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# Best Practices for Sustainable Cotton Farming Systems

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**Abstract** Cotton is a major fiber crop in the world and plays an important role in the agricultural economy. However, conventional cotton production faces sustainability challenges such as excessive use of pesticides, water waste and soil degradation. This study focuses on "Best Practices in Sustainable Cotton Cultivation Systems", reviews the current background and problems of global cotton production, explores agronomic practices, socioeconomic strategies, technological innovations and policy support mechanisms to achieve sustainable development, and analyzes the practical effects based on a case study in Gujarat, India. The study found that agronomic practices such as integrated pest management, soil health maintenance and water-saving irrigation can effectively reduce chemical inputs and maintain or increase yields; strengthening cotton farmer training, ensuring labor equity and expanding market channels can improve cotton farmers' livelihoods and enhance the industry's risk resistance; the application of precision agriculture, biotechnology and digital platforms is improving cotton production efficiency and environmental performance; and policy support such as certification standards, government subsidies and RandD investment is crucial for the large-scale promotion of sustainable cotton practices. Based on real data from case studies, we summarize the successful experience of sustainable cotton cultivation and make recommendations for future expansion, strengthening climate adaptability and deepening international cooperation. The research aims to provide scientific basis for major cotton producing countries and relevant stakeholders, and to help the green transformation and sustainable development of the global cotton industry.

**Keywords** Cotton; Sustainable agriculture; Integrated pest management; Soil health; Water-saving irrigation

## 1 Introduction

Cotton is widely grown in more than 80 countries around the world and is an important cash crop and raw material for the textile industry. According to statistics, the global cotton production in 2019-2020 was about 24.339 million tons, and it increased to about 26.095 million tons in 2021-2022. The main cotton producing countries include China, India, the United States, Brazil, etc., among which China and India are at the forefront of the world. For example, India's cotton planting area is about 11.91 million hectares, accounting for 36% of the world's total, of which the lint cotton production ranks second in the world, second only to China (Nagaraj et al., 2024).

Despite the huge output, traditional cotton production has brought severe challenges to the environment and society. First, cotton consumes a lot of water. In arid areas, large-scale irrigation has caused rivers and lakes to dry up frequently, and ecological disasters such as the shrinking of the Aral Sea in Central Asia are partly attributed to cotton field irrigation (Abdullayev, 2010). According to statistics, 97% of the water in the Indash River in Sindh Province, India is used for irrigation purposes, including cotton. Secondly, the problem of excessive use of pesticides and fertilizers is prominent. Since the second half of the 20th century, the amount of pesticides applied per unit area in cotton fields worldwide has far exceeded that of other crops, which not only harms soil and water quality, but also threatens farmers' health and biodiversity (He, 2023). In my country, the amount of nitrogen fertilizer applied to cotton in Xinjiang has increased from 150 kg/ha in the 1980s to 598 kg/ha in 2020, and the accumulated amount of residual film in farmland has reached 255 kg/ha, both of which are significantly higher than the national average. Thirdly, long-term continuous cropping and improper tillage have led to soil degradation and accumulation of pests and diseases, and salinization and organic matter decline in cotton fields are common (Chen et al., 2021). Climate change has exacerbated these risks, and unstable rainfall and extreme high temperatures have posed a threat to cotton production. For example, a multinational study pointed out that

global warming and pest outbreaks have led to a decline in global cotton production in recent years, endangering the safety of the textile industry (Crossley et al., 2023). In addition, the cotton industry also involves complex social issues, including the fragility of smallholder livelihoods and insufficient protection of labor rights. Based on the above background, governments, scientific research institutions and industry organizations are increasingly paying attention to the sustainable transformation of cotton production and conducting many practical explorations.

This study aims to systematically sort out the key areas and best practices of sustainable cotton cultivation, including agronomic, socio-economic, technical and policy initiatives, and provide empirical evidence through the case of Gujarat, India, and finally propose directions and suggestions for promoting the sustainable development of global cotton in the future.

## 2 Best Agronomic Practices

### 2.1 Integrated pest management (IPM)

The sustainability of cotton cultivation depends first on the improvement of field management measures. Traditional cotton farmers rely heavily on chemical pesticides to control pests such as bollworms and aphids, which has led to high control costs and ecological risks. Sustainable cultivation emphasizes the use of integrated pest management (IPM) strategies, combining insect-resistant varieties, biological control and scientific pesticide use to reduce the use of chemical pesticides. Since the end of the 20th century, the promotion of genetically modified insect-resistant cotton has significantly reduced the dependence on pesticides in cotton fields. In China, the commercial cultivation of insect-resistant cotton (Bt cotton) has reduced the total amount of pesticides used in the country by about 2.19 million tons from 1997 to 2012, and farmers have saved $8.46 billion in pesticide expenses (Qiao and Huang, 2020). India and other countries have also adopted Bt cotton on a large scale. Currently, about 93% of cotton fields in India are planted with insect-resistant cotton varieties (Nagaraj et al., 2024). The application of insect-resistant cotton has significantly suppressed the damage caused by major leaf-eating pests such as cotton bollworm, achieving a win-win situation of increased production and income and reduced pesticide use. However, over-reliance on a single insect-resistant gene also brings the hidden danger of resistance of insect-resistant organisms. In response to the resistance of pink bollworm to Bt protein, researchers from various countries are exploring new strains and composite resistance strategies, such as the use of multiple insect-resistant gene stacking (gene pyramid) and new RNA interference technology to control resistant pests. Biological control is also an important part of IPM. For example, planting attractant crops (such as corn, hibiscus, etc.) in cotton fields can induce pest concentration, which is conducive to subsequent prevention and control; releasing natural enemy insects such as lacewings and seven-spotted ladybugs to prey on aphids; setting up pheromone traps to interfere with the mating cycle of cotton bollworms. These ecological strategies have achieved good results in practice. For example, a sustainable cotton project in Gujarat, India, guided farmers to intercrop green manure and corn between cotton rows to attract beneficial insects and suppress pests, set up bird perches and sex attractant traps, and the use of chemical pesticides in cotton fields was significantly reduced (Yadav et al., 2009). At the same time, local cotton farmers mastered pest and disease monitoring and precision application techniques through training, and selected high-efficiency and low-toxic pesticides when necessary and applied them correctly, thereby reducing the impact on non-target organisms and the environment. Scientific crop rotation is also an effective means to prevent the accumulation of soil-borne pests and diseases. Chen et al. (2025) showed that compared with long-term continuous cropping of cotton, the rotation of cotton and legumes can break the pest life cycle and improve the soil biological community, which helps to reduce the incidence of pests and diseases in cotton fields. The implementation of integrated pest management not only reduces the environmental load, but also reduces the input costs of cotton farmers. For example, farms that follow the agronomic practices of the Better Cotton Initiative use 47% less pesticides on average than conventional farms, and because of the reduced chemical inputs, a cost-benefit ratio of 1:2.3 is achieved, increasing the income of cotton farmers (Makhdum et al., 2012).

