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Research on Post-Harvest Management Technology to Improve Cotton Quality

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Abstract Cotton is an important cash crop worldwide, and its production is related to the livelihoods of millions of farmers. However, cotton quality faces many challenges in the post-harvest stage, such as increased impurities due to improper harvesting methods and fiber deterioration caused by poor storage. This study focuses on improving cotton quality through post-harvest management technology. It systematically analyzes the key factors affecting cotton post-harvest quality, including harvesting time and methods, field processing and transportation, storage conditions, etc.; reviews advanced post-harvest processing technologies, such as cotton ginning process innovation, fiber grading and sorting, and moisture control methods; explores new technologies for cotton quality assessment and monitoring, including fiber quality parameter testing, digital monitoring, traceability systems, and quality certification mechanisms; evaluates the sustainability and economic impact of post-harvest technology, and analyzes it from the aspects of cost-effectiveness, environmental friendliness, and social effects; and takes Xinjiang as a case to introduce regional challenges, technology introduction, and its effectiveness. Finally, the future development direction of cotton post-harvest management technology is prospected, such as digital intelligent system integration, localized customization, and policy and institutional support. This study aims to provide a reference for improving cotton quality and value and promote the high-quality development of the cotton industry chain.

Keywords Cotton; Post-harvest management; Quality improvement; Ginning technology; Quality monitoring

1 Introduction

Cotton plays an important role in the global agricultural economy. According to statistics, the cotton industry is related to the livelihoods of millions of farmers and families in 80 countries on five continents around the world (Khan et al., 2020). Cotton is also an important source of foreign exchange for many low- and middle-income countries. China is the world's major cotton producer and consumer, with Xinjiang's cotton production accounting for more than 90% of the country's total and about 20% of the world's total (Feng et al., 2024). High-quality cotton fiber not only directly determines the quality of textiles, but also affects farmers' income and the competitiveness of the textile industry. However, cotton is easily affected by a variety of factors during post-harvest processing, transportation and storage, resulting in quality degradation (Salimov et al., 2022).

The main challenges faced by cotton after harvesting include: improper harvesting time and method may lead to impurities and fiber damage. For example, although mechanical harvesting improves efficiency, it is often accompanied by a high impurity content (Kazama et al., 2015); if the field processing and transportation are not well managed, cotton will be exposed to rain or moisture, which will cause the fiber to mold and turn yellow, forming "moldy cotton" (Anthony, 2003); improper storage conditions will cause the cotton pile to heat up and the fiber strength to decrease. Long-term storage of cotton may also cause fermentation due to excessive moisture content (Jaime et al., 2013). In the face of these problems, how to maintain and improve the quality of cotton fiber by improving post-harvest management technology has become an urgent issue to be solved.

The goal of this study is to review and analyze post-harvest management technology to improve cotton quality. The research content covers eight aspects, including factors affecting cotton post-harvest quality, post-harvest processing technology, quality assessment and monitoring technology, sustainability and economy of technology, as well as case analysis and future development direction in Xinjiang. By combing through relevant research and practical results at home and abroad in the past five years, this study aims to propose effective strategies to improve post-harvest management of cotton and provide a scientific basis for improving cotton quality and industrial benefits.

2 Factors Affecting Cotton Quality after Harvest

2.1 Harvesting time and method

From field harvesting to processing, storage and transportation, the handling methods of each link will affect the final fiber quality. The selection of cotton harvesting time and picking method are directly related to the quality of seed cotton. Timely harvesting can prevent the fiber from being overly exposed to adverse weather and deteriorating. For example, if the cotton is picked at night or in the early morning when the dew is heavy, the moisture content of the seed cotton is high, fiber spots are prone to appear and the subsequent processing is more difficult (Van Der Sluijs and Delhom, 2017). On the contrary, harvesting when there is sufficient sunlight, the cotton bolls are fully opened and the cotton bolls are dry is conducive to keeping the fiber clean and strong. In addition, the difference in harvesting methods has a significant impact on cotton quality. Manual hand-picked cotton is picked one by one, with low impurity content and complete fiber, and high quality; while mechanical cotton picking harvests the entire cotton boll at one time, which inevitably carries cotton husks, leaves and other debris, and the impurity rate is usually higher than hand-picked cotton (Figure 1) (Kazama et al., 2015). The study by Zhang et al. (2021) showed that the content of foreign fibers and impurities in machine-picked cotton fibers increased significantly, which is one of the important factors affecting cotton quality. Therefore, while promoting mechanized harvesting, it is necessary to improve the front-end impurity removal technology to reduce the quality decline caused by the harvesting method.

