Sensors and Materials, Vol. 37, No. 11 (2025) 5247–5268
MYU Tokyo

S & M 4243

Moisture Management Technologies in Cotton Ginning Industry: Enhancing Quality and Efficiency

Suyog Pundlikrao Jungare,[1*] Prasad Vilas Joshi,[2]
Mahendra Kumar Sharma,[3] and Manoj Kumar[4]

[1]Electronics & Communication Engineering, IIIT Nagpur, Maharashtra, India
[2]Department of Basic Sciences, IIIT Nagpur
[3]Bajaj Steel Industries Ltd., Hingna, Nagpur-440016
[4]Chemical and Biochemical Processing Division, ICAR - Central Institute for Research on Cotton Technology, Mumbai 400019, India

(Received June 20, 2025; accepted October 22, 2025)

Keywords: cotton fiber, moisture, ginning industry, processing, ginning techniques, quality

Moisture content is a key parameter in cotton ginning, which has a direct impact on fiber strength, seed separation capacity, and overall processing efficiency. Excess moisture reduces fiber strength, while excessive dryness leads to breakage and low productivity. Old methods of moisture control, such as spray-based conditioning, natural drying, and oven drying (as standardized in the American Society for Testing and Materials, ASTM D2495-07), offer limited precision and flexibility for high-speed ginning operations. To solve these issues, in this work, we assess traditional approaches and innovative sensor-based solutions, ranging from sophisticated systems such as the Vomax Model 760, Intelligin platforms, capacitive sensors, near-infrared spectroscopy, and IoT-facilitated monitoring tools. These technologies provide real-time accurate moisture sensing and adaptive control, minimizing the loss of fibers and enhancing energy efficiency. The originality of the present work is in combining sensor-based technologies with current ginning practices to offer a comprehensive view on both the improvement of fiber quality and process sustainability. We also emphasize new technology trends, including automation and Industry 4.0 integration, which are transforming the future of cotton ginning. The results indicate that efficient sensor-based moisture management not only enhances fiber quality but also increases operational efficiency, bringing significant advantages to both cotton producers and textile manufacturers.

1. Introduction

Cotton is the most widely grown natural fiber and remains a major part of global markets, making up almost one-third of total fibers in use.[1] It also plays a key role in the textile industry. Its by-products, such as cottonseed, hulls, and stalks, supply material for oil extraction, animal feed, compost, and bioenergy.[2] The economic and social importance of cotton goes beyond just

*Corresponding author: e-mail: dtei21ece002@iiitn.ac.in
https://doi.org/10.18494/SAM5772

ISSN 0914-4935

being a fiber. It supports millions of farming families and supplies essential raw materials to many industries.

The ginning process is the first and most critical stage of cotton processing, where seed cotton is transformed into lint suitable for spinning. First, cotton is harvested from the field, then opened and dried to facilitate cleaning. Conditioning with humidification systems is carried out before ginning, where the seed and fiber are separated.(3) The fibers are further cleaned in lint cleaners, after which moisture is adjusted again to maintain fiber quality. Finally, the lint is pressed into bales and stored. Each of these steps affects the fiber properties such as length, strength, and fineness,(4) while ginning efficiency also determines the value of cottonseed and by-products that support parallel industries.(5) Figure 1 illustrates the principal stages of cotton processing, along with corresponding moisture content levels.

Among all process variables, moisture content (MC) is consistently regarded as the most critical factor affecting fiber quality and ginning performance. Cotton absorbs and releases moisture depending on the humidity and temperature of its surroundings.(6) When the moisture content is too high, the fibers become too soft, which reduces cleaning efficiency. It also

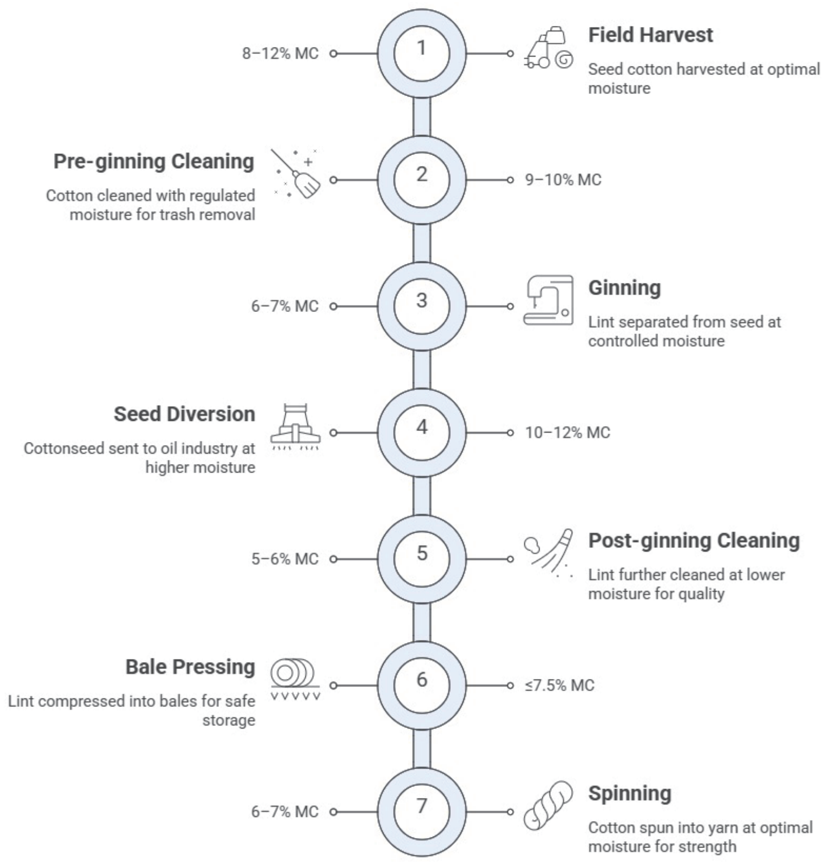

Fig. 1. (Color online) Stages of cotton processing with corresponding MC levels. The process begins with seed cotton harvesting at optimal MC, followed by pre-ginning cleaning, ginning, seed diversion, post-ginning cleaning, bale pressing, and finally, spinning, ensuring regulated MC for quality, storage safety, and yarn strength.

increases the chance of microbial growth during storage. Plus, high moisture content increases the energy needed for bale pressing.[7] When fibers are too dry, they become brittle. This causes fiber breakage, increases the amount of short fibers, and creates more dust, which weakens yarn strength.[8] To prevent these problems, lint is usually maintained at a moisture content of 6 to 7%. This range is considered optimal for keeping fibers intact, using energy efficiently, and ensuring bale stability.[9] However, ensuring precise moisture regulation across all stages of ginning seed, lint, and bale remains a technical challenge for the industry.

Historically, moisture management depended on basic methods such as natural drying, spray-based humidification, and oven-drying standards such as ASTM D2495-07.[8] Although these techniques set early standards, they are slow in measurement and are lab-based techniques, which are not suited for today's high-capacity gins. Later, resistance-based portable meters came into use. However, they had limited accuracy because they were affected by ambient temperature and the density of the samples.[10] These issues highlighted the need for reliable, nondestructive, real-time measurement methods.

