ET-blue	142 ± 4
Types of Irrigation (%)	
Flood irrigation (%)	30 ± 1
Furrow irrigation (%)	43 ± 1
Sprinkler/Pivot irrigation (%)	8 ± 0
Drip/Trickle irrigation (%)	19 ± 1
Irrigation	
Irrigation Water Requirement (mm/ha)	344 ± 8
Irrigation Water Applied (mm/ha)	388 ± 8
Excess irrigation (mm/ha)	44 ± 3
Water Withdrawal for Agriculture (Trillion L)	2,760 ± 4.0
Total Irrigation Water Applied (Trillion L)	52.77 ± 0.9
Water Footprints (L/Kg Lint)	
Consumptive Green water Footprint	4,690 ± 128
Consumptive Blue water Footprint	1,593 ± 31
Consumptive Total Water Footprint	6,238 ± 112
Applied Irrigation Water Footprint	2,158 ± 40

Footnotes

- **Effective Precipitation (mm/ha):** The portion of total rainfall during a crop season that is available for plant use, after accounting for losses due to runoff, evaporation, and deep percolation.
- **Effective Rainwater in Cotton Farms (Trillion L):** Total volume of effective precipitation (rainwater) utilized by cotton crops.
- **Potential Crop Evapotranspiration (*ETc*, mm/ha):** The total amount of water lost through evaporation from the soil and transpiration from plants during a specific period, typically measured over a crop's growing season.
- **Adjusted Crop Evapotranspiration (*ETc*, mm/ha):** The actual water used by a crop under non-ideal conditions, accounting for soil moisture stress (partial depletion of available water), environmental factors (e.g., dry winds, salinity) and crop management practices (e.g., mulching, partial canopy cover).
- **rrigation Water Requirement** *(IWR) (ETc-Pe). (mm/ha):* The total amount of irrigation water needed by a crop to meet its evapotranspiration needs and ensure optimal growth over its growing season.
- **Irrigation Water Applied:** Irrigation water applied as mm/ha and total volume of irrigation water applied in trillion liters.
- **Excess irrigation:** Excess irrigation is the gap between theoretical demand (*IWR*) and actual field delivery of irrigation water applied (*IWA*), varying by irrigation method and soil type.
- **Consumptive ET-green:** The portion of crop water use supplied by effective precipitation (rainfall stored in the root zone)
- **Consumptive ET-blue:** The portion of crop water use supplied by irrigation (surface or groundwater)
- **1 mm rainfall** = 10 m^3/ha = 10,000 L/ha
- **Consumptive Blue water Footprint (L/Kg Lint):** Total irrigation water used by the plant (liters) ÷ Total lint produced (kg)
- **Consumptive Green water Footprint (L/Kg Lint):** Total 'effective precipitation' water use (liters) ÷ Total lint produced (kg)
- **Consumptive Total water Footprint (L/Kg Lint):** Total water used by the crop (effective precipitation + irrigation water used) in liters ÷ Total lint produced (kg)
- **Applied Irrigation Water Footprint:** Total irrigation water applied (liters) ÷ Total lint produced (kg)
- **Water Withdrawal for Agriculture (FAO) (Trillion Liters):** Value presented is minus water withdrawn for aquaculture and livestock.

Despite this, cotton's consumptive use of irrigation water (43.99 trillion liters) accounted for only 1.59% of the of the total irrigation water (2,757 trillion liters) used by arable crops (AQUASTAT, FAO). Additionally, the annual average applied irrigation water (52.77 trillion liters) accounted for only 1.91% of the total irrigation water used by arable crops. The annual average effective rainwater received on cotton farms was 157.4 trillion liters per season.

The annual average water footprint of the cotton crop was 6,238 liters to produce one kilogram of lint, comprising 4,690 liters/Kg lint as rainwater footprint and 1,593 liters/kg lint as blue water footprint from irrigation water.