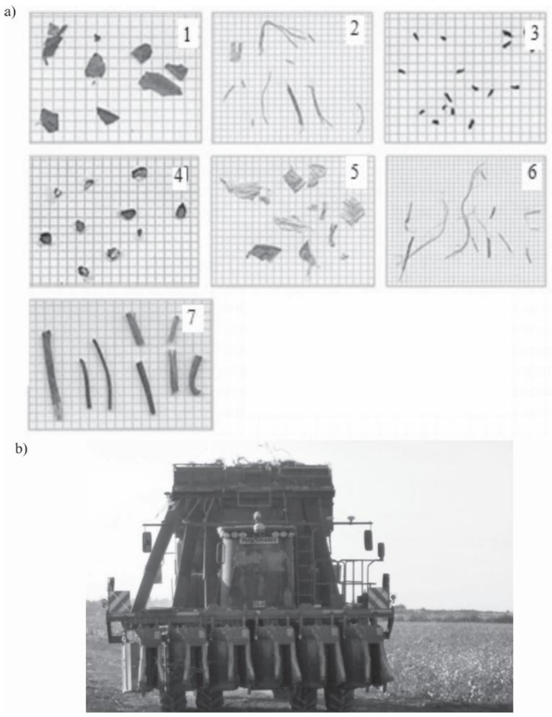

Figure 1 Classification of machine and hand picked cotton pollution a) 1-leaf, 2-stem, 3-funiculi, 4-seed coat, 5-shale, 6-grass, 7-steck; John Deere is a cotton picker b) (Adopted from Egamberdiev et al., 2024)

2.2 Field processing and transportation

The field processing and transportation methods of cotton after harvesting will also affect the fiber quality. If the cotton seeds are not dried in time after harvesting and are bagged and stacked, the excessive moisture and temperature will easily cause the cotton pile to heat up and mold, causing the fiber color to turn yellow and the strength to decrease. For example, when the cotton seeds are soaked in water, the wax on the fiber surface is destroyed, the color is yellow-brown, and the humidity increases. Long-term stacking will breed mold and form moldy cotton (Birrer et al., 2021). In addition, if the mixing of field impurities is not effectively avoided after harvesting, such as mud, plant fragments, etc. adhering to the cotton seeds, the vibration during transportation will cause these impurities to be further embedded in the fiber, increasing the difficulty of subsequent cleaning. Improper transportation and loading methods may also compact the cotton pile and cause mechanical damage to the fiber. In order to reduce the adverse effects of transportation on quality, cotton bags or molded packaging with good air permeability should be used, and the transportation tools should be kept clean and dry to prevent rain and secondary pollution. In addition, while the new seed cotton mold technology improves transportation efficiency, it should be covered with waterproof tarpaulins to avoid moisture in open-air storage.

2.3 Storage conditions

The storage environment of seed cotton and lint cotton is crucial to maintaining quality. Appropriate storage should control temperature and humidity and prevent insect and mildew damage. Excessive moisture content is the main cause of quality deterioration during storage. If the storage environment is poorly ventilated and the humidity is high, the cotton pile will release heat due to microbial activity, causing the "heat cotton" phenomenon, resulting in reduced fiber strength and spinnability (Salimov et al., 2022). A study on factors affecting cotton storage pointed out that high moisture and excessive impurities are the key factors that lead to the decline of fiber and seed quality during storage (Van Der Sluijs and Delhom, 2016). Therefore, the moisture content of seed cotton should be reduced to a safe range (generally not higher than 10% to 12%) before storage, and as much weeds as possible should be removed. The warehouse should be kept dry and ventilated, and the bottom of the stack should be raised to prevent ground moisture from invading. If long-term storage is required, regular stacking inspections can be considered to monitor the temperature and humidity of the cotton bales. Once signs of condensation and heating are found, ventilation and cooling should be carried out in time. Only by strictly controlling the adverse factors in each link after harvest can the original quality of cotton be maintained to the greatest extent.

