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Cotton production in the Yellow River Basin of China: reforming cropping systems for ecological, economic stability and sustainable production

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Cotton cropping systems are critical for ensuring the stability and sustainability of cotton production, which is of vital importance to both the agricultural and economic sectors of China. This review examines the historical evolution, challenges, and potential reforms of cotton cropping systems in Shandong Province, a key cotton-producing region in China. The study highlights the effects of economic, technological, and ecological factors on cotton production in the region, emphasizing the importance of optimizing cotton cropping systems to stabilize production, enhance efficiency, and promote rural revitalization. Based on empirical evidence, the review suggests several innovative approaches, including advanced cotton cultivation systems and large-scale mechanization, designed to enhance the sustainability of cotton farming. Furthermore, the research highlights the critical need to balance cotton cultivation with national food security goals by addressing the challenges of saline and alkaline soils and promoting sustainable cotton industry development in the Yellow River Basin; it further offers forward-looking policy recommendations for Shandong, advocating for the integration of advanced agricultural technologies, the establishment of robust agricultural insurance systems, and the implementation of region-specific strategies to ensure both ecological resilience and economic viability—ultimately positioning cotton farming as a key driver of rural revitalization and green development. The findings of this study provide valuable insights for policy-making, guiding the sustainable development of cotton farming in Shandong and other regions with similar requirements.

KEYWORDS

cropping system, cotton, agricultural sustainability, agronomic improvement, Yellow River Basin

1 Introduction

As a pivotal economic and livelihood industry, cotton production is significant in promoting economic growth, securing employment, and facilitating rural revitalization (Zhang et al., 2023a). Shandong Province represents the Yellow River Basin cotton region, one of China's three major cotton region (the Yellow River Basin, Yangtze River Basin, and Xinjiang cotton regions) (Wang et al., 2019). For years, Shandong has ranked second after Xinjiang Province in cotton cultivation area and total output, with its cotton maintaining one of the

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largest economic scales in the country; in 2017, the cotton textile benefit is 1.2 trillion yuan, accounting for approximately 16.5% of the province's GDP (Wang et al., 2019; Zhang et al., 2022).

However, due to various factors, including low comparative benefits, substandard cotton quality, and changes in the domestic and international cotton supply and demand patterns, cotton production in Shandong has suffered a severe contraction and industrial decline in recent years (Xu et al., 2024a). In 2024, the actual planted area and total output of the Yellow River Basin cotton region decreased to 1.84 one hundred thousand hectares and 2.25 one hundred thousand tons, respectively, representing year-on-year decreases of 3.4 and 1.3% (National Bureau of Statistics, 2025). Notably, cotton-planted area and output in Shandong declined significantly to 1.18 one hundred thousand hectares and 1.36 one hundred thousand tons, reflecting decreases of 7.7 and 8.4%, respectively (Wang et al., 2023). Therefore, stabilizing the cotton output in Shandong has become an urgent and strategically significant task for revitalizing rural industries in cotton-growing regions and promoting high-quality development in the Yellow River Basin. Theoretical studies and practical evidence from cotton production in Shandong suggest that optimizing the cotton cropping system, improving cultivation techniques, and enhancing the overall economic efficiency of cotton fields are effective measures for stabilizing yields (Chi et al., 2023).

The cropping system constitutes an integrated technical framework encompassing the planting regime and associated land maintenance practices within a specific region or production unit (Martin et al., 2013). In cotton-growing regions, this system forms a complex, interconnected structure encompassing crop arrangement (species selection, planting density, and spatial distribution with cotton as the dominant crop), cultivation patterns (intercropping, mixed cropping, relay cropping, and multiple cropping), and planting regimes (continuous cropping or crop rotation) (Matloob et al., 2020; Ruiz et al., 2023; Vitale et al., 2024). The land maintenance system, tailored to the cropping system, encompasses a comprehensive set of agronomic measures to improve soil productivity. These measures include field infrastructure development, soil fertility management, water supply–demand balance, tillage practices, and farmland conservation (Bünemann et al., 2018). Implementing a rational cropping system is a critical strategy for achieving sustained yield improvement, quality enhancement, income growth, and resource-environmental conservation in cotton-growing regions, thereby promoting comprehensive and sustainable agricultural development.

Cropping systems play a dual role in agricultural development: by providing technical guidance and supporting production planning and decision-making, thus integrating technology and management into a coherent framework (Augarten et al., 2023). Generally, cropping systems demonstrate robust applied technical characteristics rooted in technological research and application, yet they differ significantly from individual cultivation techniques (Gebhardt et al., 1985). They encompass multidimensional technical integrations addressing crop–climate, crop–soil, and crop–crop interactions, including (i) site-specific cotton layout optimization (Niu et al., 2021); (ii) three-dimensional intercropping and mixed farming techniques (Li X.-F. et al., 2021); (iii) multiple cropping and rotation/continuous cropping strategies (Chai et al., 2021); (iv) integrated grain-cotton-forage production systems (Sparr, 1970); (v) synergistic land-use and soil conservation practices; and (vi) design and optimization of unit-or regional-level cropping systems (Pemsl and Waibel, 2007). These techniques, which are intricately integrated into cotton-growing regions, exemplify comprehensiveness, regional specificity, and multi-objective coordination. In addition, cropping systems emphasize systematicity, holism, and regional adaptability. They focus on macro-level resource-production allocation, ensuring a balance between agricultural development and environmental constraints. In alignment with strategic agricultural objectives, they refine land-use planning, optimize crop structure and cropping intensity, enhance soil conservation strategies, and design regionalized cropping systems tailored to local natural and socioeconomic conditions (Malézieux, 2012). Over various developmental stages, China has accumulated extensive empirical expertise in this domain. In 1970, in response to severe national food and cotton security challenges, the Yangliuxue Brigade in Huimin District (Binzhou city) innovatively implemented a wheat–cotton relay intercropping system integrated with Yellow River water irrigation for alkali soil remediation. This approach achieved sustained high yields in both crops for 7 consecutive years (Wang et al., 2007). Since 2016, crop rotation and fallow programs have been initiated in ecologically fragile zones (e.g., Northeast cold regions, Northern agro-pastoral ecotones, Hebei groundwater depletion areas, Hunan heavy metal-contaminated soils, and degraded ecosystems in Southwest/Northwest China). In 2022, Shandong Province policy implemented a policy that emphasized the utilization of saline-alkali land for cotton and green manure cultivation under its “Top Ten Industries” plan and Yellow River Basin ecological conservation strategy (Li et al., 2022). These government-led decisions exemplify the macro-regulatory role of cropping systems. Scientifically designed cropping systems effectively balance immediate requirements with long-term goals, facilitating systemic agricultural optimization and coordinated sustainable development of rural economies.