However, the applied irrigation water footprint was 2,158 liters/kg, which indicates a possibility to save 565 liters of irrigation water per Kg cotton lint, which in effect translates to saving of about 17.5 trillion liters of irrigation water. The average annual effective rainfall received in cotton farms was 508 mm (5.08 million liters per hectare), while the average annual potential crop evapotranspiration (*ETc*) was 565 mm. The adjusted crop evapotranspiration (ET_{adj}) was 512mm, comprising of 370mm as green-evapotranspiration (ET-green) derived from effective rain and 142mm as blue-evapotranspiration (ET-blue) from irrigation. The computed crop irrigation requirement (*ETc-Pe*) was 344mm. The estimated annual average irrigation water applied in irrigated fields was 388 mm (3.88million liters per hectare).

In recent decades, cotton farming has increasingly adopted precision irrigation methods like furrow, sprinkler/pivot, and drip irrigation to enhance water efficiency and productivity. Currently, irrigation methods are distributed as follows:

- 29.6% flood,
- 43.0% furrow,
- 8.0% sprinkler/pivot, and
- 19.2% drip irrigation.

This shift reflects efforts to replace inefficient flood irrigation with more water-efficient alternatives, highlighting progress while emphasizing the need for further optimization to minimize water wastage and enhance sustainability in cotton production.

Discussion

Cotton production is often misrepresented, particularly regarding its water consumption, and is frequently labeled a "thirsty crop" based on calculations of water use efficiency, measured as the total water (rainfall plus irrigation) required to produce one kilogram of lint. This study revealed that the annual average water used to produce one kilogram of cotton lint was 6,239 liters, comprising 4,690 liters/kg lint as rainwater footprint and 1,593 liters/kg lint as blue water footprint from irrigation water.

While irrigation water is a critical focus in debates on water efficiency and conservation — as it is essential to avoid wastage and excessive use beyond crop needs — the emphasis on total water use (e.g., stating that 6,239 liters of water are required to produce one kilogram of lint) or even rainwater use alone (4,690 liters/kg lint) distorts the narrative. This approach misleads consumers into believing that cotton is unnecessarily water-intensive, which is a flawed argument for several reasons. First, crops and plants have a natural right to utilize rainwater, which is integral to their growth cycle. Second, humans have no control over rainfall, making it unreasonable to criticize a crop for using rainwater, as it is not a resource that can be managed or conserved like irrigation water. Third, excessive rainwater is detrimental to crop health and often leads to lower yields, further complicating the discussion.

Thus, focusing on rainwater use is misleading and serves no practical purpose in assessing water management. Instead, scientific analysis of irrigation water use can help identify regions where inefficiencies exist, enabling the adoption of precision technologies to optimize irrigation, reduce inefficiencies, and improve sustainability. Therefore, the focus should remain on improving irrigation practices rather than conflating the issue with rainwater use, which is both natural and beyond human control.

Studies by Mekonnen and Hoekstra (2010) and Safaya *et al.* (2016) estimated the global water footprint of cotton at 233 billion cubic meters per year, closely aligning with this study's estimate of 210.2 billion cubic meters per year (2020–2024), with 75.0% from rainwater and 25.0% from irrigation. The commonly cited figure that cotton accounts for 2.6% of global water use (Hoekstra & Chapagain, 2008) is proportionate to its land use, as cotton occupies 2.21% of global arable land (1,397 million hectares) and closely aligns with this study's finding that consumptive irrigation water used by cotton accounts for 1.59% and applied irrigation water use accounts for 1.91% of the total water withdrawn (2,757 Trillion liters) for agriculture (minus aquaculture and livestock). Additionally, 56.0% of global cotton acreage (17.4 million hectares) is rainfed, contributing to more than 45.0% of total cotton production, further countering the "thirsty crop" misconception.

In recent years, water-use efficiency has improved significantly, with traditional flood irrigation increasingly replaced by drip and sprinkler systems. Additionally, growing awareness of regenerative practices—such as no-till farming, cover cropping, mulching, and biochar application—is further enhancing soil moisture retention, reducing runoff, and promoting sustainability, strengthening efforts in water conservation. This study underscores the need to shift the debate on cotton's water use from rainwater inclusion to irrigation optimization. By focusing on irrigation efficiency, stakeholders can achieve higher yields, increased profitability, and improved environmental sustainability, offering a balanced and practical approach to water use in cotton production.