3 Post-Harvest Processing Technology

3.1 Innovation in cotton ginning process

In response to the problems of high impurities and high moisture content in cotton after harvest, modern cotton processing technology is constantly innovating to improve processing efficiency while protecting fiber quality. Ginning is a key process to separate seed cotton into lint and cotton seeds, and its process level directly affects fiber length and purity. Traditional sawtooth gins are highly efficient, but have a certain cutting effect on the fiber; while roller gins are gentler on the fiber but have a slow processing speed. Technological innovations in recent years have been committed to achieving a balance between the two (Armijo et al., 2017). Jean Luc Chanselme, partner and technical director of Cotimes do Brasil and an expert in cotton ginning engineering and technology, said, "The art of ginning lies in achieving the best balance between positive effects and negative effects, and producing lint of target quality at the lowest cost." To this end, the industry has continuously improved mechanical structure and process parameters. For example, in order to adapt to the situation where machine-picked cotton has more impurities, the new cotton ginning equipment has added pre-cleaning and multi-sawtooth combination design to improve the impurity removal ability while minimizing fiber damage. Researchers in the United States and China are developing automatic foreign body removal devices based on machine vision and mechanical sorting, which can remove foreign fibers such as plastic film in real time during seed cotton feeding and ginning (Zhao et al., 2018). In Xinjiang, many ginning mills have introduced high-capacity ginning production lines and automated control systems to achieve continuous and uniform feeding and process parameter optimization, which not only ensures efficient impurity removal of machine-picked seed cotton, but also reduces fiber breakage and curling. In order to ensure that cotton of different varieties and qualities are used in their proper places, some local standards require enterprises to process cotton according to its variety, category and grade, and establish a ginning quality traceability system. This not only maintains the stability of fiber quality, but also provides a basis for subsequent quality management and responsibility traceability.

3.2 Fiber grading and sorting

The grading of cotton fiber quality is a bridge connecting production and textile utilization. Traditional grading relies on artificial sensory experience, which is highly subjective and lacks consistency. In recent years, the instrumentation and digitization of fiber testing have significantly improved the objective accuracy of grading.

The universal HVI (high-capacity fiber tester) can measure the length, strength, micronaire value, color, impurities and other indicators of a large number of cotton samples in a short time. At present, the international cotton trade generally uses HVI test results as the basis for pricing, and more than 50% of the world's cotton is graded through the HVI system. Since the implementation of cotton notarization inspection, China has also fully promoted instrumental inspection. Fiber inspection agencies in various places are equipped with standardized HVI equipment to conduct notarization inspections on each bale of lint and issue quality certificates. A study analyzed the results of HVI comparison tests of fiber laboratories across the country and found that the consistency of cotton fiber test data in various laboratories was high, which verified the accuracy and reliability of instrumental detection, which provided a scientific basis for cotton quality evaluation (Delhom et al., 2020). In addition to HVI, some advanced fiber sorting technologies are also being explored and applied. For example, the use of image recognition technology to intelligently sort cotton color and foreign fibers can assist in manually picking out cotton bundles with serious impurities or colored fibers, thereby improving the purity of the batch (Du et al., 2020). In addition, in large-scale storage and trading markets, the introduction of automatic sorting and packaging systems based on quality parameters, and the classification and stacking of lint according to indicators such as length and strength, will help textile companies select materials on demand. In general, the development direction of fiber grading and sorting technology is based on objective data to achieve fast and fine quality grading, and provide stable and reliable quality assurance for downstream cotton.

3.3 Moisture control technology

In the post-harvest processing of cotton, effective control of moisture is crucial. Appropriate moisture is conducive to reducing fiber processing damage, but too high or too low will have an adverse effect on quality. Therefore, modern cotton ginning plants are generally equipped with drying and rehumidification devices to adjust the moisture content of seed cotton and lint. Pre-drying the seed cotton before processing to ensure that the moisture content is reduced to a safe range can avoid the effect of impurity removal due to the adhesion of wet cotton during ginning. During the ginning process, in order to reduce fiber static electricity and breakage, the lint is often treated with moderate rehumidification by spraying water or steam to keep the fiber toughness and spinnability (Pelletier and Byler, 2020). In the process of opening the cotton bundle to extract impurities, it is necessary to find and comply with the appropriate temperature and humidification level to balance the efficiency of impurity removal and the preservation of fiber characteristics. In this process, digital sensing and control technology plays an important role. The online moisture sensor developed in recent years can monitor the moisture of seed cotton and lint in real time, and control the drying temperature or the start and stop of the humidifier in a linked manner to achieve closed-loop regulation. For example, a research project of the United States Department of Agriculture has developed a cotton ginning moisture control system based on microwave sensing, which can accurately identify the moisture changes in the cotton flow and automatically adjust it, so that the moisture of the processed lint is more uniform (Anthony, 2013). In addition, simulation of the processing of seed cotton with different moisture contents can provide data support for the formulation of the optimal drying and rehumidification process. The advancement of moisture control technology not only ensures the stability of fiber quality, but also reduces energy consumption (avoiding over-drying) and safety risks (preventing spontaneous combustion of cotton) during processing. Through the precise management of moisture during the cotton ginning process, the natural toughness and luster of the fiber can be better maintained, laying the foundation for improving the quality of cotton.