### 2.2 Soil health management

Soil is the foundation of cotton production, and maintaining soil fertility and ecological functions is essential for sustained high yields. For a long time, unreasonable farming and continuous cropping of cotton fields have led to

prominent soil degradation problems, such as decreased organic matter, nutrient imbalance, salinization, and accumulation of soil-borne diseases. In cotton-growing areas such as Xinjiang, due to years of monoculture and high chemical inputs, soil carbon and nitrogen nutrients have significantly decreased, pH and conductivity have increased, and microbial diversity has decreased. A long-term positioning study on cotton fields in Xinjiang showed that soil total nitrogen, available phosphorus, potassium and microbial biomass carbon decreased significantly after continuous cropping for more than 10 years, while salt and harmful nematodes increased significantly. The number of plant parasitic nematodes in cotton fields with continuous cropping for 25 years increased several times compared with that in fields with continuous cropping for 5 years (Chen et al., 2021). To restore soil health, rotation and fallow have been proven to be effective measures. Short-term fallow or rotation with leguminous crops can promote soil nutrient circulation and reduce continuous cropping obstacles. Chen et al. (2021) showed that the soil health index of cotton fields in Xinjiang dropped to the lowest level after about 7 years of continuous cropping, but it can be gradually restored after proper rotation. In some cotton-growing areas, promoting the "cotton-forage" or "cotton-grain crop" rotation model, rotating alfalfa or wheat every two years, can significantly improve the physical and chemical properties of cotton field soil and reduce soil-borne diseases. At the same time, attention should be paid to conservation tillage and increased application of organic fertilizers. Measures such as crushing straw and returning it to the field, planting green manure, applying compost or bio-organic fertilizer can help improve soil organic matter and microbial activity, and enhance the soil's ability to retain water and fertilizer. For example, in the organic cotton production system, the use of chemical inputs is strictly prohibited. Soil fertility and ecological balance are maintained through organic fertilization and biological control, and soil nutrient recycling is achieved (Miao and Ma, 2009). In order to reduce soil compaction and erosion, some areas adopt no-till or minimum-till technology, combined with planting cover crops to protect the surface and reduce wind erosion and water erosion. These soil health management practices not only improve soil productivity, but also enhance the cotton field's ability to resist stress such as drought, which is conducive to the long-term stability of cotton production.

### 2.3 Water-saving irrigation

Cotton has a large demand for water, and water shortage is becoming a key factor restricting the sustainable development of cotton areas. Traditional flood irrigation methods are wasteful, often causing field runoff and deep seepage, and low water use efficiency. In arid and semi-arid cotton areas, it is imperative to promote efficient water-saving irrigation technology. Among them, drip irrigation technology is widely regarded as one of the best practices for cotton water conservation due to its precise water and fertilizer supply capabilities (Figure 1). Xinjiang, China, began to introduce Israeli drip irrigation systems in the mid-1990s, and has been rapidly promoted under the national western development policy and subsidy support. The drip irrigation area has grown from almost zero in the early 1990s to more than 3 million hectares at present, making Xinjiang the world's largest drip irrigation area and the most diverse crop types. At present, the film coverage rate of cotton fields in Xinjiang has reached 100%, and drip irrigation technology has been fully popularized, realizing precise water supply on demand. Thanks to this, despite drought and little rain, Xinjiang's cotton yield has long been among the highest in the country, and the per hectare yield has remained the highest in the country for more than 20 years (Zhao et al., 2009). Water-saving irrigation is not limited to areas with irrigation conditions such as Xinjiang. In rain-fed cotton areas such as India and West Africa, the construction of small-scale water storage and sprinkler irrigation facilities and the promotion of moisture storage and water conservation agronomy (such as mulching, deep plowing and water conservation) are also crucial to improving the efficiency of natural precipitation utilization. Studies have shown that precision irrigation can save a lot of water while ensuring yield. A study based on meta-analysis summarized the results of many trials of drip irrigation cotton in Xinjiang and found that compared with full irrigation, moderate deficit irrigation treatment increased water use efficiency by an average of 7.39%, and only reduced seed cotton yield by about 15%. When the deficit irrigation ratio is within 90%, the yield decrease is very small, and the water efficiency is significantly improved (Xu et al., 2024). Therefore, through precise irrigation scheduling, appropriate control of irrigation volume in the late growth period can achieve "significant water saving with slight reduction in yield". In addition, the application of "soil measurement-moisture content-weather" digital monitoring combined with intelligent irrigation system makes on-demand irrigation possible. For example,

some cotton-growing areas in China have begun to use IoT soil moisture sensors and remote sensing monitoring technology to guide cotton fields in real time when and how much water to irrigate, so as to achieve optimal allocation of water resources (Ahmed et al., 2024).

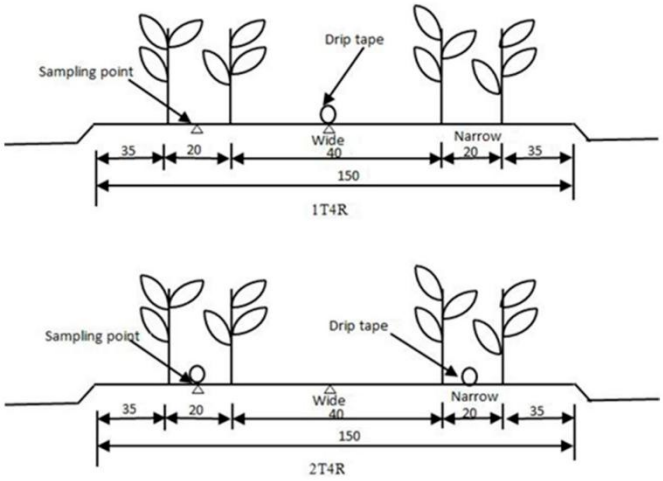


Figure 1 Schematic diagram of cotton planting method and drip irrigation belt layout (cm) (Adopted from Wang et al., 2022)