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Table-2: Country-wise Data (mm/ha) of Consumptive Water Use, Evapotranspiration, Effective Precipitation and Irrigation. Data Presented as Average Values of 5 years (2020-2024), with Standard Error of the Mean (Mean ± SE)

Country	**Consumptive Water Use (mm/ha, Mean ± SE)**			**(mm/ha, Mean ± SE)**			
	ET-green	*ET-blue*	*ET-adj*	*ETc*	*Pe*	*IWR*	*IWA*
Argentina	466 ± 18	40 ± 8	506 ± 24	623 ± 17	509 ± 16	112 ± 11	200 ± 37
Australia	412 ± 24	155 ± 36	567 ± 14	595 ± 17	426 ± 30	16 ± 10	229 ± 49
Bangladesh	471 ± 8	0 ± 0	471 ± 8	476 ± 7	932 ± 40	0 ± 0	18 ± 10
Benin	298 ± 24	0 ± 0	298 ± 24	582 ± 5	725 ± 34	0 ± 0	70 ± 6
Brazil	513 ± 14	2 ± 2	515 ± 14	536 ± 23	696 ± 19	4 ± 5	42 ± 16
Burkina Faso	449 ± 9	0 ± 0	449 ± 9	499 ± 12	715 ± 24	0 ± 0	18 ± 2
Cameroon	460 ± 27	0 ± 0	460 ± 27	548 ± 11	619 ± 35	0 ± 0	55 ± 12
Chad	413 ± 19	0 ± 0	413 ± 19	483 ± 7	665 ± 24	0 ± 0	24 ± 5
China	172 ± 16	370 ± 18	543 ± 11	598 ± 13	188 ± 17	460 ± 22	414 ± 26
Colombia	393 ± 2	20 ± 9	413 ± 7	419 ± 10	599 ± 23	50 ± 28	98 ± 34
Cote d'Ivoire	370 ± 9	0 ± 0	370 ± 9	370 ± 9	621 ± 32	0 ± 0	0 ± 0
Egypt	4 ± 2	705 ± 14	708 ± 14	779 ± 17	4 ± 2	776 ± 18	823 ± 22
Ethiopia	365 ± 4	0 ± 0	365 ± 4	404 ± 4	761 ± 33	7 ± 4	44 ± 15
Greece	182 ± 26	298 ± 28	480 ± 10	517 ± 12	182 ± 26	342 ± 30	293 ± 21
India	426 ± 10	35 ± 2	461 ± 11	487 ± 7	620 ± 17	128 ± 4	240 ± 10
Indonesia	316 ± 46	183 ± 29	499 ± 17	603 ± 9	324 ± 53	200 ± 41	266 ± 28
Iran	143 ± 27	494 ± 33	637 ± 9	695 ± 14	143 ± 27	574 ± 42	505 ± 36
Kazakhstan	159 ± 17	531 ± 23	691 ± 14	760 ± 16	159 ± 17	625 ± 26	570 ± 25
Kenya	446 ± 7	10 ± 7	456 ± 7	466 ± 8	624 ± 42	27 ± 14	44 ± 16
Malawi	437 ± 13	5 ± 8	442 ± 15	510 ± 12	648 ± 38	8 ± 13	117 ± 16
Mali	444 ± 16	0 ± 0	444 ± 16	500 ± 14	803 ± 19	0 ± 0	52 ± 5
Mexico	183 ± 21	503 ± 25	686 ± 11	748 ± 14	183 ± 21	585 ± 27	648 ± 28
Mozambique	363 ± 11	0 ± 0	363 ± 11	398 ± 6	637 ± 36	0 ± 0	0 ± 0
Myanmar	448 ± 12	0 ± 0	448 ± 12	453 ± 12	605 ± 24	3 ± 4	42 ± 13
Nigeria	412 ± 18	3 ± 2	415 ± 17	591 ± 13	608 ± 38	32 ± 18	235 ± 24
Pakistan	394 ± 32	333 ± 43	727 ± 12	772 ± 16	394 ± 32	410 ± 52	467 ± 58
South Africa	419 ± 25	130 ± 27	549 ± 6	614 ± 10	436 ± 24	222 ± 43	332 ± 33
Spain	85 ± 18	491 ± 22	576 ± 6	655 ± 9	85 ± 18	566 ± 25	508 ± 21
Sudan	168 ± 21	120 ± 2	288 ± 47	706 ± 33	422 ± 36	581 ± 34	698 ± 35
Tanzania	452 ± 23	0 ± 0	452 ± 23	519 ± 11	749 ± 32	86 ± 32	180 ± 60
Togo	416 ± 5	0 ± 0	416 ± 5	443 ± 7	712 ± 18	0 ± 0	0 ± 0
Türkiye	94 ± 18	558 ± 4	653 ± 11	727 ± 14	94 ± 18	646 ± 27	555 ± 25
Turkmenistan	42 ± 9	792 ± 19	834 ± 11	928 ± 14	42 ± 9	952 ± 21	890 ± 24
Uganda	431 ± 15	9 ± 5	440 ± 11	463 ± 13	593 ± 13	0 ± 0	0 ± 0
USA	448 ± 18	89 ± 22	537 ± 4	586 ± 16	499 ± 27	166 ± 33	283 ± 28
Uzbekistan	64 ± 11	642 ± 2	706 ± 12	812 ± 16	64 ± 11	781 ± 26	716 ± 24
Zambia	313 ± 15	0 ± 0	313 ± 15	469 ± 20	675 ± 46	0 ± 0	0 ± 0
Zimbabwe	327 ± 28	1 ± 1	328 ± 28	488 ± 24	543 ± 53	0 ± 0	0 ± 0
World	**370 ± 8**	**142 ± 4**	**512 ± 5**	**565 ± 4**	**508 ± 6**	**344 ± 7**	**388 ± 8**