4 Quality Assessment and Monitoring Technology

4.1 Fiber quality parameter testing

Cotton fiber quality is usually characterized by parameters such as length, fineness (micronaire), strength, maturity, color grade and impurity content. Accurate determination of these parameters is the basis for quality assessment. With the promotion of instrumental testing, cotton quality parameter testing has been standardized and scaled up. As the most widely used fiber tester, the HVI system can measure the average length of the upper half of each bale of lint, specific strength, micronaire, color (reflectance Rd and yellowness +b) and impurity content of each bale of lint in one measurement (Kelly and Hequet, 2018). Since 2015, China has fully implemented the "cotton notarization inspection". The national fiber inspection agency samples each bale of lint for sale, and the centralized laboratory uses HVI for testing, and the results are used as the basis for quality inspection and trade settlement. After years of practical verification, the HVI test results of various laboratories have maintained good consistency and accuracy. This shows that instrumental testing technology can meet the requirements of cotton quality evaluation (Turner et al., 2022). At the same time, some more sophisticated testing technologies are also being studied and applied. For example, AFIS (single fiber comprehensive analyzer) for fiber fineness and maturity analysis can provide more in-depth information such as fiber diameter distribution and short fiber content, which helps spinning mills optimize process parameters (Li et al., 2023). Another example is the use of near-infrared spectroscopy to quickly determine chemical indicators such as sugar content and wax content of cotton fibers, providing a basis for storage and dyeing performance evaluation. In addition, for the detection of foreign fibers (plastic fibers, chemical fibers and other mixed materials), in addition to manual sorting, professional instruments and equipment (such as foreign fiber detectors) have also appeared to achieve automatic identification and alarm through optical imaging and machine learning algorithms. Overall, fiber quality parameter testing technology is developing in the direction of automation and intelligence, and multi-dimensional data collection provides more comprehensive support for cotton quality assessment.

4.2 Digital monitoring and traceability system

With the development of the Internet of Things and big data technology, the quality monitoring of cotton post-harvest has gradually been digitized and informationized. In modern cotton ginning plants, key equipment such as cotton cleaning machines, sawtooth cotton gins, and balers are equipped with sensors and controllers to monitor parameters such as temperature, current, and vibration in real time. Once an abnormality (such as blockage or overtemperature) occurs, the system automatically alarms or shuts down to avoid quality accidents. In addition, through the workshop information management system (MIS), processing batches, equipment status, and product quality test results can be stored in association to form a complete data chain. Quality management personnel can view the processing status and test indicators of each batch of cotton in real time through the central control room to achieve full-process quality monitoring. For large-scale cotton circulation, the establishment of a traceability system is particularly important. For example, the "cotton quality traceability platform" promoted by major production areas such as Xinjiang gives each batch of lint a unique identity, and the key node information from harvesting, processing to warehousing and transportation is recorded. Once downstream users discover quality problems, they can trace back to the source processing company and batch data through the traceability system (Hardin et al., 2015). Internationally, the "Better Cotton Initiative (BCI)" has built a global cotton traceability system. Suppliers in the supply chain register transaction information on the BCI platform to track the source and content of physical "good cotton", extending from the cotton ginning plant to the brand retailer. This chain monitoring effectively improves the transparency and trust of the supply chain. China's sustainable cotton project is also drawing on similar practices, integrating data from the production environment, quality inspection and circulation process to create a quality archive "from field to spinning mill". At the domestic standard level, local standards have required cotton processing companies to establish a quality traceability system to record and analyze seed cotton purchase inspection data and grading and processing procedures. Through digital monitoring and traceability systems, early warning, prevention and control, and closed-loop management of cotton quality issues can be achieved, which is of great significance to improving the quality management level of the entire industry.

4.3 Certification mechanism

The cotton quality certification system helps to standardize industry standards and improve market recognition of high-quality cotton. There are currently many cotton-related certifications in the world. In addition to the aforementioned Better Cotton (focusing on sustainable planting and supply chain management), there are also organic cotton certification (ensuring that chemical synthetic pesticides and genetically modified seeds are not used in the production process of cotton) (Partzsch et al., 2019), OEKO-TEX Standard 100 (detection of harmful substances in textile raw materials), etc. These certification mechanisms provide quality and credibility guarantees for downstream buyers. In China, cotton is mainly graded by national standards (such as GB 1103 "Sawtooth

Processed Fine Cotton" series standards), and notarized inspections are used to ensure fairness and justice. Each bale of cotton is sold with a "Cotton Notarized Inspection Certificate" issued by the fiber inspection department, which states the various quality indicators of the bale of cotton, which is equivalent to an official quality certification. Textile companies pay particular attention to whether these indicators meet their raw material requirements when purchasing. With the strengthening of the concept of sustainable development, more and more international buyers also require cotton in the supply chain to comply with BCI or organic certification. It is reported that since October 2023, BCI has launched a new chain of custody standard that allows physical tracking of BCI good cotton in the global supply chain, achieving label separation and controlled mixing from origin to product. This means that if Chinese cotton obtains BCI certification in the future, its identity can be tracked all the way to the garment manufacturing stage, which will be of great help in expanding the international high-end market.