## 3 Socio-Economic Level

### 3.1 Farmer training and capacity building

Sustainable cotton cultivation not only involves field technology, but also has a close relationship with the well-being of cotton farmers and related labor. Smallholders are the main force of global cotton production, and improving their skills and knowledge is the basis for promoting sustainable agriculture. Cotton farmers in many developing countries have limited education and lack of understanding of new technologies and sustainable concepts. Therefore, various farmer field schools and training programs have emerged to teach cotton farmers advanced cultivation techniques and management experience. For example, the better cotton initiative (BCI), known as the world's largest cotton sustainable development project, has promoted farmer training around the world since the 2010s (Ghori et al., 2021). The training content covers safe use of pesticides, soil improvement, water-saving irrigation, and business management. Practice has shown that systematic training can significantly improve cotton farmers' productivity and income. The impact evaluation of the "Cotton Yield" project under the "African Cotton Manufacturing" initiative in Zambia showed that cotton farmers who received regular training had a 38.1% increase in cotton yield per unit area compared to those who did not receive training (Ngulube, 2021). Training also brings about the dissemination of knowledge and the change of concepts. In project villages in Africa, training has improved farmers' awareness of children's education, gender equality and the hazards of child labor. In projects in India and other countries, training has promoted the formation of mutual assistance networks among farmers, and experienced farmers have passed on knowledge to more peers as field instructors, improving the overall planting level of the community. In addition to technical training, financial and risk management skills have also been gradually incorporated into training courses, such as guiding cotton farmers to conduct simple cost-benefit analysis, encouraging diversified planting to spread risks, and raising their awareness of participating in price insurance and weather insurance. These measures all help to enhance the ability of small farmers to cope with market fluctuations and climate anomalies.

### 3.2 Labor equity and welfare protection

The cotton industry chain involves hundreds of millions of workers, and protecting their legitimate rights and interests and living standards is a natural requirement for sustainable development. In the cotton planting process, there have traditionally been problems such as high seasonal labor intensity, low pay, child labor and forced labor. Some international standards and projects have incorporated labor standards into the certification requirements for sustainable cotton. For example, the BCI standard explicitly prohibits child labor and forced labor and requires safe working conditions; the China cotton sustainable development project (CCSD) standard launched by China in 2021 also emphasizes workers' rights and labor safety, and regards labor equity as an important part of

sustainability. Improving labor equity can be achieved through both technology and institutions. On the one hand, the promotion of technologies such as mechanized harvesting reduces labor intensity while also reducing the large demand for temporary workers during the picking season, reducing potential irregular employment from the source. For example, in recent years, Xinjiang, China has vigorously promoted the mechanization of cotton production throughout the process, and by 2024, the comprehensive mechanization rate of cotton sowing and harvesting has reached 97%. Machine cotton picking has replaced the heavy manual cotton picking in the past, improving production efficiency and avoiding labor shortages and labor-capital disputes during peak employment periods. In countries such as South Asia, where the degree of mechanization is temporarily limited, the treatment of pickers can be improved by strengthening labor organization and contract norms. For example, it is encouraged to establish a cooperative for pickers or a labor intermediary platform, make the wages and payment process public, ensure that wages are paid on time and in full, and provide necessary protective equipment and medical insurance. On the other hand, the international market has increasingly stringent social responsibility requirements for the cotton supply chain. Brands and buyers promote the improvement of labor conditions upstream by performing due diligence. This pressure forces the governments and enterprises of the producing areas to improve their compliance awareness and protect the rights and interests of workers. Through third-party certification (such as fair trade cotton, responsible cotton standards, etc.), cotton field workers can obtain moral premiums in the market, thus forming an incentive mechanism. For example, cotton products that have obtained "Fair Trade" certification will promise to return the additional premium to the production community for public welfare projects such as education and medical care, which directly improves the welfare of local workers and their families. The improvement of labor fairness is not only a moral requirement, but also contributes to the long-term development of the industry. When cotton farmers and workers are reasonably rewarded and respected, their willingness to work and production enthusiasm will increase, and experience and skills will be accumulated and passed on, which provides a reliable human resource guarantee for sustainable production.

### 3.3 Market access and industry resilience

Establishing a fair, transparent and profitable market system is a key driving force to encourage cotton farmers to adopt sustainable practices. Many sustainable cotton projects have designed market access incentives to allow cotton farmers who adopt good production methods to sell cotton at higher prices or more stable channels, thereby compensating for the risks of increased expenditure and reduced production that they may face during the transition period. For example, after farmers who join the BCI project obtain the "Better Cotton" license, their cotton can be sold as sustainable raw materials to textile companies participating in the project. Although BCI cotton is not directly distinguished from ordinary cotton in appearance, the brand has promised to gradually increase the proportion of BCI cotton purchases, which is equivalent to providing stable sales channels and market share for project cotton farmers. According to the Better Cotton 2023-2024 Annual Report, the production of "Better Cotton" in 2022-2023 reached 5.47 million tons, accounting for 22% of the global cotton supply. This shows that more and more market demand is leaning towards sustainable sources, and cotton farmers participating in the project have therefore enhanced sales guarantees. Market diversification is also an important aspect of improving risk resistance. Traditional small farmers often have a single sales channel and weak bargaining power, and are easily subject to middlemen and price fluctuations. To this end, some development projects help cotton farmers form cooperatives to directly connect with textile companies or exporters, reduce intermediaries and improve bargaining power. In addition, promoting the localization of the cotton textile industry is also one of the ways to enhance resilience. Developing spinning and weaving processing industries in cotton-producing countries can consume cotton locally, increase added value, and reduce dependence on single raw cotton exports. Gujarat and other places have established textile parks to attract investment in spinning mills, so that local cotton farmers have more diversified sales options and are no longer completely affected by international raw cotton price fluctuations. Finally, the improvement of financial support mechanisms can also help improve cotton farmers' ability to resist risks. Developing weather index insurance and price insurance suitable for small farmers can provide basic compensation in the event of disasters or price plunges. For example, cotton weather index insurance was introduced in pilot projects in Maharashtra and Gujarat, India, but the current insurance coverage rate is still low due to reasons such as awareness and procedures (Mahadevaswamy and Kotreshwar, 2018). In the

future, it is necessary to strengthen publicity and simplify the claims process so that more cotton farmers are willing to participate in insurance. In general, by expanding market access for sustainable cotton, ensuring reasonable prices, and providing financial risk buffers, the resilience of all links in the industry chain can be effectively improved. When cotton farmers no longer worry about their livelihoods and dare to invest in new technologies, the sustainable transformation of cotton cultivation can truly achieve a virtuous cycle.