Footnotes:

- mm/ha: 1 mm = 1 L per M^2 = 10,000 L per hectare
- Excess Irrigation (mm/ha): Excess irrigation water applied beyond crop requirements = Irrigation applied – crop water requirement
- World: global averages calculated across all countries listed

Table-3: Water (Billion Liters) in Cotton Farms, Water Footprint of Irrigation and Consumptive Water Use. Country Data presented as Average Values of 5 years (2020-2024), with Standard Error of the Mean (Mean ± SE)

Country	Water Footprints (L/Kg Lint, Mean ± SE)				Water Withdrawal Agriculture Mean (BL)	Water Used in Cotton Farms Mean ± SE (BL)	
	Applied Irrigation	Consumptive Water Footprints					
		Blue Water	Green Water	Total		irrigation Water	Effective Rainwater
Argentina	542 ± 88	180 ± 31	7,274 ± 238	7,454 ± 256	27,930 ± 0	183 ± 44	2,688 ± 174
Australia	876 ± 199	631 ± 143	1,889 ± 135	2,520 ± 79	9,090 ± 431	912 ± 92	2,037 ± 361
Bangladesh	28 ± 14	0 ± 0	8,744 ± 1,557	8,744 ± 1,557	31,500 ± 0	1 ± 0	325 ± 39
Benin	15 ± 1	0 ± 0	6,178 ± 461	6,178 ± 461	45 ± 0	4 ± 0	4,219 ± 171
Brazil	20 ± 8	2 ± 2	2,938 ± 39	2,939 ± 39	36,293 ± 75	59 ± 20	11,655 ± 871
Burkina Faso	4 ± 0	0 ± 0	10,207 ± 739	10,207 ± 739	421 ± 0	1 ± 0	3,932 ± 358
Cameroon	15 ± 3	0 ± 0	7,739 ± 521	7,739 ± 521	737 ± 0	2 ± 0	1,425 ± 95
Chad	2 ± 0	0 ± 0	20,821 ± 1,274	20,821 ± 1,274	672 ± 0	0 ± 0	1,559 ± 113
China	1,865 ± 123	1,767 ± 91	873 ± 69	2,640 ± 37	361,677 ± 339	10,984 ± 738	5,592 ± 512
Colombia	292 ± 106	142 ± 78	4,072 ± 295	4,214 ± 339	16,086 ± 155	3 ± 1	68 ± 6
Cote d'Ivoire	0 ± 0	0 ± 0	9,124 ± 1,391	9,124 ± 1,391	600 ± 0	0 ± 0	2,585 ± 0
Egypt	11,274 ± 535	9,657 ± 378	50 ± 28	9,707 ± 400	61,350 ± 0	917 ± 110	4 ± 2
Ethiopia	224 ± 77	0 ± 0	5,447 ± 224	5,447 ± 224	9,000 ± 0	12 ± 4	605 ± 51
Greece	2,310 ± 151	2,342 ± 174	1,493 ± 351	3,834 ± 317	8,107 ± 0	688 ± 68	445 ± 52
India	1,987 ± 114	710 ± 37	9,656 ± 265	10,366 ± 286	688,000 ± 0	10,974 ± 609	77,626 ± 3,561
Indonesia	4,243 ± 852	3,064 ± 530	10,055 ± 2,639	13,119 ± 3,002	177,171 ± 0	1 ± 0	3 ± 0