Based on field investigations into the evolution of cotton cropping systems and representative cotton-producing areas in Shandong, this review proposes systematic and targeted strategies for reforming the cotton cropping system. The findings aim to establish a high-efficiency cotton cultivation framework specifically designed for Shandong's diverse ecological zones under current conditions. This framework is expected to increase farmer incomes, improve industry productivity, and ultimately facilitate the recovery of cotton cultivation areas and the sustainable development of the cotton industry. To collect relevant literature, we searched Web of Science, Scopus, and CNKI databases for studies published between 2000 and 2024 using the following keywords: “cotton cropping system,” “intercropping,” “green manure,” “reduced nitrogen,” and “Shandong cotton.” In addition, we also research related report, news, and books to complete this review.

2 Historical evolution of cotton cropping systems in Shandong cotton regions

2.1 Development and transformation of regional cotton layout in Shandong

Cotton production in Shandong has a long history, with its cropping systems evolving in response to political and socioeconomic developments, and market dynamics. During the Ming (1368–1644) and Qing (1644–1912) dynasties, extensive cotton cultivation and export were documented (Feng et al., 2022). The Shandong General

Annals: Natural Products Records from the Jiajing era (1522–1566) of the Ming Dynasty indicate that cotton was cultivated across all six prefectures, with Dongchang being particularly noted for its abundance (Li, 2024). By 1930–1932, 13 counties reported cotton cultivation exceeding 13,333 hectares, with Caoxian County surpassing 66,667 hectares (Stewart, 2021). Post-1949 surveys conducted by the Shandong Department of Industry revealed 76 counties with more than 667 hectares of cotton, encompassing nearly all regions except the mountainous heartlands of Taiyi-Mengshan and Jiaodong hills.

Shandong cotton production experienced rapid recovery and expansion after 1949, with regional layouts aligning closely with national and local socioeconomic development. Following the reform and opening-up policy in 1978, Shandong's cotton industry surged, witnessed a significant surge, leading the nation in terms of acreage and output for 12 consecutive years (1980–1991). To optimize regional adaptability, Shandong was divided into five ecologically distinct cotton-growing zones in the 1980s: Southwest Shandong, Northwest Shandong, North Shandong, East Shandong, and South Shandong (Pemsl and Waibel, 2007). From 1983 to 1985, these zones accounted for 28.8, 38.9, 14.7, 14.2, and 3.38% of the provincial cotton acreage, respectively (Figure 1). After 1992, cotton acreage sharply declined due to bollworm infestations, reduced profitability, and structural crop adjustments (Wang J. et al., 2021). Despite ongoing state planning in cotton production, the relative shares of each region remained relatively stable, with Southwest Shandong gaining prominence while Northwest Shandong diminished (Niu et al., 2021). Following reforms in the cotton circulation system, market liberalization, and the introduction of pest-resistant cotton varieties in 1998, Shandong's cotton production experienced a rebound, prompting regions to prioritize crops best suited to local conditions (Cui, 2011). Consequently, the cotton-growing zones in the eastern and southern Shandong gradually contracted. By 2005, Shandong's cotton cultivation had consolidated into three primary regions Southwest Shandong Double-Cropping Zone: Centered in Heze and Jining, part of the Yellow River-adjacent cities (Niu et al., 2021). Northwest Shandong Mixed Single/Double-Cropping Zone: Spanning Liaocheng, Dezhou, and Jinan. North Shandong Single-Cropping Zone: Dominated by Binzhou and Dongying, encompassing the coastal saline-alkali cotton zone in the Yellow River Delta. These three regions accounted for 36.9, 29.8, and 24.8% of provincial cotton acreage, respectively, collectively representing over 90% of Shandong's total cotton cultivation (Figure 1). After 2009, under the influence of various factors, the three major cotton areas planted cotton area, respectively, accounted for the proportion of the province's cotton area fluctuated, but the pattern of the three major cotton areas did not change (Table 1).