## 4 Technological Innovation

### 4.1 Precision agriculture technology

The application of modern science and technology has injected new impetus into traditional cotton planting. Innovative elements such as precision agriculture, biotechnology and digital platforms are changing the way cotton is produced and improving its sustainability. Precision agriculture achieves the goal of optimizing input and output through the perception and targeted management of field heterogeneity. In cotton cultivation, precision agriculture is mainly reflected in precision fertilization, precision plant protection and precision irrigation. Using remote sensing and geographic information systems (GIS), the soil nutrients, water and vegetation growth distribution maps of cotton fields can be finely drawn, so as to achieve variable input on demand. For example, cotton farmers in the United States and Australia have widely adopted variable fertilization technology, applying fertilizers in different zones according to the differences in soil nitrogen and phosphorus content, which not only avoids excessive waste but also ensures sufficient nutrients for cotton. In the plant protection link, the combination of hyperspectral remote sensing and digital monitoring methods such as insect monitoring lights and sex traps makes cotton field pest monitoring more timely and accurate. Some research teams have developed an intelligent insect monitoring platform based on the Internet of Things, which uses field sensors and image recognition to automatically count pest density and automatically notify farmers to take control measures when the threshold is exceeded (Ahmed et al., 2024). The application of unmanned aerial vehicles (UAVs) in cotton fields is also becoming more and more widespread. Plant protection drones can spray pesticides at low altitudes, with the advantages of high efficiency and low drift, which is very suitable for the integrated prevention and control of pests and diseases in large areas of cotton fields. In China, Xinjiang and other places are equipped with tens of thousands of plant protection drones for cotton field management, which not only reduces the amount of pesticides used, but also reduces the risk of human exposure to pesticides (Liu et al., 2024). Drones can also carry multispectral cameras to inspect cotton fields, detect problems such as seedling shortages, drought, and diseases, and realize precision agricultural technology services. Automatic navigation machinery is another important aspect of precision agriculture. Modern tractors and cotton pickers use GPS Beidou navigation to achieve centimeter-level automatic driving and operation, greatly improving the quality and efficiency of operations. For example, the precise navigation of trenching and film laying machines ensures that the drip irrigation tape is laid evenly and reduces waste; the automatic walking path of the cotton picker avoids overlap and omissions, and improves the cleanliness of the harvest. These technological innovations ultimately point to the optimization of resource input and the increase of yield per unit area, which is in line with the concept of sustainability. A research report by Dudhatra (2021) pointed out that among American cotton farmers, the adoption of precision agriculture technology has significantly improved the efficiency of fertilizer and pesticide utilization, reduced non-point source pollution, and maintained a high yield level. With the decline in equipment costs and the popularization of technical services, precision agriculture is expected to be implemented in more cotton-producing countries, helping to build a fine, efficient and environmentally friendly cotton cultivation system.

### 4.2 Biotechnology innovation

Biotechnology has shown great potential in cotton improvement and pest and disease control. The Bt insect-resistant cotton is a successful case of transgenic breeding, which has greatly reduced the use of pesticides. But the role of biotechnology is far more than that. On the one hand, by combining traditional breeding with genetic engineering, scientists are breeding more stress-resistant cotton varieties. In the face of drought and heat waves caused by climate change, one of the coping strategies is to breed drought-resistant and high-temperature-resistant varieties. Some studies have used gene editing technology (CRISPR-Cas) to knock out genes related to cotton stomatal development, reducing plant transpiration and water consumption, thereby

improving drought tolerance; others have enhanced deep water extraction capacity by improving the root system architecture of cotton plants. These explorations provide genetic resources for the future cultivation of climate-resilient cotton. On the other hand, new biotechnology products are emerging in an endless stream in the prevention and control of pests and diseases. For example, for stubborn soil-borne diseases such as cotton Verticillium wilt, some people have tried to transfer disease-resistant genes or colonize engineered bacteria to enhance plant immunity. Another example is the use of RNA interference (RNAi) technology to design cotton to express specific double-stranded RNA fragments, which silences the genes of feeding pests and causes their death (Nagaraj et al., 2024). This transgenic RNAi cotton is expected to fight against piercing-sucking pests (such as planthoppers and aphids) that are currently ineffective against Bt cotton. In addition, the development of new biological pesticides is also worthy of attention. Fungal toxins, botanical pesticides, and biological control agents for cotton pests and diseases are constantly emerging, and some products have been put into commercial use. For example, *Bacillus thuringiensis* (Bt) preparations can be used to control lepidopteran larvae in organic cotton fields; biochemical pesticides such as chitinase and chitin synthesis inhibitors have a selective killing effect on cotton pests. Biotechnology has also promoted the improvement of cotton fiber quality. By regulating fiber development-related genes, breeders strive to improve fiber length and strength while increasing yields to meet high-end textile needs. It is worth mentioning that in recent years, Chinese researchers have used synthetic biology to cultivate colored cotton, and cotton fibers are naturally pink, thereby reducing chemical pollution in the subsequent dyeing process (Li et al., 2022). This type of innovation enriches the connotation of sustainable cotton. Biotechnology has brought new possibilities to cotton cultivation. It will take time to move from the laboratory to the industry, but its prospects in improving cotton stress resistance, reducing chemical inputs and improving quality are exciting.