Iran	5,584 ± 430	5,590 ± 425	1,752 ± 330	7,342 ± 275	86,000 ± 0	399 ± 36	125 ± 24
Kazakhstan	5,506 ± 227	5,167 ± 194	1,701 ± 183	6,868 ± 150	11,842 ± 136	594 ± 22	184 ± 24
Kenya	162 ± 185	81 ± 94	40,199 ± 13,501	40,279 ± 13,585	2,937 ± 0	0 ± 0	65 ± 7
Malawi	138 ± 22	8 ± 11	11,613 ± 548	11,621 ± 542	1,166 ± 0	1 ± 0	98 ± 17
Mali	16 ± 2	0 ± 0	12,291 ± 958	12,291 ± 958	5,000 ± 0	3 ± 1	4,524 ± 861
Mexico	3,607 ± 230	2,820 ± 210	1,086 ± 110	3,906 ± 173	66,704 ± 113	921 ± 101	277 ± 46
Mozambique	0 ± 0	0 ± 0	13,931 ± 947	13,931 ± 947	1,005 ± 0	0 ± 0	750 ± 0
Myanmar	285 ± 86	0 ± 0	6,904 ± 211	6,904 ± 211	29,570 ± 0	31 ± 10	1,026 ± 34
Nigeria	198 ± 16	17 ± 9	26,639 ± 1,942	26,656 ± 1,934	4,549 ± 0	14 ± 2	2,764 ± 243
Pakistan	7,116 ± 900	5,108 ± 596	6,261 ± 1,314	11,368 ± 1,574	172,400 ± 0	9,399 ± 869	8,270 ± 955
South Africa	1,534 ± 116	876 ± 168	4,732 ± 443	5,609 ± 312	11,818 ± 40	25 ± 2	80 ± 4
Spain	5,274 ± 1,883	5,095 ± 1774	1,067 ± 410	6,162 ± 2,121	17,367 ± 5	229 ± 1	46 ± 12
Sudan	2,466 ± 623	1,753 ± 438	3,415 ± 765	5,168 ± 852	25,910 ± 0	349 ± 83	1,215 ± 312
Tanzania	1 ± 0	0 ± 0	27,150 ± 1,600	27,150 ± 1,600	4,425 ± 0	0 ± 0	2,799 ± 324
Togo	0 ± 0	0 ± 0	14,323 ± 518	14,323 ± 518	46 ± 0	0 ± 0	595 ± 0
Türkiye	2,978 ± 112	2,967 ± 107	539 ± 120	3,506 ± 140	46,268 ± 164	2,419 ± 227	438 ± 91
Turkmenistan	23,896 ± 940	21,264 ± 867	1,128 ± 247	22,392 ± 747	16,022 ± 11	4,831 ± 258	228 ± 48
Uganda	0 ± 0	0 ± 0	14,139 ± 1,091	14,139 ± 1,091	259 ± 0	0 ± 0	311 ± 43
USA	910 ± 92	447 ± 97	4,668 ± 289	5,115 ± 204	163,007 ± 0	2,889 ± 215	16,501 ± 2,150
Uzbekistan	8,875 ± 413	8,073 ± 367	1,004 ± 160	9,078 ± 223	41,785 ± 1,314	5,929 ± 179	671 ± 118
Zambia	0 ± 0	0 ± 0	12,842 ± 5,176	12,842 ± 5,176	1,152 ± 0	0 ± 0	511 ± 0
Zimbabwe	0 ± 0	0 ± 0	15,071 ± 2,834	15,071 ± 2,834	4,146 ± 34	0 ± 0	1,170 ± 106
World	**2,158 ± 40**	**1,593 ± 31**	**4,690 ± 128**	**6,283 ± 112**	**2,758,999 ± 4,000**	**52,775 ± 962**	**157,413 ± 2,810**