The introduction of new sensor technologies has transformed moisture control. Capacitive sensors detect changes in dielectric properties. They are often used in seed cotton monitoring because they respond quickly. However, they need regular calibration. Microwave sensors offer nondestructive bulk analysis. They are less sensitive to changes in density, which makes them suitable for both seed cotton and lint.[11] NIR spectroscopy offers precise moisture estimation using fiber absorption spectra. It works well during lint drying and cleaning.[12] RF sensors improve this process by enabling the continuous inline monitoring of moisture along the ginning line.[13] Recently, integrated platforms such as Vomax 760 and IntelliGin™ have brought together different sensors, including those for trash and color, with automated controls for drying, humidification, and cleaning. This helps to lower reliance on labor, save energy, and maintain fiber quality.[14]

While much of the attention in the literature has focused on lint, the roles of cottonseed and bale moisture are equally important to overall process performance. Cottonseed retains moisture that directly affects fiber–seed separation efficiency and determines the usability of the seed for oil extraction and feed. Excess moisture complicates separation and increases the incidence of seed coat fragments in lint, whereas overly dry seeds hinder efficient separation. Capacitive and microwave sensors are often used at this stage to ensure safe MC levels. This helps improve both lint purity and the quality of by-products.[11,15,16] Similarly, bale moisture content is critical for storage stability and international trade. Bales with more than 7.5% moisture content risk microbial growth, heating, and damage during storage or shipping. Bales that are too dry require more energy for pressing, which can harm the fibers. To prevent these issues, resistance-based and RF sensors are used in bale pressing lines to measure moisture content before compression. Warehouse monitoring systems track humidity and temperature. This helps maintain the quality of bales during long-term storage.[9]

These stage-specific applications show that moisture sensors serve as more than just diagnostic tools and are crucial to modern ginning control. At the seed level, sensors ensure efficient separation and increase the value of seed by-products. At the fiber level, they help balance drying and cleaning while keeping fiber strength and length intact. At the bale level, they ensure safe storage and follow international trading standards. These improvements show that moisture management has shifted from a supportive measure to an essential factor in quality, efficiency, and sustainability in cotton ginning.

Despite these technological improvements, current research is still fragmented. Many studies are focused on individual devices or specific stages without providing comparisons across the entire ginning chain.[10] Older references dominate much of the literature, with limited coverage of recent developments in commercial bale monitoring systems and integrated platforms. In addition, few studies are focused on accuracy, speed, cost, scalability, and industrial feasibility.[17,18]

In this paper, we address these gaps by presenting a comprehensive framework for moisture management technologies in cotton ginning. Unlike in earlier studies, we systematically integrate traditional, emerging, and advanced sensor-based approaches across seed, lint, and bale levels. We highlight both the technological innovations and the industrial challenges, discuss trends in sensor-based automation, and clarify the novelty of stage-wise integration for fiber preservation, process efficiency, and by-product utilization. By positioning moisture as a controllable parameter throughout the ginning process, this study contributes a unique synthesis that strengthens both academic understanding and industrial practices. The findings show that moisture-sensing technologies improve fiber quality and ginning efficiency. They also protect the value of cottonseed and bales. This helps build a more competitive and sustainable cotton industry.

2. Significance of Moisture Content in Cotton and Ginning Industry

Moisture content has a critical effect on cotton ginning as it affects the fiber properties, seed separation, energy demands, and general process economics. Although the fundamental relationship between moisture and fiber performance is well documented, the relevance to present industry practices is in the integration of sensor-based monitoring and intelligent control systems, enabling real-time operation under commercial conditions. In this section, we emphasize the key effects of moisture and their positions in the context of new technologies.

2.1 Effect on fiber quality

Cotton fiber quality is very sensitive to moisture content. Fibers with high moisture (more than 10%) swell and become sticky. This increases nep formation, roller wrapping, and short fiber content during mechanical processing.[19,20] High-moisture cotton also makes lint cleaning more difficult. Sticky fibers attract dust and plant trash, which leads to higher contamination levels. On the other hand, cotton that is too dry (less than 5% moisture) becomes brittle and can break easily. This results in shorter fiber lengths, a higher short fiber index, and more seed coat fragments.[21,22] Yarn made from such lint is weak, uneven, and breaks more often during spinning.

It is important to keep the moisture content at an optimal level to improve spinnability. This generally falls between 6 and 8% in lint. Effective moisture results in fiber flexure, lower fiber breakage, and more even yarn.(23) Recent work with real-time and on-line moisture sensors shows that moisture regain can be measured very precisely in seed cotton and lint.(10,20) Therefore, monitoring moisture levels carefully during ginning is essential to achieve the quality standards of the textile industry. Figure 2 shows the impact of moisture levels on the quality of cotton fiber and ginning efficiency. It highlights three distinct scenarios: low moisture, optimal moisture, and high moisture.

2.2 Impact on seed separation and ginning efficiency

Moisture also affects lint separation from seeds. In saw gins, high-moisture seed cotton resists the saw teeth, lowering throughput and leaving partially ginned seeds.(24) On the other hand, when cotton is too dry, the saws grip the fibers more tightly, which increases fiber breakage and produces seed coat fragments that lower the quality of the lint.(25) Roller gins, which rely on friction, also struggle with moisture extremes. They create too much entanglement under wet conditions or strip fibers under dry conditions.(25)

Experimental studies have shown that poor moisture management can decrease ginning efficiency by 10 to 15%.(25) Since industrial gins often handle several bales each hour, these losses lead to significant drops in overall productivity. Additionally, uneven moisture within a bale can cause variations in gin stand performance, making automation efforts more difficult. Table 1 summarizes the comparative effects of high moisture and low-temperature freezing on the mechanical properties, surface morphology, and crystalline structure of cotton fiber, using data from Cao *et al.*(19)

2.3 Energy consumption and processing costs

Energy is a significant operational cost in ginning. Drying systems make up nearly one-third of total energy use.(26) Overdrying cotton wastes fuel, whereas underdrying requires reprocessing. Recent IoT-enabled sensor networks can cut drying energy by 15 to 20% through

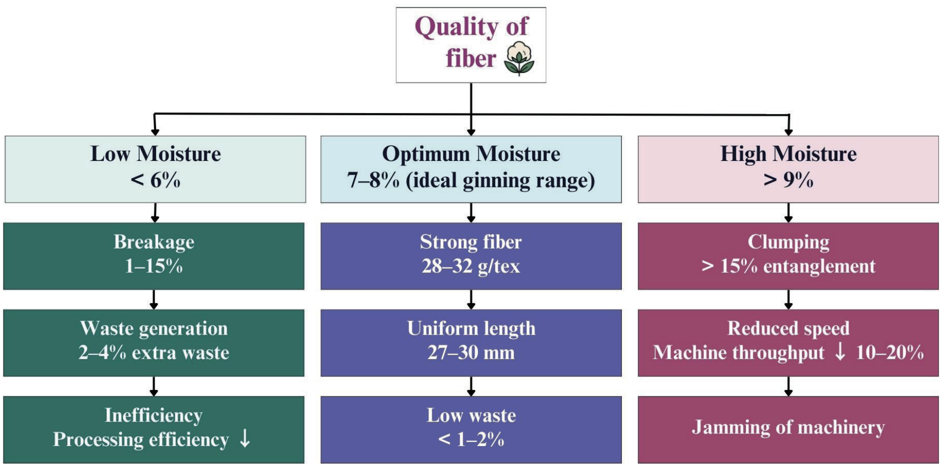

Fig. 2. (Color online) Impact of moisture levels on cotton fiber quality and ginning efficiency.

Table 1.
Effects of moisture and low-temperature treatment on cotton fibers.[19]

Sample condition	Mechanical properties	Surface morphology	Crystallinity & crystal structure	Effect on fiber quality
Control: 8.5% MR 0 freezing days	Serves as the baseline for comparison	Relatively smooth surface with no obvious damage	XRD Index: 67.58% NMR Index: 68.62% Crystal Types: Cellulose Iβ (85.27%), Cellulose Iα (6.77%), Cellulose II (5.2%), Paracrystalline (2.86%)	The fiber maintains its inherent structural integrity and mechanical performance
Treated: 75% MR 1–8 freezing days	Fracture Strength: Decreased (min. 388.71 MPa at 3 days) Elongation at Break: Decreased (min. 7.7% at 8 days) Initial Modulus: Decreased by 29.76% after 8 days	Exhibited fractures, localized holes, fold-like damage, and enhanced cracking	XRD Index: 64.39% (at 8 days) NMR Index: 65.61% (at 8 days) Crystal Types (at 8 days): Cellulose Iβ (84.97%), Cellulose Iα (4.48%), Cellulose II (7.57%), Paracrystalline (2.97%)	Fiber quality is degraded, making it weaker and more prone to fracture during processing

MR: Moisture regain

real-time monitoring and control. These results show that managing moisture not only affects quality but also sustainability and cost.

2.4 Industrial and economic implications

Cotton with improper moisture content often faces penalties in global markets owing to poor spinnability and low yarn quality. Recent reviews stress that moisture differences from bale to bale are a major source of economic loss in the supply chain. Commercial platforms such as Intelligin and Vomax 760 now combine multi-sensor arrays with cloud analytics. This stabilizes bale quality and provides predictive process control.