2.2 Main factors affecting the cotton regional layout

The changes in the regional layout of cotton in Shandong Province are analyzed, particularly after the reform of the cotton circulation system. The shifts in cotton planting regions result from the dual role of economic and social development and progress in cotton planting technology. From the economic development perspective, farmers primarily grow cotton to achieve desired economic returns. In 1984, the cotton planting area in Shandong Province reached 1.712 million hectare, accounting for the area of one-fourth of the country, marking the highest level in history (Kubo, 2004). In many rural areas, the cotton sector played a crucial role in enabling households to build new

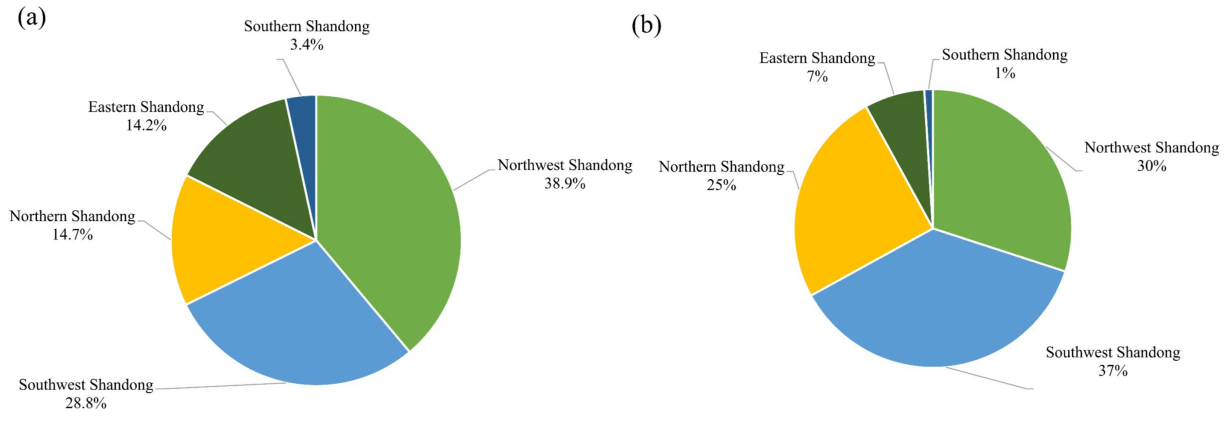

FIGURE 1
Proportion of cotton-growing areas in Shandong Province was shown in 1983 **(a)** and 2005 **(b)**, respectively.

TABLE 1 Distribution of three major cotton regions in Shandong.

Cotton region classification	Southwest Shandong cotton region	Northwest Shandong cotton region	Northern Shandong cotton region
Cotton region distribution range	Heze City, Jining City, Pingyin County, Dongping County, Feicheng City	Liaocheng City, Dezhou City, Shanghe County, Licheng District, Changqing District	Binzhou City, Dongying City, Gaoqing County, Shouguang City, Changyi City

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homes and fund their children's higher education. Cotton has played a pivotal role in driving local economic development. At that time, "Golden Gaotang" and "Silver Xiajin" in northwestern Shandong gained their names due to the prominence of cotton cultivation. Since this century, with the economic and social development of rural areas, cotton fields have increasingly concentrated in regions characterized by higher comparative efficiency in cotton planting. During 2003–2005, there was a noticeable negative correlation between farmers' income and the area dedicated to cotton cultivation (Figure 2). In eastern Shandong, due to its advanced economic development, the accelerated process of rural industrialization, rural labor force transfer, and melon and vegetables and other efficient crops developing fast, the comparative efficiency of cotton planting has diminished, leading to a gradual reduction in cotton acreage (Pemsl, 2006). Conversely, in southwestern Shandong, where economic development lags relatively behind, rural labor remains plentiful, and cotton planting is an important source of farmers' income, thus maintaining a higher proportion of cotton cultivation within the province.

In terms of advances in cotton planting science and technology, innovative cotton varieties, technologies, the popularization and business application, and cropping system reforms have affected the cotton sustainable production (Chi and Dong, 2024). For instance, the large-scale promotion and application of film covering technology and saline cotton planting technology have greatly propelled the advancement of the saline cotton industry. During the "Twelfth Five-Year Plan," the saline-alkali cotton planting area in the northern Ru region once accounted for over 45% of the province's total cotton planting area (Chi et al., 2021). The garlic–cotton intercropping area represented by Jinxiang County and Jiaxiang County in southwest Shandong Province has taken the lead in exploring the "two white and one red" ternary intercropping technology model, of cotton, garlic, and pepper, with an income of nearly 15 thousand yuan per hectare, which has become a bright business card for the reform of the national cotton planting system (Dai and Dong, 2016). Because of this, the cotton-growing areas in nine mainland provinces have sharply declined in recent years. However, the cotton planting area in the Southwest Shandong Garlic Cotton Region has remained relatively stable (Dai et al., 2015).

2.3 Shandong cotton area cotton cultivation technology research and application progress

Shandong's cotton-growing region historically belonged to a system of cotton fields. Since the founding of New China, with the development of the cotton-growing area's economy and society, agricultural scientists and extension workers have summarized the experience of farmers and promoted new technological combinations. This has led to the successful development of a series of cotton cultivation techniques suitable for China's large population and limited arable land situation, including mulching film application, seedling transplantation, chemical regulation, and double-cropping systems. In particular, the double-maturity cultivation technology combining cotton grains (garlic, vegetables, fruit, etc.) has become a uniquely advanced achievement in China's cotton planting sector, setting it apart from other cotton-producing countries worldwide (Dai and Dong, 2016).