Footnotes:

- World: Global averages represent mean values across all listed countries, with the exception of water withdrawal data (FAO). * For this metric, the total world figure includes water withdrawal from both cotton-growing and non-cotton-growing countries.

Table-4: Distribution of Irrigation Technologies: Country-wise Data presented as Average Values of 5 years (2020-2024), with Standard Error of the Mean (Mean ± SE)

	Area '000 Hectares	Yield Kg/ha	Production '000 Tonnes	Irrigated Area Mean ± SE		% Distribution of Irrigation Technologies (Mean ± SE)			
	Mean ± SE	Mean ± SE	Mean ± SE	'000 Ha	%	Flood	Furrow	Sprinkler	Drip
Argentina	528 ± 41	640, ± 29	338 ± 23	92 ± 6	18	31 ± 2	45 ± 1	20 ± 2	5 ± 1
Australia	478 ± 56	2,179 ± 61	1,041 ± 118	398 ± 46	83	8 ± 1	67 ± 1	18 ± 0	7 ± 1
Bangladesh	35 ± 4	539 ± 87	19 ± 5	3 ± 1	7	13 ± 2	87 ± 2	0 ± 0	0 ± 0
Benin	582 ± 26	483 ± 14	281 ± 15	6 ± 0	1	100 ± 0	0 ± 0	0 ± 0	0 ± 0
Brazil	1,674 ± 102	1,746 ± 47	2,923 ± 232	139 ± 8	9	15 ± 2	54 ± 1	26 ± 1	4 ± 1
Burkina Faso	550 ± 56	440 ± 30	242 ± 32	5 ± 0	1	100 ± 0	0 ± 0	0 ± 0	0 ± 0
Cameroon	230 ± 3	595 ± 12	137 ± 4	4 ± 0	2	100 ± 0	0 ± 0	0 ± 0	0 ± 0
Chad	234 ± 20	198 ± 6	46 ± 3	0 ± 0	0	100 ± 0	0 ± 0	0 ± 0	0 ± 0
China	2,981 ± 62	1,976 ± 46	5,891 ± 106	2,656 ± 42	87	7 ± 0	22 ± 3	4 ± 1	67 ± 3
Colombia	11 ± 1	966 ± 79	11 ± 1	3 ± 0	25	0 ± 0	73 ± 2	27 ± 2	0 ± 0
Cote d'Ivoire	416 ± 20	406 ± 49	169 ± 25	0 ± 0	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Egypt	111 ± 12	730 ± 20	81 ± 9	111 ± 12	100	62 ± 1	23 ± 1	12 ± 1	3 ± 1
Ethiopia	80 ± 6	671 ± 28	53 ± 4	27 ± 2	36	8 ± 1	90 ± 1	2 ± 0	0 ± 0
Greece	244 ± 14	1,220 ± 81	298 ± 35	235 ± 13	96	0 ± 0	38 ± 3	40 ± 1	23 ± 2
India	12,526 ± 328	441 ± 4	5,524 ± 159	4,564 ± 151	35	38 ± 2	52 ± 1	0 ± 0	10 ± 2
Indonesia	1 ± 0	314 ± 31	0.28 ± 0.08	0 ± 0	54	47 ± 1	53 ± 1	0 ± 0	0 ± 0
Iran	87 ± 5	819 ± 26	71 ± 6	79 ± 4	91	38 ± 2	56 ± 2	1 ± 1	6 ± 1