2.5 Sustainability and Industry 4.0 implications

The significance of moisture management extends beyond process optimization to sustainability and digital transformation. Capacitive, microwave, and dielectric sensors, when coupled with IoT, edge computing, and machine learning, enable predictive adjustments to gin operations in real time.[11,15,27] These systems improve resilience in dusty, high-throughput environments and align with Industry 4.0 objectives of automation, data-driven decision-making, and energy-efficient manufacturing. In addition to capacitive and dielectric approaches, resistive sensors have been refined for real-time moisture monitoring, with pressure-compensated designs achieving high accuracy ($R^2 \approx 0.986$, $RMSE \approx 0.204\%$) and demonstrating strong potential for rapid industrial applications.[10] The novelty of this work lies in the synthesis of traditional fiber–moisture knowledge with emerging sensor-based control strategies, providing a comprehensive framework for next-generation ginning operations.

3. Traditional Techniques of Moisture Management and Estimation

Moisture content has always been a defining parameter in cotton ginning, influencing fiber processability, mechanical performance, and final textile quality. Before the development of advanced sensors, a range of traditional techniques was developed to manage and measure moisture in cotton, such as automated conditioning systems and real-time feedback technologies. These methods, while varied in principle, share a common objective: to bring cotton into its optimal moisture window for ginning and to quantify that condition with sufficient accuracy for commercial and scientific purposes. The following sections provide a comprehensive account of six principal traditional approaches—natural drying/sun, spray conditioning, oven drying, resistance-based meters, psychrometric methods, and Karl Fischer titration—emphasizing their scientific principles, applications, and continued significance in the cotton industry.

3.1 Natural/ sun drying of seed cotton

Natural/sun drying is the most fundamental technique of moisture control, practised historically across cotton-growing regions. In this method, seed cotton is spread in thin layers in open fields or on ventilated platforms, where solar radiation, wind movement, ambient humidity, and temperature act as the drivers of water evaporation.(28–30) Natural drying not only remains relevant in smallholder contexts but also provides the first empirical data for developing cotton sorption isotherms and drying models.

The kinetics of natural drying are described by thin-layer drying equations. A commonly applied model expresses the moisture ratio (*MR*) as an exponential function of time, as below.

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \exp(-kt) \tag{1}$$

Here, M_t represents moisture content at time t, M_0 is the initial moisture, M_e is the equilibrium moisture content, and k is the drying constant that varies with air velocity and temperature.(31,32) This formulation, originally developed for grains, was later validated for seed cotton and forms the basis of cotton drying simulations used even today.(33)

Natural drying has significant scientific relevance. Studies of thin-layer drying in seed cotton helped define cotton's equilibrium moisture content (EMC), which is central to understanding moisture regain behavior.(34,35) These empirical models continue to guide modern drying systems, where mechanical dryers replicate natural processes under controlled conditions. In addition, sorption isotherms derived from natural drying experiments remain a reference for storage studies, packaging design, and moisture modeling in fiber science.(36,37)

3.2 Spray-based conditioning

Spray-based conditioning emerged as a complementary practice to natural drying. Cotton that becomes too dry loses flexibility, leading to a higher proportion of short fibers during ginning. To restore fibers to their optimal processing range of 6–8% moisture, operators introduced atomized water into cotton streams, increasing average moisture.(38)

The expected moisture change is expressed by a simple mass balance equation:

$$M_f = M_i + \frac{W_a}{W_c} \times 100\,, \quad (2)$$

where M_f is the final moisture percentage, M_i is the initial moisture, W_a is the water mass added, and W_c is the cotton mass.(39)

Historically, spray conditioning has been applied both at the feeder stage and in lint-cleaning operations to improve fiber elasticity before pressing into bales.(40) Its use is well documented in United States Department of Agriculture (USDA) ginning guidelines, which recommend the targeted application of water for improved ginning efficiency.(41) In contemporary studies, spray application techniques continue to be refined through the exploration of nozzle designs and misting systems for improved homogeneity.(42) Spray conditioning thus represents one of the earliest examples of active moisture management rather than passive reliance on environmental conditions.

3.3 Oven drying method (ASTM D2495-07)

Oven drying remains the most widely accepted laboratory procedure for determining cotton moisture content. Standardized under ASTM D2495-07, the method involves drying samples at 105 ± 2 °C until a constant weight is achieved.(7) Moisture content is then calculated as

$$MC(\%) = \frac{W_{wet} - W_{dry}}{W_{wet}} \times 100\,, \quad (3)$$

where W_{wet} denotes the initial weight of the sample and W_{dry} the oven-dry weight.

This method is scientifically important because it provides an absolute measurement that is independent of electrical, optical, and environmental variability.(43) The accuracy of oven drying, typically within ±0.1–0.2%, has made it the reference standard for cotton research worldwide.(7,44,45) Almost all modern sensor technologies, from microwave to NIR spectroscopy systems, are calibrated against oven drying data.(46)

Applications of the oven drying method extend beyond research laboratories to regulatory frameworks. International cotton trade standards often reference oven-dry values for arbitration in disputes.(47,48) In addition, oven drying data underpin sorption isotherm models and drying kinetics equations, linking laboratory analysis directly to industrial practice.(49) Despite being destructive, oven drying remains the backbone of cotton moisture determination and continues to play a central role in calibration and validation protocols.(43)

3.4 Electric resistance meters

Resistance-based meters represent one of the first attempts to provide portable, nondestructive tools for moisture estimation in cotton. The principle relies on the inverse relationship between fiber moisture and electrical resistance. As water increases ionic conductivity in the fiber matrix, resistance decreases. The empirical relation between resistance (R) and moisture content (MC) can be approximated as

$$MC = a - b \cdot \log(R), \tag{4}$$

where a and b are calibration constants derived experimentally.

Resistance meters have been widely applied in warehouses, cotton markets, and bale storage facilities for rapid inspections.[41] They provide readings within seconds and are particularly useful for quality assurance during bale certification processes. USDA studies in the 20th century established calibration curves for resistance meters against oven-dry values, creating standardized procedures for industrial use.

In addition to their widespread adoption, resistance meters have also been used in research contexts to gather large datasets on cotton bale moisture.[50] Their speed and portability made them valuable in field studies where destructive laboratory methods were impractical.[51] Even with the advent of advanced microwave and dielectric sensors, resistance-based devices remain in circulation as cost-effective tools for preliminary moisture evaluation.

3.5 Psychrometric methods

Psychrometric methods are among the earliest scientific approaches of cotton moisture estimation. The technique involves measuring the relative humidity of air equilibrated with cotton using wet-bulb and dry-bulb thermometers and then relating this humidity to equilibrium moisture content (EMC) through sorption isotherms.[52] The general form of EMC is expressed as a function of RH and temperature.

$$EMC = f\left(RH,\ T\right) \tag{5}$$

The development of moisture regain curves for cotton was largely based on psychrometric studies. These sorption isotherms describe the relationship between environmental conditions and cotton moisture content, providing critical data for designing storage and packaging systems.[37]

Applications of psychrometric methods extend beyond cotton ginning into textile manufacturing, where EMC directly affects yarn strength, dimensional stability, and dye uptake.[53] In agricultural engineering, psychrometry has also been used to design storage facilities and predict moisture changes under varying climatic conditions.[54] Contemporary studies continue to refine cotton EMC models, integrating psychrometric data into advanced sorption modeling approaches.(55) Thus, psychrometry has enduring significance in linking cotton's hygroscopic nature with both ginning efficiency and textile performance.

3.6 Karl Fischer titration

Karl Fischer titration is a chemical method that remains the most precise traditional technique for moisture determination in cotton. It is based on the quantitative reaction of water with iodine and sulfur dioxide in the presence of alcohol and a base catalyst.

$$H_2O + I_2 + SO_2 + 3RN \rightarrow 2(RNH)I + RNSO_3 \quad (6)$$

Here, RN represents an organic base.