In the comprehensive cotton cultivation technology, seedling transplantation, film mulching, and chemical control have played a transformative role in China's cotton production. These technologies are recognized as the "three major technological breakthroughs" (Stewart, 2021). Over the past 50 years, the above technologies have been demonstrated in Shandong's cotton-growing regions and have become an essential technical measure in different cotton cropping systems (Rui et al., 2021; Li, 2024; Meng and Yuhua, 2025). According to the Shandong provincial agricultural and rural sector survey, in 2021, the province's cotton intercropping areas with garlic, wheat, onion, and melon covered 3.66-million-hectare, accounting for 41.6%

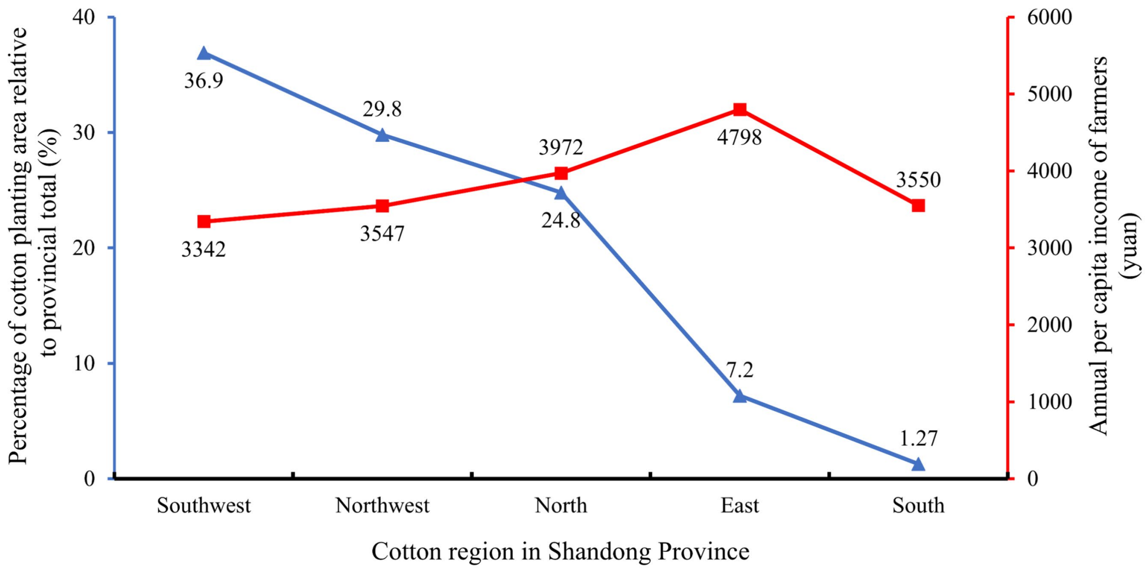


FIGURE 2
Comparison between the proportion of cotton planted area and the per capita income of farmers in different cotton regions from 2003 to 2005.

of the total cotton area The saline-alkali cotton fields and two-season cotton–wheat rotation areas using mulching technology totaled 5.72 ten-thousand-hectare, accounting for 65% of the total cotton planting area. The application rate of chemical control technology reached 100% (Du et al., 2022; Xu et al., 2023).

In the two-maturing cotton system, Shandong's cotton-growing region began experimenting with and promoting intercropping systems involving wheat and cotton, cotton and garlic, and cotton melons (vegetables) in the early 1950s (Table 2). Among them, the wheat and cotton set of a two-crop system has been an important and effective solution to the conflict between grain and cotton land use. However, in recent years, due to the labor-intensive nature of wheat–cotton intercropping and its high costs, the planting area has decreased significantly, accounting for only 2.1% of the total cotton-growing area in 2021, gradually phasing out of agricultural practice (Li et al., 2020; Yunfeng et al., 2024; Wei, 2025). In contrast, the cotton–garlic (melon, vegetable) intercropping systems, which offer higher comparative economic returns, continue to maintain a substantial planting area.

In a matured saline cotton cropping system, in the relatively less saline cotton areas of north and northwest Shandong, early measures to prevent salt seedlings primarily involved ditch construction, bordering ditches, early plowing without harrowing, sun district to raise bumps as well as cofferdams and flat planting, storage of fresh alkali, turning silt alkali, and other measures (Wei, 2025). Subsequently, water conservancy measures were taken to draw, store, and irrigate water in the plains. In the process of implementing water conservancy measures to improve cotton cultivation, the practice of promoting ditching to prevent salinization has been adopted. Specifically, from pre-sowing to the onset of the rainy season, a series of techniques have been applied, including alkali extraction, open ditch drainage, bottom-of-ditch seeding, double planting for seedling retention, fertilization around alkali removal areas, timely irrigation and hoeing, ridge loosening, and flat groove management, as well as returning sun-dried soil to its original position. These methods have effectively enhanced the rate of seedling preservation (Stewart, 2021), which included open ditch, high ridge cultivation, and concentrated fertilizer application at the bottom of ditches. During the 1980s, increased use of organic fertilizers and mulching techniques, combined with comprehensive agricultural development efforts, further improved the production conditions of saline cotton fields. The construction of cotton terrace fields and the application of mulching technology have improved the comprehensive production capacity of cotton fields, leading to substantial increases in yield (Xu et al., 2022). Since the beginning of this century, through in-depth research on saline-alkali soil management laws and the interaction between fertilizers and water transport in cotton cultivation, the technological level of saline-alkali cotton planting has been significantly enhanced. The coastal saline-alkali cotton planting technology developed by the Shandong Academy of Agricultural Sciences Cotton Research Center of the coastal saline and alkaline cotton planting technology was awarded the First Prize for Scientific and Technological Progress in Shandong Province and the Second Prize for National Scientific and Technological Progress. In 2021, the province's saline and alkaline cotton planting area accounted for 23% of the total cotton planting area (Xu et al., 2022).