### 4.3 Digital platform and informatization

In modern agriculture, timely acquisition and communication of information are of great value to decision-making optimization. The cotton industry chain is complex, and the application of digital technology can improve the collaborative efficiency and transparency of each link. First, at the planting end, agricultural technology digital service platforms are emerging. For example, some mobile phone applications provide customized guidance for cotton farmers. They only need to input local weather, variety and growth data, and the system can push corresponding management suggestions, including fertilization and irrigation timing, pest and disease warning, etc. This allows small farmers to enjoy expert consulting services and narrows the information gap. An Indian startup team has developed a digital application for cotton farmers, integrating satellite remote sensing and ground data to provide farmers with full guidance from sowing to harvesting (Sarkar et al., 2023). These digital platforms often combine voice and image functions to facilitate farmers with limited literacy. Secondly, in supply chain management, blockchain and Internet of Things technologies have begun to be used for cotton traceability. Brands hope to prove that the cotton they purchase meets sustainable standards, which requires a reliable origin verification system. For example, the "Better Cotton" organization launched a digital tracking system in 2023, allowing the flow of cotton from farms to spinning mills to be recorded in the chain, improving supply chain transparency. Consumers can also scan the QR code on the clothing label to understand the origin and planting specifications of the cotton used in the product, thereby enhancing their confidence in sustainable products. Thirdly, e-commerce and information platforms have built a direct bridge between cotton farmers and textile enterprises. Cotton farmers in some developing countries directly publish cotton supply and demand information through online platforms, obtain market price information, and avoid regional information islands. This digital marketing method helps farmers choose the right time to sell and improve bargaining power. For example, in Xinjiang, China, there is an "Internet + Cotton" comprehensive service platform that brings together information such as supply and marketing, logistics, warehousing, and financial insurance, providing one-stop transactions and services for cotton farmers and cotton ginning factories. It is reported that after the platform went online, the average selling price of local cotton increased by 3%-5%, and the transaction efficiency increased by more than 40% (from relevant industry reports). Finally, digital technology has also promoted international knowledge sharing. Scientific research institutions and agricultural organizations have disseminated sustainable cotton practice experience across borders through online meetings and remote training. For example, academic activities

such as the "World Cotton Research Conference" have been broadcast online in recent years, enabling agricultural technicians in developing countries to easily obtain the latest knowledge and apply it to local practices. It can be foreseen that with the improvement of rural communication infrastructure and the improvement of digital literacy, informatization will empower the cotton cultivation system to a greater extent, break through geographical restrictions, achieve optimal resource allocation and full-process quality control, and provide strong technical support for sustainable development.

## 5 Policy Support Mechanism

To achieve a comprehensive and sustainable transformation of the cotton industry, it is inseparable from the guidance and support at the policy level. Governments and international organizations can create a policy environment conducive to the promotion of sustainable practices by formulating certification standards, providing economic incentives and increasing RandD investment.

### 5.1 Certification standards and industry norms

Sustainable certification builds a communication bridge between producers and markets and is an important policy tool to promote green production. In the past decade, a number of international cotton sustainability standards have been established, such as the BCI, organic cotton certification, fair trade cotton, and the cotton initiative for Africa (CmiA) (Partzsch et al., 2019). These standards set out different environmental and social guidelines for cotton production, and independently audit qualified cotton farmers or farms to give their products the identity of "sustainable cotton". In the global supply chain, certification standards have become a pass for sustainable products to enter the high-end market. For example, organic cotton requires no use of chemical synthetic inputs and genetically modified seeds throughout the process, and has a high production cost, but organic cotton products can get a premium, and some brands are happy to purchase them to meet their environmental commitments. According to the Organic Cotton Market Report released by the Textile Exchange in 2021, organic cotton production set a new record between 2019 and 2020, mainly driven by market demand for organic cotton. For most ordinary farmers who do not meet organic requirements, participating in looser standards such as BCI is a realistic path. The BCI standard covers six major principles, including soil, water, pests, fiber quality and labor conditions, providing a framework for gradual improvement in large-scale cotton production. As of 2022, BCI's good cotton production has accounted for more than one-fifth of the world's total. This model encourages farmers to continuously improve their production methods through market recognition. At the national level, some cotton-producing countries have also formulated localized sustainable cotton standards. For example, the China Cotton Association jointly issued the "Cotton China Sustainable Development Project (CCSD)" standard with relevant departments in 2021. This standard combines China's national conditions and involves indicators such as pesticide and fertilizer reduction, water and energy conservation, and labor protection, which are in line with international standards. The implementation of these standards has set clear goals for the government and the industry and promoted the upgrading of industry norms. Of course, the vitality of standards lies in implementation. It is recommended that the government strengthen supervision of the certification system, prevent false propaganda, and actively participate in dialogue and cooperation on international standards, promote mutual recognition and integration of various standard systems, and avoid burdening farmers with repeated certification. By improving the certification standard system, the "visible hand" can be used to guide cotton production in a more sustainable direction.

### 5.2 Government subsidies and financial incentives

Policy incentives are one of the direct driving forces for farmers to change traditional production methods. Many countries subsidize cotton production to ensure farmers' income and stabilize cotton supply. If subsidies can be linked to sustainable practices, it will have a huge driving force for green transformation. For example, the government can give additional subsidies to cotton fields that adopt environmental protection measures such as drip irrigation and soil testing and fertilization to compensate for their equipment investment. The experience in Xinjiang shows that fiscal subsidies have a significant effect on the promotion of drip irrigation. Since the late 1990s, the Xinjiang government has subsidized drip irrigation materials and well power facilities, and with the introduction of international cooperation projects, millions of acres of cotton fields have been converted from

flood irrigation to drip irrigation in just over ten years (Fan et al., 2012). For example, some countries provide transition subsidies or tax breaks to farmers in the organic cotton conversion period to help them get through the painful period of declining production and rising costs. In addition to direct subsidies, the government can also use credit and insurance policy levers to support sustainable cotton. For example, provide interest-subsidized loans to farmers who purchase cost-saving and efficiency-enhancing equipment such as cotton pickers and precision seeders to lower their capital threshold. In developing countries with low labor productivity, such subsidies for the purchase of agricultural machinery can reduce dependence on cheap labor and improve labor-capital relations to a certain extent (Sriram et al., 2024). In terms of insurance, the government can provide premium subsidies for cotton farmers to purchase weather index insurance to encourage more farmers to participate in insurance, thereby reducing government disaster relief expenditures in disaster years and ensuring stable farmers' income. It is also important that policies should take into account regional balance and vulnerable groups. For example, in areas where drought and water shortages must be maintained but agricultural production must be maintained, the government should invest in the construction of water conservancy and water-saving facilities, and provide water subsidies to local farmers or reward farmers with outstanding water-saving results. For example, for women cotton farmers, ethnic minority cotton farmers and other groups, special reward and subsidy projects can be designed to increase their opportunities to participate in training and technology upgrades, thereby narrowing the gender and group gap. In general, combining fiscal and financial tools with sustainable goals is an effective way for the government to guide industrial transformation. This can not only accelerate the spread of green technology, but also convey a clear policy signal: future subsidies will flow more to environmentally friendly and socially responsible producers, which will encourage more and more cotton farmers to join the ranks of sustainable development.