Karl Fischer titration can detect moisture content with an accuracy up to ±0.1%, making it invaluable as a calibration method.(7,56) It has been widely used in laboratory research to validate emerging sensor technologies, providing high-precision reference values for cotton samples.(57) The method also plays an important role in comparative studies where absolute accuracy is required, such as evaluating moisture migration during storage or validating bale conditioning systems.

Beyond cotton, Karl Fischer titration is a standard analytical tool in polymer science and agricultural engineering, but in cotton research, its significance lies in providing the definitive benchmark for moisture content.(56,58) Even in the context of advanced inline sensors, Karl Fischer titration continues to serve as the ultimate laboratory reference.

Taken together, these six traditional approaches provide a comprehensive framework for moisture management in cotton. Natural drying offered the first empirical insights into cotton's drying behavior; spray conditioning provided an early form of active intervention; oven drying established the reference standard for absolute accuracy; resistance meters enabled portability and rapid testing; psychrometry generated foundational sorption isotherms; and Karl Fischer titration defined the upper bound of laboratory precision. Each method contributed not only to cotton ginning practices but also to broader fiber science, textile engineering, and agricultural research. Their enduring value lies in the fact that modern technologies, from microwave sensors to IoT-enabled monitoring, continue to rely on these traditional techniques as benchmarks, calibration references, and sources of fundamental knowledge.

4. Emerging Techniques of Moisture Management and Estimation

Moisture control is still one of the key issues of cotton ginning and fiber processing, affecting not just seed separation efficiency but also final fiber quality on entering the world textile supply chain.(8) Classical methods such as oven drying, resistance meters, and psychrometric measurements are scientifically sound but constrained by speed, mobility, and applicability in inline industrial processing.(7) In addressing these constraints, the last few decades have witnessed the emergence of new technologies that leverage advances in dielectric physics, microwave engineering, optical sensing, and data analytics.(11,59) These new techniques have revolutionized moisture measurement from being a laboratory procedure to a sensor-based, real-time practice incorporated directly into ginning processes.(60) Following the needs of automation, traceability, and sustainability, sensors of moisture in seed cotton and bales have emerged as the cornerstone of these new paradigms supported by optical imaging and machine-learning-based calibration.(10,61,62) In the following section, all these innovations are discussed in detail, highlighting their operating principles, industrial significance, and technological trends.

4.1 Moisture sensors for seed cotton

Seed cotton presents a unique challenge for estimating moisture because of its mixed structure and low bulk density.(10,11) It includes fibers tangled with seeds and varying amounts of foreign particles, with water spread unevenly among these elements.(11,63) Typical lab methods do not reflect this variability in real time. As a result, dielectric and microwave-based sensors have been developed for dynamic cotton flows.(11)

The main idea behind seed cotton sensors is the clear difference in dielectric properties between dry cotton and water. Dry cotton exhibits a dielectric constant (ε_c) of approximately 2–4, whereas liquid water has a dielectric constant (ε_w) near 80 at room temperature.(11) The effective dielectric constant of the cotton mass can be modeled as a volumetric mixture:

$$\varepsilon_{eff} = \varepsilon_c(1-\phi) + \varepsilon_w \phi\,, \tag{7}$$

where ε_{eff} is the effective dielectric constant of the moist cotton mass, and φ is the volumetric water fraction.(11) This relationship ensures that even small changes in moisture content lead to detectable changes in dielectric response.

Building on this principle, microwave transmission sensors measure attenuation and phase shift as waves propagate through the cotton stream.(11,63) Attenuation is proportional to both frequency and the dielectric loss factor ε'', which rises with increasing water content:

$$\alpha \propto f \cdot \varepsilon''\,, \tag{8}$$

where α is attenuation and f is frequency.(11) Devices such as the USDA Vomax Model 760 exemplify this technology, providing inline, nondestructive, and continuous monitoring of seed cotton moisture during ginning.(45) Its deployment across several ginning plants has demonstrated how dielectric sensing can improve process control by maintaining cotton moisture in the optimal range of 6–8%, thereby preventing fiber breakage or excessive toughness.(45)

Another commonly used technology is capacitive sensing, in which changes in capacitance between electrode plates are measured as moist cotton affects the dielectric environment. Although capacitive sensors are less accurate than microwave systems, they are attractive for small- and medium-sized gins because they are inexpensive and simple to implement. They are often utilized in feeder systems where relative accuracy is more important than absolute accuracy.

NIR sensors provide extra features. Water absorbs well at wavelengths near 1400 and 1900 nm.(64,65) NIR spectroscopy uses these absorption peaks to estimate moisture. Handheld NIR sensors are used for quick field inspections and evaluations on the gin floor. More advanced systems with fiber optic probes are used for inline applications. Although NIR measurements have limited penetration depth, they give valuable surface moisture estimates. These estimates often help calibrate dielectric sensors.(66,67)

Recent advances show the trend of integrating multiple sensors. By combining microwave, capacitive, and NIR data, sensor fusion platforms achieve better accuracy, especially with the help of machine learning models.(10) Neural networks trained on oven-dry reference datasets cut down on calibration errors caused by changes in density, temperature, and foreign matter. In recent research, adaptive calibration models have been found to work better than static curves, providing reliable measurement under various conditions. Another key trend is miniaturization.(10,61) Compact microwave modules are now designed for direct mounting on gin feeders, which allows for distributed measurement throughout processing lines.

The industrial significance of these developments is that they enable the integration of seed cotton moisture sensing into gin automation systems. Real-time monitoring allows users to adjust drying and conditioning equipment as necessary. This reduces energy use and keeps fiber quality high.(68) By making measurement a vital part of process control, seed cotton sensors have become important for precise ginning.

4.2 Moisture sensors for bales

Bale moisture measurement faces unique challenges compared with seed cotton owing to its high density and the probability of uneven moisture distribution. A standard cotton bale, compressed to densities over 450 kg/m^3, may have wet areas that surface probes cannot detect. These wet regions can promote microbial growth or cause fiber discoloration. Current bale moisture sensors focus on deep penetration, volumetric averaging, and working with baling operations.

RF and microwave probes are commonly used in bale sensing.(17) They take advantage of the dielectric properties of water in dense cotton. By applying transmission line models, attenuation and phase shift measurements are converted into bulk moisture estimates. Unlike resistance-based probes that only provide localized readings, RF and microwave systems penetrate more deeply, generating representative volumetric assessments.

A leading industrial platform is the Intelligin system. It integrates dielectric sensors directly into bale presses.(69) The system samples bale moisture at several points and frequencies during compression, calculating average values in real time.(11) Its capacity to interface with gin automation allows immediate feedback, enabling operators to condition cotton prior to bale completion. This integration of sensing with process control exemplifies the evolution of bale moisture monitoring from a quality assurance task into a dynamic component of automated ginning. Optical techniques are being studied for bale surfaces. NIR hyperspectral imaging creates moisture maps that show surface differences.(61) This helps spot uneven conditioning. Hyperspectral imaging extends on this method by identifying leaf trash at the same time. Although these methods remain limited to surface assessment, when combined with dielectric probes, they provide a comprehensive view of bale quality.

An emerging approach integrates sensor data with predictive modeling of moisture redistribution. Fick's second law describes the diffusion of water in compressed cotton:(70)

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial x^2}, \tag{9}$$

where M is the local moisture content, t is time, x the spatial coordinate, and D the diffusivity. Coupling sensor readings with such models enables the prediction of moisture migration, enabling the identification of potential hotspots during storage. This predictive capability highlights a growing trend toward combining real-time sensing with computational analytics in bale monitoring.

Overall, bale moisture sensors have shifted from post-hoc inspection tools to proactive devices embedded in processing lines. Their contribution lies in preventing quality loss during storage and ensuring that cotton bales entering supply chains meet international standards for moisture content.

4.3 Optical and imaging-based techniques

Beyond dielectric and RF sensors, optical and imaging technologies are receiving more attention as additional methods for estimating moisture. NIR spectroscopy uses water absorption bands near 1400 and 1900 nm to provide quick, noncontact surface measurements of both seed cotton and bales. Hyperspectral imaging builds on this by producing spatial maps of moisture distribution while also identifying foreign matter and maturity differences. Recent studies have also looked into mid-infrared and terahertz sensing for deeper penetration, but industrial use is still limited.(71) These optical methods often work with machine learning for real-time analysis.(72) They show the trend toward multifunctional sensing platforms that combine moisture monitoring with broader quality assessments.