In recent years, due to the low cotton production benefits, cotton agronomist development a cotton green and simplified planting technology with reduction in cotton planting labor and physical and chemical inputs (Mu, 2022). In summary, the development and evolution of Shandong's cotton system remain closely aligned with the economic and social development of cotton areas. When a cotton system no longer meets the needs of regional economic and social development, reform of that system becomes inevitable, leading to the establishment of a new cotton system (Li et al., 2020; Koudahe et al., 2021).

3 The reform of the cotton cropping system on the implementation of the "Yellow River Strategy" of practical significance

Farmland diversified cropping system has a long history in China and represents the essence of traditional agriculture. It is a product of intensive agricultural cultivation in our country and a significant advantage of our cropping system (Radhakrishnan, 2017). Fully utilizing natural and labor resources, these systems play a crucial role in increasing food and cash crop production. Cotton multi-cropping has a long tradition with diverse cultivation modes that effectively tap into the yield potential of cotton, enhance light energy utilization, and achieve synergistic benefits in cotton fields (Stewart, 2021). Especially under the backdrop of China's "Yellow River Strategy," optimizing the cotton cropping system to promote synergistic and efficient intercropping of grain, cotton, oil, vegetables, and melons is essential. This approach

TABLE 2 Development of two-crop cotton system in Shandong cotton region.

Cotton cropping type	Development review
Wheat–Cotton Intercropping	Experimental trials began in the 1950s, with high-yield varieties emerging in the late 1970s. Wheat–cotton configurations included 3–2, 4–2, and 3–1 patterns. Direct wheat seeding evolved into seedling transplanting and plastic film mulching. From 1982 to 1990, wheat–cotton double cropping covered 24% of provincial cotton fields. By 2008, this rose to 41% but declined to 2.1% by 2021.
Cotton–Garlic Intercropping	Developed in the early 1980s. Garlic is sown in mid-October and harvested in early June; cotton seedlings are raised in April and transplanted in mid-May. Since 2000, cotton–garlic intercropping in southwestern Shandong has stabilized at 0.1 million hectares annually. In 2021, it accounted for 38% of the province's total cotton planting area.
Cotton–Watermelon Intercropping	Experimental demonstrations began in Changle County (1982). Watermelon is covered with double plastic films, and cotton is transplanted as seedlings. By the mid-1980s, […] *Additional context:* Large-scale provincial promotion enabled counties such as Dongming and Huimin to develop unique cotton–watermelon cultivation methods, significantly boosting cotton field benefits. As of 2021, cotton–watermelon (vegetable) fields accounted for ~10% of total area.

*Data Source: Survey data of Shandong agricultural and rural sector.

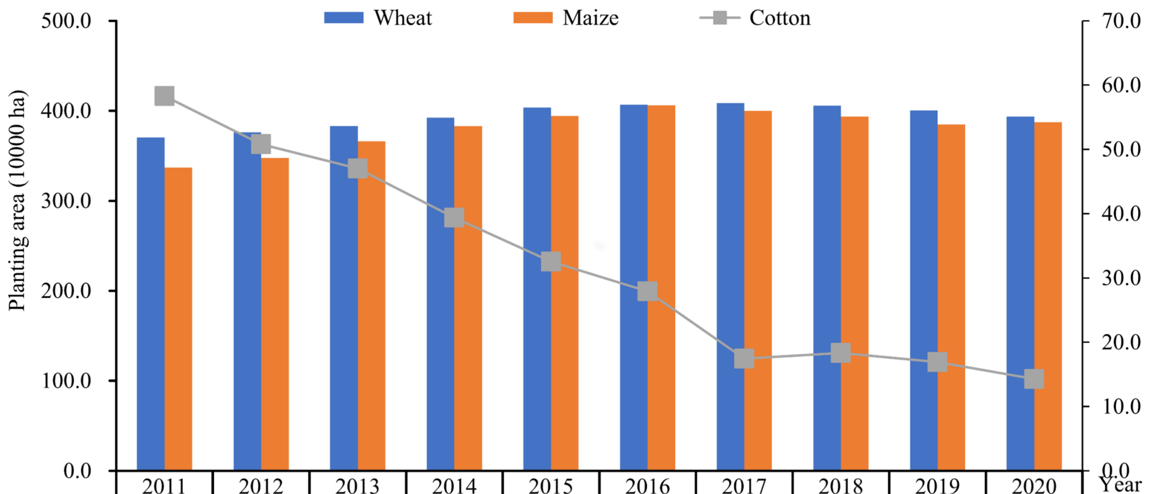
focuses on addressing issues such as inefficient stubble management, poor articulation between operational links, and weak inter-industry technological synergy, thereby improving the overall economic efficiency of cotton production. Such efforts contribute significantly to rural revitalization, industrial development, and high-quality development in the Yellow River Basin (Zhang et al., 2023c; Zhang et al., 2024).