5 Sustainability and Economic Efficiency of Post-Harvest Technology

5.1 Cost-benefit analysis

While promoting post-harvest quality improvement technologies for cotton, it is necessary to comprehensively consider the environmental sustainability and economic feasibility of these technologies. The application of any new technology needs to be tested by economic accounts. Post-harvest management technologies such as mechanical harvesting, advanced cotton ginning equipment, and digital monitoring systems often require large initial investments, but can bring long-term benefits by improving efficiency and quality (Shao et al., 2022). In Xinjiang, the large-scale use of cotton pickers to replace manual cotton picking has effectively reduced harvesting costs. Although the purchase and maintenance costs of mechanical harvesting equipment are high, the unit output cost is significantly reduced for large-scale planting. In addition, the improvement of cotton quality can also bring price premiums. For example, the purchase price of cotton with less impurities and longer fibers in the market is often hundreds of yuan higher per ton than ordinary cotton. In the spinning stage, high-quality raw cotton can improve the strength and yarn yield of the yarn, reduce the breakage rate, and thus reduce the production cost of the textile mill. These values will eventually be reflected in the cotton purchase price. Therefore, from the perspective of the entire value chain, investing in post-harvest quality management technology has a clear economic driver. Some cost-benefit evaluation studies have shown that the introduction of cleaning equipment and automated grading systems slightly increased the processing cost per ton of lint cotton, but the added value brought by quality improvement was greater, and the net benefit was positive (Tian et al., 2018). Of course, the economic benefits vary with different business entities and scales: for large cotton companies or cooperatives, the scale effect of technology investment is obvious; but for small farmers, it may be necessary to share the initial costs through cooperative organizations or government subsidies to ensure their enthusiasm for adopting new technologies.

5.2 Environmental friendliness and waste treatment

A large number of by-products and wastes will be generated during cotton harvesting and processing, such as cotton seeds, cotton linters, cotton stalks, fallen impurities and cotton dust. How to reasonably utilize these by-products and reduce the impact of waste on the environment is an important aspect of measuring the sustainability of technology. First of all, cotton seeds, as the main by-product after cotton ginning, have a high oil content and are an important oil and protein feed resource. Traditionally, cotton seeds can be stripped and pressed to produce cottonseed oil and cottonseed meal, realizing economic value and recycling. At present, some cotton ginning enterprises have built supporting processing projects that can process hundreds of thousands of tons of cotton seeds per day to make full use of cotton seeds. Secondly, cotton seed linters (short fibers attached to cotton seeds after ginning) can be obtained through the delinting process and can be used to produce medical absorbent cotton, cellulose materials, etc. (Orr, 1978). Thirdly, cotton straw is the plant residue after harvesting in the field, including the stems, branches, leaves and shells of cotton plants, etc., rich in cellulose and lignin, and is a renewable biomass resource. It is estimated that China's annual production of cotton straw reaches tens of millions of tons. In the past, cotton stalks were mostly burned or discarded on the spot, causing environmental pollution. Nowadays, the comprehensive utilization rate of cotton stalks is constantly improving through the promotion of straw crushing and returning to the field, making feed, cultivating edible fungi, producing biomass fuel or artificial board materials (Phadtare and Kalbande, 2024). This not only reduces waste emissions, but also brings additional benefits to farmers. In addition, cotton dust and debris generated during ginning and spinning, such as cotton shells and leaf scraps, can also be used as organic fertilizer raw materials or biomass power generation fuel. A study found that making biochar from waste impurities produced by cotton processing for soil improvement can increase soil organic matter and help fix carbon (Howell et al., 2024). Another example is that cottonseed hulls are mixed with other agricultural and forestry wastes to make pellet fuel, which can partially replace fossil energy. In general, while improving cotton post-harvest management technology, by building a comprehensive utilization system for by-products, we can achieve a win-win situation for the environment and the economy, and promote clean production and circular development of the cotton industry chain.