4.4 Technology tendencies and industrial perspectives

The development of moisture management technologies shows several overarching tendencies. First, there is a clear movement toward automation integration, where sensors are part of closed-loop control systems that dynamically regulate drying, conditioning, and baling. This keeps cotton within the ideal moisture range throughout processing. Second, sensor fusion and AI are reshaping measurement as data from microwave, capacitive, and optical devices are being combined and interpreted through adaptive machine learning algorithms. This significantly improves accuracy and reliability under varying conditions. Third, miniaturization and IoT connectivity are boosting distributed monitoring. Compact, low-power sensors can now be installed across multiple points in ginning lines, with data transmitted to cloud platforms for centralized analytics. Such connectivity also enables supply-chain traceability, an increasingly important requirement for global textile markets. Fourth, multifunctionality has become essential. Modern systems are expected to measure not only moisture but also contamination, fiber maturity, and colorimetric properties. Finally, sustainability drives much of the innovation by encouraging precise, real-time monitoring and new technologies that reduce energy use, reduce overdrying, and promote environmentally friendly cotton production.

4.5 Comparative assessment of moisture measurement techniques

While a wide range of methods exist for monitoring moisture in cotton, in many prior studies, these techniques were simply listed without providing comparative insight into their performance. As noted by reviewers, comparative analysis is essential to highlight the advantages of modern sensor-based methods over classical laboratory techniques. To strengthen the soundness of this review, in this subsection, we present two comparative tables supported by case studies, offering a clear evaluation of accuracy, response time, implementation feasibility, and cost. Table 2 shows the accuracy, response time, feasibility, and cost across methods, showing the advantages of real-time sensor-based approaches over traditional laboratory tests.

Table 2
Performance metrics of traditional and emerging methods for cotton moisture measurement.

Method	Accuracy (% error)	Response time	Industrial feasibility	Relative cost	Key reference
Oven-dry (ASTM D2495)	±0.1–0.2% (reference standard)	~24 h	Laboratory only	High (time and labor intensive)	(41, 48)
Resistance meter	±2–3% (surface-dependent)	<10 s	Portable, field and gin spot checks	Low	(7, 73)
Psychrometry	±1–2% (depending on calibration, ambient airflow, and operator skill)	5–15 min	Field and lab, Portable	Low–Medium	(41, 74)
Karl Fischer titration	±0.05–0.1% (most precise lab method)	30–60 min	Laboratory only	High (equipment + reagents)	(56, 75)
Microwave dielectric (Vomax 760)	±0.5–1.0%	Real time (<1 s)	Inline gin systems	High (capital cost)	(44, 76)
RF/microwave bale sensor (Intelligin)	±0.5%	Real time (<1 s)	Bale press integration	High (capital cost)	(77)
NIR spectroscopy	±1–2% (calibration-ependent)	<5 s	Lab, field, limited gin use	Medium	(12, 78)
Hyperspectral imaging	±0.5–1% (experimental, lab only)	Seconds (imaging-based)	Not commercial	Very High	(62, 72, 79)

4.5.1 Case study

USDA Vomax 760 for Seed Cotton: Vomax 760, developed by USDA engineers, is a microwave transmission sensor designed for real-time, inline moisture monitoring of seed cotton. Deployed in several U.S. cotton gins, it has been instrumental in reducing overdrying incidents by approximately 20%, leading to significant energy savings and enhanced fiber strength. By maintaining cotton within the optimal moisture range of 6–8%, the system also mitigates nep formation and fiber breakage, underscoring the industrial value of microwave dielectric sensing for continuous process control.(11)

Intelligin Bale Moisture System: The Intelligin system integrates RF-based dielectric sensors directly into bale presses. In a U.S. commercial gin, the adoption of this system reduced bale-to-bale moisture variability from ±2.5% to ±0.8%. This improvement minimized microbial spoilage risk and ensured compliance with international standards. By embedding sensing in the baling operation, Intelligin exemplifies the shift toward closed-loop automation, where measurement and control occur simultaneously.(80)

NIR Optical Sensing in Harvesters: In trials in China, portable NIR sensors were employed for the rapid screening of seed cotton moisture during harvesting. The noncontact readings enabled operators to determine whether drying was needed before transport to the gin. Using NIR guidance reduced unnecessary predrying by 15–18%, lowering fuel costs while preserving fiber integrity. Although surface-limited, NIR systems are highly suitable for field applications and provide useful calibration support for dielectric-based systems.(12)

These comparisons illustrate the progression from traditional laboratory methods, which are valued for precision but restricted in speed and industrial relevance, to emerging technologies that deliver real-time, inline, and automation-compatible measurements. The case studies further demonstrate that microwave and RF sensors are already delivering tangible benefits in commercial gins, while NIR devices are proving useful in harvest and field contexts. Optical and hyperspectral imaging methods, though still experimental, highlight the next frontier of multifunctional sensing. Together, these results confirm that moisture management has evolved from a static quality test into a dynamic control variable at the core of modern cotton ginning.

The metrics and case studies demonstrate that while traditional methods remain essential as reference standards, their industrial feasibility is restricted by slow response times and labor demands. In contrast, emerging dielectric, RF, and optical systems deliver fast, accurate, and scalable measurements that integrate seamlessly with gin automation (Table 3). Case studies such as those of the Vomax 760 and Intelligin platforms provide compelling evidence that sensor-based technologies not only improve measurement accuracy but also enhance energy use efficiency, fiber quality, and bale uniformity. This evolution marks a decisive shift in cotton processing. Moisture management is no longer a post-hoc laboratory measurement but a dynamic control variable at the core of precision ginning operations.

Table 3
Overview of traditional and emerging methods in cotton moisture management.(10,11,81)

Category	Traditional methods	Emerging methods
Examples	Oven drying, Psychrometry, Resistance meters, Karl Fischer titration	Microwave dielectric (Vomax 760), RF bale sensors (Intelligin), NIR spectroscopy, Hyperspectral imaging, IoT sensor fusion
Accuracy	Very high in lab (±0.1–0.5%), but low in field (±2–3%)	High in lab and inline (±0.5–2% typical)
Response time	Slow: minutes to hours (oven drying up to 24 h)	Real time or near real time (milliseconds to seconds)
Implementation feasibility	Laboratory or manual spot checks only	Fully automatable; inline monitoring in gins and bale presses
Cost	Low capital but highly operational (time, labor, consumables)	Higher initial investment; lower operating costs with automation
Scalability	Limited sample-based use	Highly scalable; distributed sensors across gin lines
Industrial role	Calibration standards and regulatory testing	Primary tools for precision ginning and real-time quality assurance

5. Limitations and Challenges in Moisture Management in Ginning Industry

Moisture management in cotton ginning remains a critical factor influencing fiber quality, ginning efficiency, and economic returns. Despite decades of research, achieving accurate, fast, and reliable estimation of moisture remains challenging, particularly under the heterogeneous and dynamic conditions of commercial gins. While traditional methods such as oven drying and resistance meters are still regarded as reference or baseline techniques, recent sensor-based approaches such as microwave, NIR spectroscopy, hyperspectral imaging, and IoT-enabled systems, have advanced the field considerably. Nevertheless, limitations persist across both domains. These challenges fall into categories of accuracy, sampling representativeness, calibration stability, environmental sensitivity, economic feasibility, and regulatory acceptance. Understanding these constraints is critical to framing future research and industrial implementation.

Traditional methods continue to serve as standards but are hindered by operational constraints. The oven-dry method, as standardized under ASTM D249507, is considered a benchmark for moisture determination, achieving high precision of typically ±0.1–0.2% within a single laboratory and ±0.2–0.5% between laboratories for cotton samples. However, the method requires drying until constant weight is reached, a process that can take several hours, making it unsuitable for real-time process control.[48,82] Resistance meters are the most widely adopted real-time method owing to their portability and low cost and have demonstrated that, with pressure compensation, resistive sensing achieved an RMSE of ~0.20% and a coefficient of variation of 2.22% for cotton moisture regain measurements.[10] However, without corrections for density, pressure, and temperature, their error margins can rise to ±2–3%, which significantly reduces reliability under the dynamic conditions of a commercial gin. Their performance is further compromised by variations in compression and airflow during ginning. The Karl Fischer titration method provides the most precise determination of water content across agricultural materials, achieving ±0.05–0.1% accuracy under ISO 760 protocols.(75) Despite its accuracy, it is expensive, requires skilled handling of reagents, and is not scalable to the industrial environment of gins. Consequently, its use remains limited to research laboratories and quality control facilities rather than production floors.