### 5.3 Research investment and promotion system

Another focus of policy support is to strengthen the construction of scientific research and promotion systems to provide technical supply and talent support for sustainable cotton cultivation. First, the government and scientific research institutions should increase investment in cotton sustainability-related scientific research, including new variety breeding, green prevention and control technology, low-carbon planting models and other aspects. For example, in response to climate change, it is necessary to cultivate new varieties of high-yield and stress-resistant cotton; in response to the reduction of pesticides and fertilizers, it is necessary to develop high-efficiency biological pesticides and new fertilizer substitutes. These RandD often have long cycles and large investments, and enterprises alone are not motivated enough, so the public sector needs to play a leading role. During the 13th Five-Year Plan period, China launched a major project on green super rice and cotton, invested heavily in supporting the research and development of transgenic insect-resistant cotton and drought-resistant cotton, and achieved breakthroughs (Li et al., 2020). Secondly, the agricultural technology promotion system should be improved to truly transform scientific research results into the fields. Specifically, the capacity of grassroots agricultural technology promotion stations in major cotton-producing areas should be strengthened, and agricultural technicians who are familiar with both modern technology and local realities should be equipped to provide farmers with on-site guidance and consulting services. In some developing countries, the public promotion system is weak, and foreign aid projects and NGOs have played a supplementary role in this regard. For example, the "Belt and Road" agricultural cooperation platform composed of scientific research institutions in various countries has organized experts to conduct cotton cultivation technology training in Africa and South Asia in recent years, filling the gap of insufficient local extension personnel. Thirdly, policies can encourage the integration of industry, academia and research and international cooperation. Through the guidance of scientific research funds, universities, colleges, enterprises and cooperatives can be encouraged to jointly tackle the problems of sustainable cotton cultivation, such as the development of precision irrigation systems and complete sets of cotton mechanization technologies. At the international level, we should actively participate in cotton scientific research cooperation networks, such as the expert committee of the international cotton advisory committee (ICAC), to share the latest global scientific and technological achievements. Especially for transnational pests and diseases and climate issues, international cooperation in research and development has a multiplier effect. Finally, policies should attach importance to the role of traditional knowledge and farmers'

innovation. The local experience accumulated by many small farmers is still valuable in sustainable agriculture. Practices such as mixed crop rotation and composting should be paid attention to and verified in scientific research and improved by modern science. The government can establish a farmer field experiment funding project to encourage experienced farmers to cooperate with scientific researchers to test new methods, draw inspiration from them, and form technical solutions adapted to local conditions. In summary, policy support for scientific research and promotion provides long-term impetus for the development of sustainable cotton. This ensures that under policy incentives and market demand, there are sufficient technical reserves and professional manpower to support the smooth transformation of the industry, without being hindered by lack of technology or insufficient personnel.

## 6 Case Study: Sustainable Cotton Cultivation in Gujarat, India

### 6.1 Background

Gujarat is located in western India and has an arid and semi-arid climate. It is one of the largest cotton-producing states in the country, with smallholder farming and rain-fed cotton fields dominating. For a long time, local cotton farmers have faced challenges such as poor soil quality, frequent droughts and volatile market prices. However, in the past decade, a series of sustainable cotton cultivation projects have been implemented in Gujarat with remarkable results. Gujarat has a long history of cotton cultivation, and cotton is the backbone of the state's rural economy. The state's cotton cultivation area is about 2.6 million hectares, and the annual output accounts for more than 30% of India's total output (data source: Annual Report of the Indian Cotton Board). Traditionally, local cotton farmers are mostly smallholders, with families operating a few hectares of land, and mainly rely on monsoon rainwater to grow rain-fed cotton, with limited irrigation facilities. When pests such as cotton bollworms were rampant in the late 20th century, cotton farmers used large amounts of pesticides, which even caused pesticide poisoning incidents (Bharpoda et al., 2000). At the same time, due to the lack of improved varieties and technical guidance, the cotton yield has been low for a long time, not as good as that of the irrigated cotton areas in northern India. In response to these problems, the Indian government and international organizations have carried out a number of intervention projects in Gujarat. For example, since 2011, Gujarat has become one of the focus areas of the Better Cotton Initiative (BCI), and many cotton farmers have begun to improve their planting methods in accordance with BCI standards. In 2013, the large retail company Primark, CottonConnect and local NGOs launched the "Sustainable Cotton Project" in Gujarat, initially organizing 1 251 female cotton farmers to participate in the pilot near Ahmedabad. The project was later expanded to the entire state and replicated in other parts of India and the country. It can be said that Gujarat provides an ideal testing ground for sustainable cotton practices, and its experience is representative.

### 6.2 Practices

In the sustainable cotton project in Gujarat, all the best practices mentioned in the previous chapters have been comprehensively applied. The project provides participating farmers with trained field instructors, regularly conducts farmer field school activities, and teaches technologies such as integrated pest management, soil improvement and efficient water use. Farmers switched to new insect-resistant cotton varieties, which greatly reduced the use of pesticides (Figure 2). At the same time, the project encouraged farmers to plant attractant crops such as corn around cotton fields, set up pheromone traps and yellow boards, and implement biological control measures to control insect population density (Murtaza et al., 2019). In terms of soil management, the project advocated the use of more organic fertilizers, such as composting livestock and poultry manure and returning it to the fields to increase soil organic matter. Some farmers tried intercropping and rotation of cotton with green manure crops (such as broad beans) to improve soil nitrogen cycles. In response to the local water shortage problem, the project cooperated with the government to build small reservoirs and installed low-pressure drip irrigation systems in fields with conditions. Although most cotton fields still rely on monsoon rainwater, a small number of demonstration fields using drip irrigation have shown good water-saving and yield-increasing effects and have promotion potential. The project also paid special attention to the capacity building of women cotton farmers. Since many cotton fields are actually managed by women (men work outside seasonally), the time and format of the training courses are considered to be convenient for women and increase their participation (Hirway

and Singh, 2017). In terms of market and organization, the project helped farmers to form cotton cooperatives to purchase agricultural materials and sell seed cotton in a unified manner, and directly connect with cotton ginning factories to reduce middlemen's exploitation. The cooperatives also set up emergency funds to provide small loans to members when they encounter poor harvests, enhancing the overall risk resistance of the community.