Kazakhstan	115 ± 3	937 ± 7	108 ± 3	104 ± 3	91	26 ± 1	73 ± 1	1 ± 0	0 ± 0
Kenya	10 ± 1	111 ± 19	1 ± 0	0 ± 0	4	38 ± 3	62 ± 3	0 ± 0	0 ± 0
Malawi	15 ± 2	376 ± 21	6 ± 1	1 ± 0	5	100 ± 0	0 ± 0	0 ± 0	0 ± 0
Mali	563 ± 102	362 ± 30	204 ± 44	6 ± 1	1	100 ± 0	0 ± 0	0 ± 0	0 ± 0
Mexico	152 ± 12	1683 ± 49	255 ± 24	142 ± 11	94	8 ± 1	83 ± 1	9 ± 1	0 ± 0
Mozambique	118 ± 13	260 ± 10	31 ± 4	0 ± 0	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Myanmar	170 ± 7	649 ± 5	110 ± 5	75 ± 3	44	0 ± 0	100 ± 0	0 ± 0	0 ± 0
Nigeria	455 ± 43	155 ± 6	70 ± 8	6 ± 1	1	100 ± 0	0 ± 0	0 ± 0	0 ± 0
Pakistan	2,100 ± 76	602 ± 62	1,402 ± 181	2,014 ± 73	96	84 ± 1	16 ± 1	0 ± 0	0 ± 0
South Africa	18 ± 1	886 ± 30	16 ± 1	7 ± 0	39	0 ± 0	47 ± 2	53 ± 2	0 ± 0
Spain	54 ± 2	799 ± 126	43 ± 8	45 ± 2	83	0 ± 0	34 ± 2	19 ± 0	47 ± 2
Sudan	288 ± 71	492 ± 75	142 ± 44	50 ± 11	30	15 ± 1	80 ± 1	5 ± 1	0 ± 0
Tanzania	374 ± 36	166 ± 8	62 ± 5	0 ± 0	0	0 ± 0	95 ± 1	5 ± 1	0 ± 0
Togo	84 ± 6	291 ± 11	24 ± 2	0 ± 0	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Türkiye	464 ± 35	1,750 ± 58	812 ± 59	436 ± 32	95	6 ± 1	61 ± 2	20 ± 1	13 ± 1
Turkmenistan	543 ± 15	373 ± 10	202 ± 8	543 ± 15	100	7 ± 0	92 ± 0	0 ± 0	1 ± 0
Uganda	52 ± 8	305 ± 29	16 ± 3	0 ± 0	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
USA	3,305 ± 262	960 ± 32	3,174 ± 189	1,021 ± 69	30	0 ± 0	36 ± 1	57 ± 1	7 ± 1
Uzbekistan	1,047 ± 7	638 ± 12	668 ± 16	828 ± 5	79	0 ± 0	78 ± 3	0 ± 0	22 ± 3
Zambia	76 ± 19	244 ± 64	18 ± 7	0 ± 0	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Zimbabwe	215 ± 13	217 ± 24	47 ± 6	2 ± 0	0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
World	**30,987 ± 369**	**786 ± 8**	**24,538 ± 228**	**13,605 ± 192**	**44**	**30 ± 1**	**43 ± 1**	**8 ± 0**	**19 ± 1**

Footnotes:

- Irrigated Area (%): Percentage of total cotton area that is irrigated.
- Distribution of Irrigation Technologies: Percentage (%) of irrigated area using each irrigation method, such as flood, furrow, sprinkler, drip