Emerging sensor-based technologies are aimed at resolving these limitations but face their own barriers. Microwave dielectric systems provide near-instantaneous readings and are capable of inline monitoring. Research on microwave methods for cotton fiber has shown that they are far faster than oven-drying, with response times being under one second.(46) Reported accuracies vary, with laboratory trials often achieving ±0.5–1%. However, performance is affected by factors such as lint density, trash content, and temperature, which can induce small but significant deviations. Field validation in bulk bales is less extensive, and penetration depth remains a limiting factor for high-density cotton. Calibration drift in cotton ginning equipment can elevate error margins from ±0.5% to approximately ±1.5%, highlighting the necessity for regular recalibration.(83) In bale monitoring, RF systems such as Intelligin face challenges with penetration depth, especially in dense bales where surface–core moisture content differences exceed 1.5%, leading to potential inaccuracies.(84) These limitations raise concerns regarding both accuracy and consistency in industrial use.

Optical techniques, including NIR spectroscopy and hyperspectral imaging, offer promising alternatives for cotton moisture measurement but face implementation challenges. NIR spectroscopy is rapid and nondestructive; however, it provides only surface measurements, leading to discrepancies of 2–3% compared with oven drying in dense cotton bales.(39) Seasonal variability further reduces robustness, as demonstrated by the non-generalizability of NIR models developed on one cotton variety, increasing error margins to ±2.5% without recalibration.(85) Hyperspectral imaging extends spectral information and achieves ±0.5–1% accuracy in controlled trials,(86) but operational barriers include high system costs (USD 50000–70000), large data volumes requiring machine learning models, and a lack of equipment able to withstand dusty gin environments. While machine learning integration with hyperspectral imaging systems has improved predictive accuracy, real-time industrial adoption in cotton ginning remains limited.(87–89)

Economic feasibility is another major barrier to widespread adoption. Resistance meters cost less than USD 500, making them accessible to small gins globally. In contrast, microwave dielectric or RF-based inline systems require investments of USD 20000–50000, while hyperspectral imaging systems exceed USD 70000. Even with adoption, annual maintenance costs amount to 5–10% of the system value. This disparity creates inequity in adoption: large industrial gins can justify advanced sensors, but smaller operations, particularly in developing countries, continue to rely on outdated, less accurate techniques. Economic analyses indicate that while large-scale gins may recover the cost of advanced sensors within a few years owing to efficiency gains, such technologies are typically not economically viable for small gins.

Integration with automation and IoT platforms remains underdeveloped. While digital process control is often incorporated into ginning, moisture management technologies often operate as stand-alone devices. Intelligin bale sensors, for example, provide detailed bale-level data but cannot universally interface with bale press controllers without costly customization. Multisensor IoT frameworks offer potential solutions, emphasizing that calibration drift and lack of interoperability among devices from different vendors continue to impede seamless adoption. Real-time closed-loop control of dryers based on distributed sensor input remains largely experimental, despite growing demand for intelligent, automation-ready ginning systems. Finally, regulatory and standardization issues represent a critical bottleneck. Oven drying and Karl Fischer titration are globally organized by ASTM and ISO, providing legal and trade-recognized benchmarks. However, no such standards exist for microwave, RF, NIR spectroscopy, or hyperspectral imaging methods. Without coordinated multilaboratory validation and regulatory approval, novel measurement methods cannot gain the mutual acceptance required for international harmonization and trade.[90]

The limitations and challenges in cotton moisture management span accuracy, sampling representativeness, calibration stability, environmental sensitivity, cost barriers, and regulatory gaps. Traditional methods remain benchmarks but lack scalability for industrial throughput, while emerging sensor-based technologies provide real-time data but face issues of calibration drift, limited penetration, high costs, and absence of standardization. Quantitative evidence highlights the severity of these limitations: oven drying requires 24 hours, resistance meters deviate by ±2–3%, dielectric sensors drift by ±0.5% seasonally, hyperspectral imaging systems exceed USD 70,000 in cost, and bale moisture gradients reach 3% between the core and the surface. To address these barriers, research must focus on hybrid sensing platforms, machine-learning-enabled calibration transfer, low-cost ruggedized devices, and internationally aligned standards. With such advances, moisture management can transition from a persistent challenge to a robust, automation-ready control variable for modern cotton ginning.

6. Conclusions and Future Perspectives

Moisture management is a critical determinant of fiber strength, seed separation, and overall ginning efficiency. While traditional techniques such as natural drying, spray-based conditioning, and oven testing (ASTM D2495-07) provide useful benchmarks, they are too slow and inflexible for modern high-capacity gins. Recent advances in sensor technologies, including microwave dielectric systems such as Vomax 760, RF-based Intelligin platforms, capacitive devices, and NIR spectroscopy, have begun to transform this landscape. These sensors are directly applied in cotton gins to deliver rapid, real-time moisture readings, enabling operators to adjust dryers and presses immediately. By doing so, they minimize fiber breakage, reduce overdrying, and improve both energy efficiency and product quality.

The relationship between sensors and their applications is increasingly dynamic. Instead of serving as stand-alone measurement tools, sensors are now embedded within automated control loops that treat moisture as a process variable. Their application extends from seed cotton at the feeder to final bale monitoring, providing continuous quality assurance across the ginning line. As gins adopt Industry 4.0 strategies, sensor networks combined with IoT and machine learning will create adaptive, data-driven environments.

Future progress will depend on hybrid sensing methods, cost reduction for broader accessibility, and the establishment of international standards. With these advances, sensor-based moisture management will evolve into a cornerstone of intelligent and sustainable cotton processing.

Declaration of generative AI tools

The authors declare they have not used any generative AI tools in creating this article.

Credit authorship contribution statement

Suyog Pundlikrao Jungare: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. P.V. Joshi: Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. M. K. Sharma: On-site visits to cotton ginneries for field data study, Data collection, Writing—review and editing. Manoj Kumar: Writing – original draft, Visualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1 V. Voora, C. Larrea, and S. Bermudez: Global Market Report: Cotton (2020).
2 F. P. Alege, J. S. Tumuluru, G. A. Holt, S. P. Donohoe, C. D. Delhom, J. D. Wanjura: J. Cotton Sci. **28** (2024) 79. https://doi.org/10.56454/SFRM7188
3 M. H. J. Van Der Sluijs: J. Cotton Sci. **24** (2020) 44. https://doi.org/10.56454/CPAZ3825
4 J. Qian, Y. Li, Z. Xiang, H. Cai, and P. Zhang: Text. Res. J. **92** (2022) 3782. https://doi.org/10.1177/00405175221095891
5 M. Beheary, I. Elsaid, A. El-Banna, and N. Abuahmed: J. Adv. Agric. Res. **24** (2019) 476. https://doi.org/10.21608/jalexu.2019.163483
6 Y. L. Hsieh: Text. Res. J. **65** (1995) 299. https://doi.org/10.1177/004051759506500508
7 M. G. Pelletier and R. K. Byler: J. Cotton Sci. **24** (2020) 121. https://doi.org/10.56454/TIGG3482
8 R. K. Byler: J. Cotton Sci. **10** (2006) 300.
9 R. G. Hardin, E. M. Barnes, T. D. Valco, V. B. Martin, and D. M. Culp: J. Cotton Sci. **22** (2018) 36.
10 L. Fang, R. Zhang, H. Duan, J. Chang, Z. Zeng, Y. Qian, and M. Hong: Sensors **23** (2023) 8421. https://doi.org/10.3390/s23208421
11 M. G. Pelletier, J. D. Wanjura, and G. A. Holt: Sensors **16** (2016) 1843. https://doi.org/10.3390/s16111843
12 Q. Li, W. Zhou, X. Zhang, H. Li, M. Li, and H. Liang: Front. Plant Sci. **15** (2024) 1334961. https://doi.org/10.3389/fpls.2024.1334961
13 N. Azmi, L. M. Kamarudin, A. Zakaria, D. L. Ndzi, M. H. F. Rahiman, S. M. M. S. Zakaria, and L. Mohamed: Sensors **21** (2021) 1875. https://doi.org/10.3390/s21051875
14 T. D. Valco: Proc. 2008 Beltwide Cotton Conf. (National Cotton Council, 2008) 653–659.
15 M. G. Pelletier and J. A. Viera: Sensors **10** (2010) 11088. https://doi.org/10.3390/s101211088
16 F. Furlan and P. Gallina: Sens. Imaging **22** (2021) 18. https://doi.org/10.1007/s11220-021-00338-2
17 M. G. Pelletier and E. M. Barnes: Sensors **8** (2008) 7241. https://doi.org/10.3390/s8117241
18 X. Zhang, G. Feng, and X. Sun: J. Agric. Food Res. **18** (2024) 101473. https://doi.org/10.1016/j.jafr.2024.101473
19 J. Cao, X. Liu, R. Mo, H. Liu, and H. Xu: J. Nat. Fibers **21** (2024) 2338926. https://doi.org/10.1080/15440478.2024.2338926