3.1 Cotton system reform is the need to ensure food security

The primary task of rural revitalization is to ensure food security. General Secretary Xi Jinping pointed out that the Chinese people's rice bowl should always be in their own hands, and the rice bowl should be filled with Chinese food (Chang et al., 2021). As a large country with a large population, the issue of food is of paramount importance, which means that food production cannot be relaxed at any time. To guarantee food security and to stabilize and increase grain production, the two core key elements are to increase planting area and improve yields (Bagnall et al., 2021). At present, China's grain yields are already at a high level, and a sustained increase in yields is not a 1-day effort, requiring both scientific and technological innovation and favorable weather conditions. At the same time, with the accelerating urbanization of rural areas, China is facing increasing pressure to protect its arable land red line. Stabilizing and expanding the area planted with grain has become more challenging (Spiertz, 2009). For example, in Shandong Province, the total area of arable land stock from 1949 to 2020 fluctuated between 8.73 million and 6.41 million hectares, showing an overall downward trend. Given this context, where does the increase in grain acreage originate? The explanation lies in the functionality of the cropping system, which is through the macro-control and decision-making function of the cropping system (Alletto et al., 2022). The practice of stabilizing grain supply in Shandong Province in the past 10 years also fully illustrates this point. As shown in Figure 3, despite fluctuations in the wheat and corn planting areas in Shandong Province from 2011 to 2020, the overall trend remains stable with a slight increase (Xu et al., 2024a). By 2020, the province's wheat planting area had increased by 6.2% compared to 2011, while the corn planting area had risen by 14.8%. Wheat corn two increased by 0.73 million hectares. On the contrary, the province's cotton planting area was a sharp downward trend, with the province's cotton planting area of 2,143,500 acres in 2020, a decrease of 6,605,000 acres compared with 2011, and a decrease of 75.5% (Soni et al., 2023). Cotton area reduction is a domestic and foreign market supply and demand factor, but it is also closely related to the continuous enhancement of national policies aimed at regulating and guiding food production. In the context of food security, whether cotton production should be abandoned yields a negative response. Cotton as a multi-purpose crops, in addition to the production of 40% of cotton lint, but also 60% of the output of cottonseed, and cottonseed oil and protein content and soybeans are almost the same (Pemsl and Waibel, 2007; Stewart, 2021). How to ensure the coordinated development of grain and cotton in the new era still requires achieving this goal through reforming the cotton cropping system (Malézieux, 2012). It is essential to coordinate the construction of grain and cotton, cotton and feed, cotton and other diversified planting structures, thereby promoting stable cotton production and ensuring food security along with the specialization of agricultural products in Shandong (Périnelle et al., 2022).

3.2 Development of saline and alkaline land to promote the high-quality development of agriculture in the Yellow River Basin needs

Shandong, as a province along the Yellow River, contains nearly 0.6 million hectare of saline soil resources distributed across its



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Wheat	370.3	375.9	383.1	392.5	403.5	406.8	408.4	405.9	400.2	393.4
Maize	337.1	347.7	366.3	382.9	394.4	405.9	400.0	393.5	384.6	387.1
Cotton	58.3	50.8	47.0	39.4	32.5	27.9	17.5	18.3	16.9	14.3

FIGURE 3
Change of grain and cotton planting area in Shandong Province from 2011 to 2020.

nine cities. Relevant research indicates that among crops, those with higher salt tolerance include cotton, sugar beet, sunflower, green manure, sorghum, forage rape, and forage small rye (Xu et al., 2022). Among the major crops, cotton is the most salt-tolerant, drought-tolerant, and flood-tolerant crop compared to winter wheat, peanuts, soybeans, and corn. Cotton seedlings can grow normally in soil with a salt content of 0.3–0.35%. As the plant progresses through sprouting branches and leaves, flowering and fruiting, and reaching full bloom fertility, even in soil with a salt content of approximately 0.5%, cotton can still grow, develop, mature, and produce lint (Xu et al., 2023). Therefore, cotton is widely recognized as the "pioneer crop" for the development and utilization of saline-alkaline land. On 21 October 2021, President Xi Jinping emphasized during his research in the Yellow River Delta that "we should strengthen basic research on germplasm resources, arable land protection, and utilization, change the concept of breeding, and shift from the treatment of saline and alkaline land to the adaptation of saline and alkaline land plant breeding" (Mao et al., 2019). Crops selected and bred for saline resistance to adapt to saline-alkaline land changes can unlock the potential for the development and utilization of such lands. The development of saline-resistant crops to improve land productivity is highly significant for China's grain security and plays a positive role in safeguarding the nation's food supply (Cao et al., 2021). The No. 1 document issued by the Shandong Provincial Party Committee in 2022 and the action plan for the "Ten Strong Industries" of Shandong Province proposed increasing the development and utilization of saline-alkaline land and supporting the cultivation of crops such as cotton, potatoes, alfalfa, quinoa, rice, green manure, and others on saline-alkaline soils (Wang et al., 2020). According to local conditions, classification and promotion can fully leverage the salt-tolerant advantages of cotton. Through the cotton approach, saline-alkali land that meets specific criteria can be developed into arable land in a moderate and orderly manner. This not only aligns with China's national conditions and macro-policies but also plays a significant role in stabilizing provincial food production, ensuring the supply of important agricultural products, and promoting high-quality development of agriculture in the Yellow River Basin (Zhang L. et al., 2023).

3.3 Improve the efficiency of cotton planting to stabilize the plant cotton area

In recent years, under the strong policy support for maintaining the basic stability of cotton planting areas, Xinjiang's cotton production capacity has remained stable. However, the cotton planting areas in nine mainland provinces have experienced a rapid and substantial decline (Wang et al., 2017). Between 2011 and 2020, Shandong's cotton planting area exhibited a significantly positive correlation with both the cotton planting area and the net income from cotton farming (Figure 4). According to statistics from the Development and Reform Commission of Shandong Province, starting in 2013, cotton farming in Shandong began to incur losses when accounting for the cost of farmers' own labor. Without considering self-employed labor costs, cotton farming yields a slight surplus per acre, which is far less profitable than wheat or corn cultivation. By 2019, the average loss per acre of cotton planting reached 1,272.39 yuan (Yang et al., 2021). The relatively low economic returns of cotton farming are the primary factor driving the reduction in cotton planting areas.