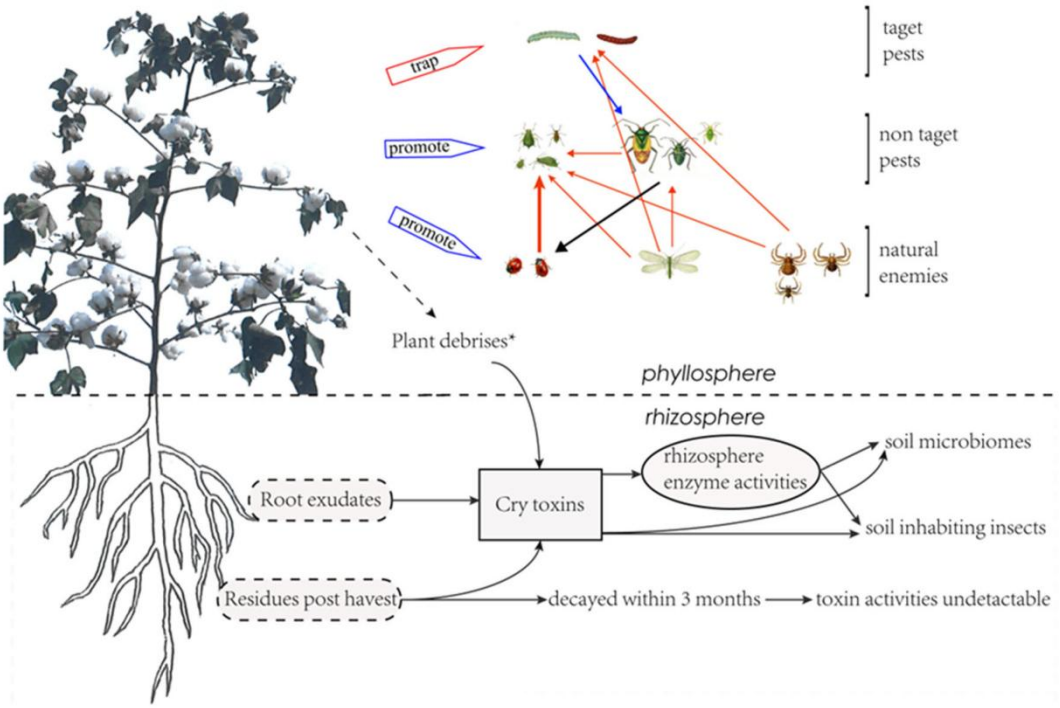


Figure 2 Changes in pest-community interactions due to Bt cotton and Bt toxins. ★ Plant debrises include defoliation, pollen falling, and sqare and boll shedding (Adopted from Razzaq et al., 2023)

### 6.3 Results

The Gujarat Sustainable Cotton Project has achieved significant economic, environmental and social benefits. The first is the increase in cotton farmers' income. According to project monitoring data, the seed cotton yield of participating farmers has increased by an average of about 15%-20% in three years, mainly due to the application of improved varieties, timely field management and the reduction of pests and diseases. More importantly, due to the reduction of inputs such as pesticides and fertilizers and the reduction of costs by the cooperative's unified purchase and sale, the net profit of farmers' cotton planting has increased more significantly. Primark reports that cotton farmers who have completed the full set of training have seen their profits nearly triple on average, which has greatly improved the living conditions of cotton farmers' families. For example, a female cotton farmer from Surendhnagar said that after adopting the new method, her family not only paid off their debts, but also purchased drip irrigation equipment to expand production. This shows that sustainable practices are economically feasible or even superior. The second is improved environmental performance. The 2014-2023 India Impact Report shows that compared with the baseline year, the use of chemical pesticides by demonstration farmers has been reduced by more than half, the use of fertilizers has also been reduced by about 1/3, and the use of water for cotton field irrigation has been reduced by nearly 29%. These agronomic improvements have effectively reduced the pressure on local land and water resources. For example, due to the reduction of highly toxic pesticides, field biodiversity has been restored, and the number of beneficial insects and animals such as predatory spiders and frogs has increased, forming a healthier farmland ecosystem. The third is social benefits. Through cooperative organizations, small farmers have strengthened their cohesion and voice, not only gaining a fairer market position, but also becoming more active in community affairs. Women played a key role in the project. Some female farmers served as managers and trainers of cooperatives, raising local awareness of gender equality. The adult literacy and basic arithmetic training provided by the project also enabled some cotton farmers to read and write for the first time, which will have a profound impact in the long run. In addition, the successful experience is also spreading in the

surrounding areas, leading more farmers who did not participate in the project to spontaneously adopt similar measures. For example, seeing that their neighbors used sex attractants to catch insects with good results, many farmers who did not participate in the training also bought traps and hung them in their own cotton fields, and the concept of sustainability spread from point to surface. The case of Gujarat shows that with the appropriate promotion model and necessary support, the small peasant economy can also quickly achieve the green transformation of the production system and achieve a "three-win" effect: increased income for farmers, improved environment and enhanced industry sustainability. This provides a valuable reference for other cotton-producing areas.