5.3 Impact on farmers and industries

The promotion of post-harvest management technology is not only reflected in micro-quality and cost, but also has a macro-impact on the livelihoods of cotton farmers and the industry structure. On the one hand, the adoption of advanced technology has improved labor productivity and product quality, which helps cotton farmers increase their income. For example, mechanical harvesting and scientific storage reduce post-harvest losses, and notarized inspection and quality traceability improve the bargaining power of high-quality cotton, which will feed back to growers. At the same time, some leading cotton processing companies have lowered post-harvest processing services through the "company + farmer" model, providing cotton farmers with unified post-harvest drying, processing and sales channels, so that small farmers can also share the benefits of technology. On the other hand, the application of new technologies may also bring short-term structural pain. For example, the large-scale use of cotton picking machinery may cause the labor force that relies on cotton picking to face employment transformation while reducing the demand for seasonal cotton pickers (Chandel and Sharma, 2022). In this regard, the government and society need to help surplus labor transfer to new links such as processing, grading, and logistics through skills training and industrial guidance to achieve the reconfiguration of labor resources. From the industry level, the improvement of post-harvest management technology will promote the development of the cotton industry in the direction of scale and intensiveness. Large-scale cotton processing companies with adequate quality management have more advantages in market competition and promote the improvement of industry concentration. At the same time, strict quality standards and traceability certification will also help to regulate market order, curb the phenomenon of selling inferior products as good ones, and maintain the overall brand image of "China Cotton". The supply of higher-quality cotton will improve the raw material security of domestic textiles, reduce the dependence on high-quality cotton imports, and have positive significance for the security of the textile industry chain. In the international market, as sustainability and high quality become mainstream requirements, Chinese cotton has achieved both quality and environmental protection standards through technological upgrades, and is expected to reshape its competitiveness.

6 Case Study: Xinjiang as an Example

6.1 Regional challenge analysis

The Xinjiang Uygur Autonomous Region is China's largest cotton-producing region and an important global cotton production base. Its special natural and social conditions make cotton post-harvest management face unique challenges, but also breed opportunities for large-scale application of new technologies (Figure 2). Xinjiang is located in an arid and semi-arid climate zone with sufficient sunshine but early frost period. Cotton needs to be harvested in a timely manner within the limited frost-free period. This has promoted the popularization of efficient mechanical harvesting (Feng et al., 2024). However, the quality problem of machine-picked cotton was also prominent at one time: due to the extensive machine-picking operation, the impurities and short fibers in the seed cotton were high, which brought pressure to subsequent processing. At the same time, the planting scale in Xinjiang production areas is large, the plots are scattered, and the individual post-harvest processing and storage and transportation capabilities of cotton farmers are limited. In history, there have been cases where cotton has become moldy or contaminated by sand due to improper open-air stacking (Tian et al., 2013). In addition, Xinjiang cotton fiber varieties are diverse, including both long-staple cotton and fine-staple cotton. The quality of different varieties varies greatly. If mixed picking and storage, it is easy to lower the overall quality grade. In terms of logistics, Xinjiang is far away from textile mills in the mainland, and maintaining stable quality during long-distance transportation of cotton bales is also a major challenge. These factors determine that Xinjiang urgently needs the support of post-harvest management technology to overcome the disadvantages of natural conditions and regions and achieve cotton quality and efficiency improvement.

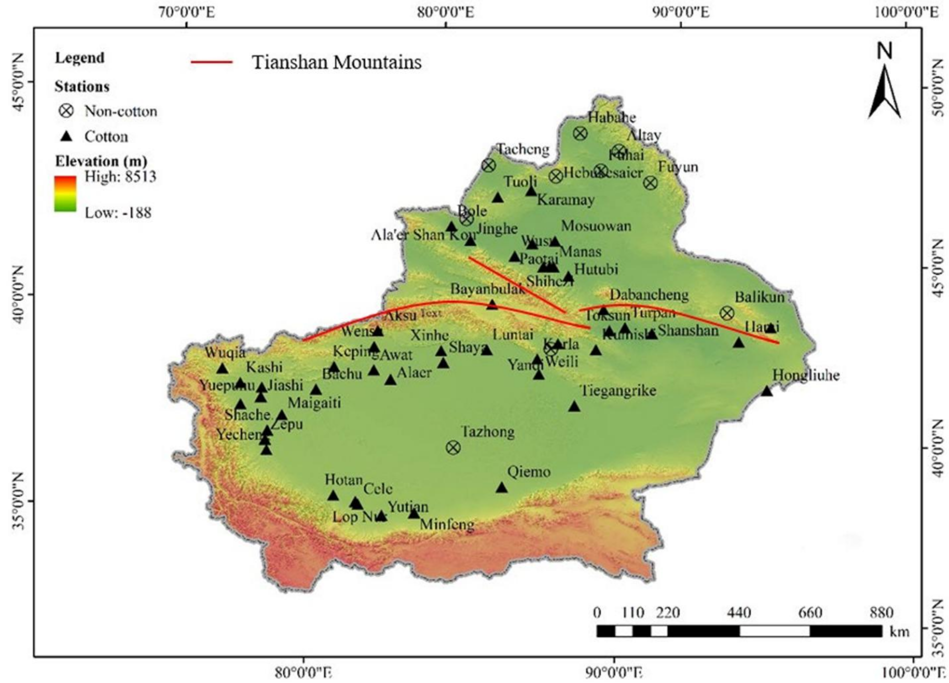

Figure 2 Research area diagram (Adopted from Dai et al., 2024)