The positive correlation between cotton planting area and benefits is further demonstrated through a survey analysis of the comprehensive benefits of cotton fields under different cotton cropping systems in the three regions: Binzhou City, Dezhou City, Xiajin County, and Jining City, Jinxiang County, from 2016 to 2019 (Figure 5). As a market-oriented garlic and cotton two-maturing high-efficiency, the Southwest Shandong cotton area is significantly influenced by fluctuations in garlic

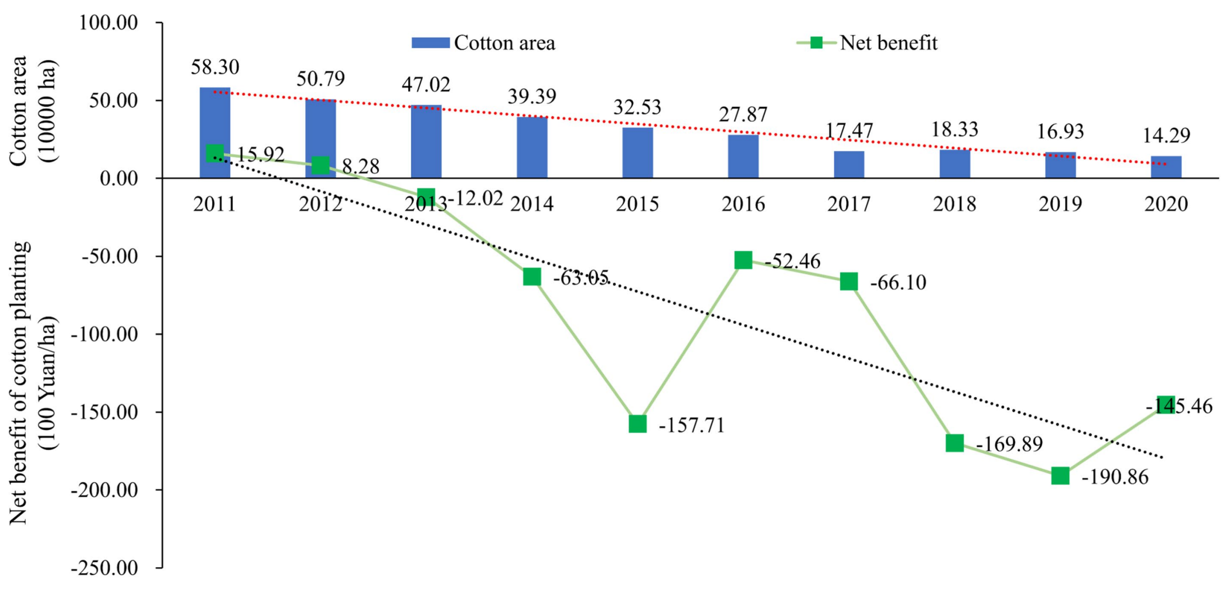
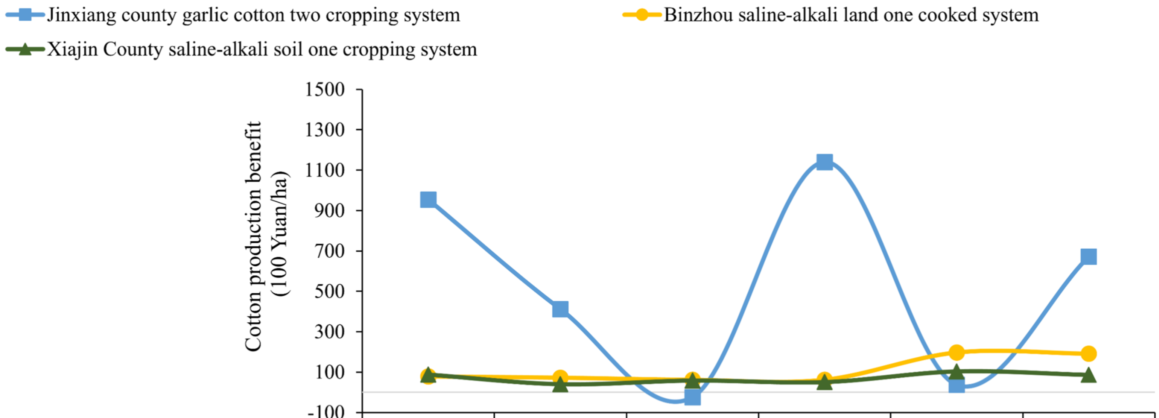
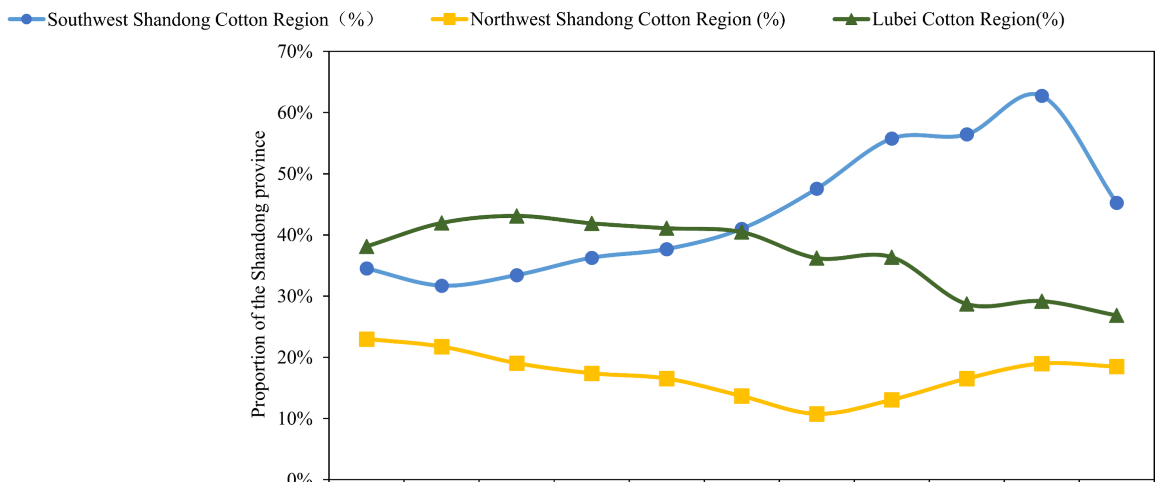