## 7 Future Directions and Suggestions

### 7.1 Expand the promotion coverage of successful experiences

Although sustainable cotton cultivation has achieved initial results worldwide, it is necessary to promote changes on a larger scale and at a deeper level to cope with more severe environmental and market challenges in the future. At present, sustainable cotton projects are mainly concentrated in some regions and farmers, and the proportion of global cotton farmers and production is still limited. For example, although projects such as BCI cover millions of farmers, it is just a beginning compared to the hundreds of millions of farmers engaged in cotton cultivation around the world. Therefore, countries should increase promotion efforts on the basis of summarizing existing successful models to achieve wider replication. First, it is recommended that the governments of major cotton-producing countries incorporate sustainable cotton into agricultural development strategies and set clear phased goals. For example, by 2030, more than 50% of the country's cotton fields will meet sustainable standards such as reducing pesticides and saving water. The government can guide more farmer cooperatives, cotton companies and NGOs to participate in the action through policy advocacy and demonstration projects. Secondly, international cooperation and knowledge exchange should be strengthened to avoid each region fighting alone. Cotton-producing countries such as China, India and the United States can establish a cotton sustainable development alliance to regularly share experiences, technologies and policy measures. On a wider platform, such as ICAC (International Cotton Advisory Committee) and ANSO (the Belt and Road International Science Organization Alliance), special seminars and training courses can continue to be held to benefit more small and medium-sized cotton-producing countries. Private sector investment also needs to be expanded. At present, many projects promoting sustainable cotton are funded by brand companies' corporate social responsibility (CSR) investment and multilateral agency assistance. In the future, more downstream textile and garment companies should be encouraged to join. For example, a "Joint Commitment on Sustainable Raw Material Procurement" can be established to call on major global textile brands to commit to increasing the proportion of sustainable cotton procurement to a certain level in the next 5-10 years. This will send a clear demand signal to the market and attract more cotton farmers to transform. In the process of expanding the scale of promotion, attention should be paid to adapting to local conditions and not copying successful cases while ignoring differences in local conditions. It is recommended to adopt a demonstration area-radiation model to create several successful models in different countries and regions, and then promote them to the surrounding areas after localized improvements to ensure that newly adopted farmers can also obtain expected benefits and consolidate confidence in sustainable practices.

### 7.2 Enhance climate resilience

The cotton industry is increasingly threatened by climate change, such as extreme high temperatures causing cotton buds and bolls to fall off, and abnormal rainfall triggering pest and disease outbreaks. Improving the climate resilience of cotton cultivation systems is a key issue for future sustainable development. First, the cultivation and promotion of climate-resilient varieties should be accelerated. This includes high-temperature and drought-resistant cotton varieties, as well as varieties that are resistant to flooding and salinity. On the basis of traditional breeding, molecular breeding and gene editing technologies should be fully utilized to accelerate the breeding process (Nagaraj et al., 2024). Gene banks in various countries should strengthen the collection and research of wild cotton relatives and local germplasm resources, because they often contain stress resistance genes. International collaborative breeding can share these valuable resources, breed together, and share results. Secondly,

improve agricultural early warning and insurance mechanisms to deal with extreme weather risks. Meteorological departments should provide cotton farmers with more refined forecasts and warnings, such as issuing high-temperature heat wave warnings in advance so that farmers can adjust the sowing period, or issuing high-risk warnings for pests for early prevention and control. At the same time, expand the coverage of cotton weather index insurance, and help low-income countries establish an agricultural insurance system with the support of the Global Climate Risk Fund. Once a disaster occurs, cotton farmers can at least receive basic compensation, avoiding falling into poverty due to a single disaster, and thus being able to continue to adhere to sustainable farming without returning to the old path of high input and high risk. Thirdly, encourage the development of climate-smart agricultural practices. For example, carbon sequestration in cotton production can be achieved through soil carbon sequestration and reduced agricultural inputs. Some studies have pointed out that the promotion of no-tillage mulching and intercropping can not only improve the climate adaptability of farmland, but also increase the organic carbon content in the soil (Adil et al., 2023). In the future, the carbon trading mechanism may be used to provide additional income to cotton farmers who adopt these practices to form economic incentives. In addition, in terms of macro-layout, countries should pay attention to the adjustment of agricultural planting structure and avoid excessive development of cotton monoculture in extremely fragile ecological areas. Through reasonable regional planning and adjustment of planting systems, cotton planting can be concentrated in areas with better water and soil resource carrying capacity, and cotton fields with high environmental costs can be gradually eliminated. This requires policy guidance and the provision of alternative livelihood solutions for cotton farmers to achieve a fair transition. Only by integrating climate resilience construction into the sustainable cotton strategy can we ensure that the cotton industry can still develop steadily under more extreme climate conditions in the future.

### 7.3 Strengthen global cooperation and responsibility sharing

Cotton is a global industry that connects many countries. Improving its sustainability requires cooperation across the entire industry chain and multiple stakeholders. First, producing countries should deepen cooperation and jointly address sustainable development challenges. For example, strengthen consultation mechanisms in cross-border pest control and water resource management (Mukhtar, 2024). The international forums and alliances mentioned above provide a good start for this. We can explore the establishment of a "Global Sustainable Cotton Roundtable" to bring together government officials, scientific research experts, corporate representatives and farmers' organizations from cotton-producing countries for regular dialogue to negotiate and resolve major issues, such as eliminating the use of the most harmful pesticides and promoting global cotton subsidy reform. Second, developed and developing countries should strengthen cooperation in financing and technical assistance. Many least developed countries (such as some cotton-producing countries in Africa) lack the funds and technology needed for transformation, and the international community has a responsibility to provide support. For example, through channels such as the Food and Agriculture Organization of the United Nations (FAO) and the Green Climate Fund, provide grants and concessional loans for sustainable cotton projects in Africa and small island countries, introduce appropriate technologies and training, and help them improve productivity and environmental performance. Agricultural research institutions and enterprises in developed countries can also cooperate with these countries to carry out technical trials and capacity building to achieve knowledge sharing. Third, multinational cotton textile companies and brands need to assume more supply chain responsibilities. This includes implementing the commitment to purchase sustainable cotton and not giving up existing progress due to temporary cost considerations; at the same time, protecting the interests of cotton farmers when cotton prices are low and avoiding excessive price cuts that cause farmers to lose money. Several disputes that have emerged in recent years have shown that the misconduct of any party in the supply chain will have an impact on the reputation and stability of the entire industry. For example, some Western brands have improperly handled labor issues in the supply chain, leading to trade frictions and lack of trust, which is not conducive to the atmosphere of global cooperation. All parties should communicate and cooperate on the basis of facts and science, seek constructive solutions, and jointly promote industry improvements rather than confrontation. Finally, consumer education is also a part of global cooperation. Only when global consumers recognize and approve sustainable cotton products can the market's pulling power be fully exerted. Governments and NGOs can guide consumers to

understand the benefits of sustainable cotton to the environment and society through public welfare publicity and marketing, so that they are willing to pay a reasonable premium for it and form a benign market feedback. Through the efforts of the entire industry chain and international collaboration, the sustainable transformation of the cotton industry will no longer be just a sporadic bright spot, but will become the mainstream of global common practice.

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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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