20 Z. Zhu, C. Zhang, H. Liu, and C. Wu: J. Text. Inst. **116** (2025) 1220. https://doi.org/10.1080/00405000.2024.2372907
21 G. B. Tesema: J. Text. Inst. **113** (2022) 101. https://doi.org/10.1080/00405000.2020.1865502
22 M. Van Der Sluijs and R. Long: Text. Res. J. **86** (2016) 1925. https://doi.org/10.1177/0040517515617426
23 Y. Zhu, J. Zhang, X. Zhao, and H. Xu: J. Nat. Fibers **21** (2024) 2338538. https://doi.org/10.1080/15440478.2024.2338538
24 J. S. Tumuluru, C. B. Armijo, D. P. Whitelock, and P. A. Funk: Processes **11** (2023) 2868. https://doi.org/10.3390/pr11102868
25 J. S. Tumuluru, J. Gottula, M. A. Hidalgo, J. King, E. Barnes, H. Ashley, D. Whitelock, P. Funk, J. Wanjura, and Matthew: J. Cotton Sci. **29** (2025) 95. https://doi.org/10.56454/QOHS1717
26 P. A. Funk and R. G. Hardin IV: J. Cotton Sci. **21** (2017) 156. https://doi.org/10.56454/TBLF7573
27 J. Liu, S. Qiu, and Z. Wei: Chemosensors **10** (2022) 376. https://doi.org/10.3390/chemosensors10100376
28 V. Patel, K. B. Judal, H. Panchal, N. K. Gupta, M. M. A. Zahra, and M. A. Shah: Int. J. Low-Carbon Technol. **18** (2023) 887. https://doi.org/10.1093/ijlct/ctad075
29 Z. U. Ortiqov: Innov. Technol. Methodical Res. J. **4** (2023) 1.
30 N. Soomro: Eur. Sci. J. **10** (2014) 303.
31 S. M. Henderson: Trans. ASAE **17** (1974) 1167. https://doi.org/10.13031/2013.37052
32 D. S. Jayas, S. Cenkowski, S. Pabis, and W. E. Muir: Dry. Technol. **9** (1991) 551. https://doi.org/10.1080/07373939108916697
33 M. G. Pelletier, J. W. Laird, G. L. Barker, and S. V. Patankar: J. Cotton Sci. **5** (2001) 234.
34 G. L. Barker: J. Agric. Eng. Res. **63** (1996) 353. https://doi.org/10.1006/jaer.1996.0038
35 W. S. Anthony: Proc. 2006 Beltwide Cotton Conf. (National Cotton Council, 2006) 2520–2529.
36 Z. He, D. Zhang, and H. N. Cheng: Foundations **1** (2021) 32. https://doi.org/10.3390/foundations1010005
37 I. Vitázek and J. Havelka: Res. Agric. Eng. **60** (2014) S52. https://doi.org/10.17221/35/2013-RAE
38 R. K. Byler: Appl. Eng. Agric. **24** (2008) 587. https://doi.org/10.13031/2013.25271
39 J. Rodgers, C. Fortier, S. Y. Kang, J. Montalvo, and T. V. Hoven: AATCC J. Res. **1** (2014) 24. https://doi.org/10.14504/ajr.1.5.4
40 E. Hughs, C. Armijo, and K. Baker: Proc. 2004 Beltwide Cotton Conf. (National Cotton Council, 2004) 2995–3001.
41 Agriculture Research Service, United States Department of Agriculture: Cotton Ginners Handbook. (U.S. Government Printing Office, Washigton Dc, 1977) 2nd ed., pp. 1–503.
42 K. D. Baker, E. Hughs, and D. T. W. Chun: Appl. Eng. Agric. **24** (2008) 491. https://doi.org/10.13031/2013.25133
43 P. A. Funk, A. A. Terrazas, K. M. Yeater, R. G. Hardin, C. B. Armijo, D. P. Whitelock, M. G. Pelletier, J. D. Wanjura, G. A. Holt, and C. D. Delhom: Trans. ASABE **61** (2018) 1985. https://doi.org/10.13031/trans.12980
44 C. Delhom and J. Rodgers: Proc. 2016 Int. Cotton Conf. Bremen (2016) 1–7.
45 M. V. Zambrano, B. Dutta, D. G. Mercer, H. L. MacLean, and M. F. Touchie: Trends Food Sci. Technol. **88** (2019) 484. https://doi.org/10.1016/j.tifs.2019.04.006
46 J. Rodgers, J. Zumba, and C. Delhom: AATCC J. Res. **4** (2017) 1. https://doi.org/10.14504/ajr.4.3.1
47 J. G. Montalvo and T. Von Hoven: Proc. 2008 Beltwide Cotton Conf. (National Cotton Council, 2008) 1511–1517.
48 ASTM International: Standard Test Method for Moisture in Cotton by Oven-Drying (Designation: D2495–07, Reapproved 2019). ASTM Int. (West Conshohocken, PA, 2019).
49 A. S. Mujumdar (Ed.): Handbook of Industrial Drying (CRC Press, Boca Raton, 2014) 4th ed., p. 1348. https://doi.org/10.1201/b17208
50 R. K. Byler, M. G. Pelletier, K. D. Baker, S. E. Hughs, M. D. Buser, G. A. Holt, and J. A. Carroll: Appl. Eng. Agric. **25** (2009) 315. https://doi.org/10.13031/2013.26881
51 V. Mahalakshmi, K. M. Pachiayappan, S. M. Udaya Krithika, and C. Prakash: J. Test. Eval. **51** (2023) 3494. https://doi.org/10.1520/JTE20220391
52 L. H. C. D. Sousa, N. C. Pereira, O. C. D. M. Lima, and E. V. Fonseca: Acta Sci. **23** (2001) 1363.
53 P. R. Armstrong and M. Weiting: Appl. Eng. Agric. **24** (2008) 617. https://doi.org/10.13031/2013.25259
54 T. L. Thompson and R. M. Peart, And G. H. Foster: Trans. ASAE **11** (1968) 0582. https://doi.org/10.13031/2013.39473
55 R. M. Myhara, S. S. Sablani, S. M. Al-Alawi, and M. S. Taylor: LWT - Food Sci. Technol. **31** (1998) 699. https://doi.org/10.1006/fstl.1998.0492
56 J. Montalvo, T. V. Hoven, and S. Cheuk: Proc. 2011 Beltwide Cotton Conf. (National Cotton Council, 2011) 1319–1329.
57 J. G. Montalvo, T. M. V. Hoven, and T. F. North: Proc. 2009 Beltwide Cotton Conf. (National Cotton Council, 2009)1163–1168.