6.2 Technology introduction and application

Faced with the above challenges, governments and enterprises at all levels in Xinjiang have actively introduced and promoted new post-harvest management technologies. First, in the harvesting process, the application of cotton pickers and supporting agronomic improvements are vigorously promoted (Xin et al., 2021). The autonomous region government actively subsidizes and promotes large-scale cotton pickers, and cooperatives and farmers widely use machine picking. By 2021, the machine picking rate of cotton in Xinjiang has exceeded 75%. In order to reduce the impurities in machine-picked cotton, the Xinjiang Production and Construction Corps and other units have studied cotton planting models and defoliant improvements to make machine picking cleaner. Second, in the processing process, Xinjiang has built and renovated a number of large-scale cotton ginning processing enterprises in recent years, and introduced advanced complete sets of cotton ginning production lines at home and abroad. Many cotton ginning mills are equipped with multi-stage pre-cleaners, metal separators and foreign fiber removal devices to meet the impurity removal needs of machine-picked cotton. At the same time, the processing process is automated and quality tested online, and the temperature, humidity and impurity discharge are monitored to ensure the stability of the quality of lint. The autonomous region has also implemented classified supervision of cotton processing enterprises, encouraging leading enterprises to merge small and backward cotton ginning factories to improve the overall processing capacity and level. Third, in the warehousing and logistics link, a new model of packaging encryption and public inspection integration has been introduced. The processed lint is packed with high density and equipped with cotton stacking robots to reduce the pollution caused by human handling. All lint cotton shipped out of the factory has been notarized and inspected, and the quality data has been uploaded to the national cotton public inspection information system, so that the quality information of each batch of cotton can be checked online. Xinjiang has also built several cotton logistics parks, where cotton bales after public inspection are stored in a centralized manner and transported by special railway trains, effectively shortening the transportation cycle and reducing quality risks. The comprehensive application of these technologies and measures has significantly improved the post-harvest management level of Xinjiang cotton.

6.3 Effectiveness evaluation

Thanks to the progress of post-harvest management technology, the quality and yield of Xinjiang cotton have been steadily improved. On the one hand, the problem of excessive impurities in machine-picked cotton has been alleviated. Data show that by improving machinery and processing technology, the average impurity rate of machine-picked cotton in Xinjiang has dropped from 6% in the early days to 3%-4%, close to the level of hand-picked cotton, and indicators such as fiber length and strength have also remained stable. The consistency of cotton fibers has been improved, meeting the requirements of textile enterprises for large-scale cotton use (Tian et al., 2017). On the other hand, the efficiency of harvesting and processing has been greatly improved, and the comprehensive economic benefits are significant. According to statistics, the total output of cotton in Xinjiang has increased from 4.5 million tons per year in the mid-2010s to about 5.4 million tons in recent years, and the proportion of high-quality lint has also increased. Lou et al. (2023) pointed out that Xinjiang cotton has achieved high-quality production, with the yield and mechanization level leading the country. At the same time, the scale of cotton planting and processing has been improved, and the income of cotton farmers has increased steadily. Taking a large cotton-growing county in southern Xinjiang as an example, through the unified machine picking of cooperatives and the joint cotton ginning of enterprises, farmers have increased their income by about 0.1 yuan per kilogram of seed cotton due to quality optimization, and the per capita income has increased by thousands of yuan throughout the year. In addition, the establishment of a quality traceability system has improved the credibility of Xinjiang cotton in the market. In recent years, domestic textile enterprises have become more aware of "Xinjiang high-quality cotton" and have increased the proportion of Xinjiang cotton used in raw material procurement. Many exported textiles are clearly marked as using Xinjiang cotton, adding value to the products.

7 Future Development Direction

7.1 Digital intelligent system integration

The Internet of Things, big data and artificial intelligence will play an increasingly important role in post-harvest management of cotton. In the future, cotton ginning plants are expected to develop into "smart cotton ginning plants" - through sensor networks, massive data from seed cotton moisture, impurity content to equipment operation status are obtained, and artificial intelligence algorithms are used for analysis and decision-making to achieve intelligent optimization of the entire process (Zhang et al., 2000). For example, the foreign fiber intelligent identification robot based on machine vision will become more mature, and can automatically remove foreign objects such as plastic film and packaging lines mixed in cotton, greatly reducing the cost of manual sorting. For another example, the introduction of digital twin technology to virtually map and simulate the actual processing process can predict the impact of different parameters on product quality, thereby optimizing process settings. Textile companies also hope that the quality of upstream raw materials will be more stable and controllable, so the data connection with cotton ginning companies will be closer, forming a big data platform for raw material-product quality to guide variety improvement and processing improvement. The in-depth application of digitalization and intelligence will enable post-harvest management of cotton to enter a new stage of precise control and autonomous optimization.