58 J. G. Montalvo, T. M. Von Hoven, T. F. North, and S. Cheuk: Proc. 2010 Beltwide Cotton Conf. (National Cotton Council, 2010) 1378–1383.
59 M. G. Pelletier: J. Cotton Sci. **8** (2004) 170.
60 R. K. Byler: Proc. 2012 Beltwide Cotton Conf. (National Cotton Council, 2012) 605–613.
61 M. Knoblich, M. Al Ktash, F. Wackenhut, V. Jehle, E. Ostertag, and M. Brecht: Textiles **3** (2023) 287. https://doi.org/10.3390/textiles3030019
62 Y. Liu, F. Tao, H. Yao, and R. Kincaid: J. Cotton Res. **6** (2023) 21. https://doi.org/10.1186/s42397-023-00158-7
63 W. Meyer and W. Schilz: J. Phys. Appl. Phys. **13** (1980) 1823. https://doi.org/10.1088/0022-3727/13/10/010
64 L. Yu, W. Gao, R. R. Shamshiri, S. Tao, Y. Ren, Y. Zhang, and G. Su: Int. J. Agric. Biol. Eng. **14** (2021) 32. https://doi.org/10.25165/j.ijabe.20211404.6404
65 Y. Bai, X. Xie, J. Zhang, Y. Jia, and H. Wang: Sci. Rep. **15** (2025) 25694. https://doi.org/10.1038/s41598-025-11127-2
66 N. Zhou, J. Hong, B. Song, S. Wu, Y. Wei, and T. Wang: J. Spectrosc. **2024** (2024) 1. https://doi.org/10.1155/2024/8180765
67 H. Stipanovic, G. Koinig, T. Fink, C. B. Schimper, D. Lilek, J. Egan, and A. Tischberger-Aldrian: Recycling **10** (2025) 152. https://doi.org/10.3390/recycling10040152
68 L. Gay: Inline real time moisture sensing for gin cotton. Theses and Dissertations. Theses and Dissertations (2023). 5838. https://scholarsjunction.msstate.edu/td/5830
69 R. K. Byler: Proc. Beltwide Cotton Production Research Conf. (National Cotton Council, 2013) 1221–1228.
70 X. Chen, S. Zhao, and L. Zhai: J. Electron. Packag. **127** (2005) 460. https://doi.org/10.1115/1.2065707
71 L. Afsah-Hejri, E. Akbari, A. Toudeshki, T. Homayouni, A. Alizadeh, and R. Ehsani: Comput. Electron. Agric. **177** (2020) 105628. https://doi.org/10.1016/j.compag.2020.105628
72 M. F. Guerri, C. Distante, P. Spagnolo, F. Bougourzi, and A. Taleb-Ahmed: ISPRS Open J. Photogramm. Remote Sens. **12** (2024) 100062. https://doi.org/10.1016/j.ophoto.2024.100062
73 R. J. Rodgers, X. Cui, V. B. Martin, and M. D. Watson: Proc. Beltwide Cotton Production Research Conf. (National Cotton Council, 2009) 1179–1184.
74 E. M. Martinez, J. J. Cancela, T. S. Cuesta, and X. X. Neira: Span. J. Agric. Res. **9** (2011) 313. https://doi.org/10.5424/sjar/20110901-295-10
75 Int. Organization for Standardization (ISO): Determination of water — Karl Fischer method (General method) ISO **760** (1978). https://webstore.ansi.org/preview-pages/ISO/preview_ISO%2B760-1978.pdf (accessed October 2025).
76 A. S. Krajewski and S. G. Gordon: Trans. ASABE **53** (2010) 1331. https://doi.org/10.13031/2013.32583
77 R. K. Byler and W. S. Anthony: Proc. 2003 Beltwide Cotton Conf. (National Cotton Council, 2003) 763–766.
78 C. A. Fortier, J. E. Rodgers, M. S. Cintrón, X. Cui, and J. A. Foulk: Text. Res. J. **81** (2011) 230. https://doi.org/10.1177/0040517510383620
79 B. Lu, P. Dao, J. Liu, Y. He, and J. Shang: Remote Sens. **12** (2020) 2659. https://doi.org/10.3390/rs12162659
80 USDA Agricultural Research Service: Quality and Utilization of Agricultural Products, National Program #306. https://www.nps.ars.usda.gov (accessed October 2025).
81 R. K. Byler: Proc. Beltwide Cotton Production Research Conf. (National Cotton Council, 2014) 568–575.
82 J. G. Montalvo and T. M. V. Hoven: J. Cotton Sci. **12** (2008) 33–47.
83 J. A. Thomasson: Appl. Eng. Agric. **8** (1992) 147. https://doi.org/10.13031/2013.26045
84 J. D. Wanjura, G. A. Holt, M. G. Pelletier, and E. M. Barnes: Proc. 2020 Beltwide Cotton Conf. (National Cotton Council, 2020) 588–609.
85 Y. Zhang, J. B. Chou, J. Li, H. Li, Q. Du, A. Yadav, S Zhou, M. Y. Shalaginov, Z. Fang, H. Zhong, C. Roberts, P. Robinson, B. Bohlin, C. Ríos, H. Lin, M. Kang, T. Gu, J. Warner, V. Liberman, K. Richardson, and J. Hu: Nat. Commun. **10** (2019) 4279. https://doi.org/10.1038/s41467-019-12196-4
86 M. Hong, L. Fang, H. Wang, H. Duan, J. Chang, H. Li, and R. Zhang: Comput. Electron. Agric. **232** (2025) 110073. https://doi.org/10.1016/j.compag.2025.110073
87 Z. Liu, L. Zhao, X. Yu, Y. Zhang, J. Cui, C. Ni, and L. Zhang: Sci. Prog. **105** (2022) 00368504221137461. https://doi.org/10.1177/00368504221137461
88 Z.-Y. Yang, W.-K. Xia, H.-Q. Chu, W.-H. Su, R.-F. Wang, and H. Wang: Plants **14** (2025) 1481. https://doi.org/10.3390/plants14101481
89 A. Khan, A. D. Vibhute, S. Mali, and C. H. Patil: Ecol. Inform. **69** (2022) 101678. https://doi.org/10.1016/j.ecoinf.2022.101678
90 A. Bas, N. Burns, A. Gulotta, J. Junker, B. Drasler, R. Lehner, L. Aicher, S. Constant, A. Petri-Fink, and B. Rothen-Rutishauser: Small **17** (2021) 2006027. https://doi.org/10.1002/smll.202006027

About the Authors

Suyog Pundlikrao Jungare is a PhD scholar in the Department of Electronics and Communication Engineering at IIIT Nagpur. He holds bachelor's and master's degrees in mechanical engineering. With over eight years of experience with cotton processing machinery, he is currently working as a Manager-New Product Development at Bajaj Steel Industries Limited, Nagpur. His research focuses on drying and humidification systems for cotton gins, moisture sensing, and moisture management in cotton processing.
(dtei21ece002@iiitn.ac.in)

Dr. P V Joshi is currently working as an assistant professor at the Department of Basic Science of Indian Institute of Information Technology, Nagpur. He holds bachelor’s and master’s degrees in mechanical engineering and a Ph.D. degree from the National Institute of Technology (NIT), Raipur. With 22 years of research experience, his expertise lies in robotics, solid mechanics, and vibration analytics.
(pjoshi@iiitn.ac.in)

Dr. M K sharma is currently a full-time director and CEO of Bajaj Steel Industries Limited, Nagpur. He holds a PhD degree from Nagpur University in cotton ginning, focusing on the management and development of the Indian ginning industry. With over 45 years of managerial experience, he has played a key role in the modernization of cotton ginning and pressing technology. He is also a board member of several companies in the USA and Africa and has held leadership positions in trade organizations such as FICCI, Vidarbha Industries Association, and the Regional Advisory Council (Central Excise).
(mks@bajajngp.com)

Dr. Manoj Kumar is a scientist (plant biochemistry) at ICAR–Central Institute for Research on Cotton Technology, Mumbai, India. He is a recipient of the prestigious “Prime Minister Fellowship Award” and “IARI Gold Medal” for his outstanding research on natural colorants from black carrots. His research interest is in the extraction and characterization of proteins and other bioactive compounds from plant-based matrices. He has published more than 200 research and review articles in peer-reviewed international journals with more than 3500 citations. (manoj.kumar13@icar.org.in)