7.2 Localized customization and differentiated management

Given the different climatic conditions, variety types and production scales in different production areas, future technical solutions need to pay more attention to localized customization. For example, in the hot and humid cotton-producing areas of the Yangtze River Basin, the focus should be on developing small, mobile seed cotton drying and storage devices to cope with scattered planting and rainy weather; while in arid areas such as Xinjiang, mechanical harvesting and large-scale centralized processing models need to be further optimized. For example, for high-end varieties such as long-staple cotton, special post-harvest processing specifications and equipment (such as slow cotton gins and separate grading and storage) can be formulated to protect their ultra-long fibers from damage and meet the raw material requirements for high-count yarn production (Yehia et al., 2021). Due to limited resources, small and medium-sized cotton producers or family farms may be able to obtain customized post-harvest management support through shared factories, hosting services and other models in the future, thereby improving the balanced development of the entire industry. In addition, China has a vast territory, and cotton harvesting seasons in various producing areas are different. We can fully explore cross-regional collaboration, such as transporting seed cotton harvested in the mainland to large-scale processing bases in Xinjiang for centralized processing, and using its advanced equipment and low-cost advantages to achieve complementary advantages. These differentiated and coordinated management ideas will make post-harvest technology more practical and maximize its benefits.

7.3 Policy and institutional support

The promotion of cotton post-harvest management technology is inseparable from policy support and the promotion of industry organizations. First, the government should continue to increase support for key links after harvesting, such as improving agricultural machinery subsidy policies, including advanced cleaning equipment and drying and storage facilities in the subsidy catalog, and lowering the threshold for cotton farmers and enterprises to adopt new technologies; tax exemptions or special subsidies should be given for cotton processing by-product utilization projects to encourage enterprises to carry out circular economy practices (Wang et al., 2022). Secondly, formulate and revise relevant standards and specifications to guide technology application. For example, improve the national standard for cotton quality grading, increase the weight of digital detection indicators; formulate cotton foreign fiber content limit standards and detection methods; promote cotton traceability standards, etc. The introduction of these standards will provide a basis for the application of new technologies and improve the acceptance of all parties. In addition, industry associations and scientific research institutes should play a bridging role and increase technical training and demonstration. By holding on-site observations and technical exchanges, mature post-harvest management experience will be promoted in cotton-growing areas across the country, so that more cotton farmers will realize the importance of "growing good cotton and managing it well". At the international level, China can also participate in and lead multilateral cooperation to improve cotton quality, such as cooperating with the International Cotton Advisory Committee (ICAC) and fiber inspection agencies to develop a global unified quality traceability system and certification, so that Chinese cotton can better integrate into the sustainable cotton supply chain. In short, policy and institutional support will provide a good external environment for the development of post-harvest cotton technology in the future and accelerate the transformation and application of scientific and technological achievements.

8 Conclusion

Cotton post-harvest management technology is crucial to maintaining and improving cotton quality. This study systematically analyzed the main factors affecting cotton post-harvest quality, sorted out the technological progress in cotton ginning technology, fiber grading, moisture control, quality monitoring, etc. in recent years, and verified the effectiveness of technical measures in combination with Xinjiang cases. The study shows that by optimizing the harvesting method, strictly controlling the impurities and moisture content, using advanced cotton ginning and grading equipment, and improving the quality monitoring and traceability system, the cleanliness and consistency of cotton fiber quality can be significantly improved. These technical measures not only improve cotton quality, but also reflect comprehensive benefits in cost savings and environmental protection, creating conditions for cotton farmers to increase income and industrial upgrading. Of course, different regions need to take local conditions into account when promoting post-harvest management technology, taking into account economic feasibility and social impact. Against the background of rapid development of science and technology, cotton post-harvest management is moving towards digitalization, intelligence, and standardization. In the future, by integrating the Internet of Things and artificial intelligence, accurate control and quality prediction of the entire post-harvest process of cotton can be achieved, further reducing human errors and losses. At the same time, strengthening policy support and international cooperation, and establishing and improving quality standards and certification systems will help consolidate the results of cotton quality improvement and expand its market influence. In short, continuously improving the level of cotton post-harvest management technology is of great practical significance for ensuring the healthy development of the cotton textile industry and enhancing the competitiveness of my country's cotton in the international market. By giving equal importance to technology and management, and innovation and promotion, all links in the cotton industry chain will work more closely together to achieve high-quality, efficient and sustainable development.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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