FIGURE 4
Comparison of cotton planting area and income in Shandong Province from 2011 to 2020.



	2016	2017	2018	2019	2020	2021
Jinxiang county garlic cotton two cropping system	954	411.81	-24.075	1139.835	37.5	671.49
Binzhou saline-alkali land one cooked system	78.9	72.75	62.145	62.55	197.325	191.31
Xiajin County saline-alkali soil one cropping system	87.84	40.305	58.29	50.82	103.23	86.235

FIGURE 5
Net income of cotton fields in different cotton growing areas of Shandong Province from 2016 to 2021.



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Southwest Shandong Cotton Region（%）	34.53%	31.72%	33.44%	36.28%	37.7%	41.01%	47.56%	55.76%	56.45%	62.74%	45.25%
Northwest Shandong Cotton Region (%)	23%	21.76%	19.06%	17.4%	16.54%	13.69%	10.78%	13.07%	16.53%	19%	18.49%
Lubei Cotton Region(%)	38.13%	41.96%	43.11%	41.9%	41.1%	40.47%	36.22%	36.38%	28.73%	29.2%	26.86%

FIGURE 6
Change of proportion of cotton planting area in three major cotton regions of Shandong Province from 2011 to 2021.

market prices. Although the inter-annual unit area of cotton planting benefits fluctuations, its overall benefit remains considerably higher than that of the single-maturing cotton system. For instance, in 2019, the net income per mu reached 0.11 million yuan, over 18 times greater than the single-maturing cotton system (Xu et al., 2024b). Consequently, since 2012, the proportion of cotton planted in the southwest Shandong region has been on the rise (Figure 6). In 2016, the cotton planting area in southwestern Shandong surpassed that of northern and northwestern Shandong for the first time. By 2019, the cotton planting area in southwestern Shandong accounted for 62.74% of the province's total cotton planting area, exceeding 60% of the provincial cotton planting area (Yunfeng et al., 2024). This fully demonstrates that the development of efficient cotton cropping systems and the improvement of comprehensive income from cotton planting are fundamental approaches to stabilizing the development of cotton production (The 4th International Symposium on Theoretical Innovation and High-Quality Development of Cooperative Economy Bengbu A P, China 2023, 2023).

4 Shandong cotton cropping system reform way

Shandong's cotton cropping system reform should fully leverage its inherent advantages and conditions, accelerate efforts to address the industry's shortcomings, seize market and policy opportunities in the new era, mitigate the threats faced, pursue a path of connotative development, and continuously enhance the industry's competitiveness in the market (Wang, 2024). For different ecological cotton areas in Shandong, the following approaches are proposed.

4.1 Garlic (wheat) after stubble live early cotton light and efficient cotton system

Southwest Shandong's two-maturing cotton planting area faces challenges such as low mechanization levels, high labor requirements, and significant input costs. To accelerate the promotion and application of garlic (wheat) after the direct seeding of early maturity cotton light and efficient cotton system, this technology introduces "five changes" compared to traditional methods: first, replacing spring cotton varieties with short-statured, high-quality early-maturing cotton varieties; second, transitioning from seedling transplantation to mechanical precision direct seeding; third, replacing the "sparse planting large trees" cultivation model with dense dwarf cultivation; fourth, shifting from intensive management to simplified management (eliminating inter-seedling and seedling care, pruning, and adopting centralized fertilization, etc.); and fifth, changing from segmented harvesting to centralized (mechanical) harvesting (Yang et al., 2022). This technology realizes the integration of agricultural machinery and agronomy, as well as the matching of high-quality seeds with advanced cultivation methods. Demonstration applications have shown that in normal years, the seed cotton yield using this technology is approximately 250 kg per mu, slightly lower than the yield of conventional spring cotton. However, labor costs are reduced by over 40% per acre, and physical and chemical inputs (pesticides, fertilizers) are decreased by more than 30% per acre. This results in cost savings and efficiency improvements exceeding 700 yuan per acre (Zhang et al., 2016).

4.2 Cotton, garlic, and pepper three-win efficient cotton system

Southwest Shandong's cotton garlic pepper planting pattern faces significant challenges in the pepper market due to price fluctuations and natural risks such as susceptibility to waterlogging and crop rotation limitations. To address these issues, Wang et al. (2022) proposed the adoption of a garlic–cotton–pepper "two white and one red" ternary composite cropping system. This system builds upon the traditional garlic–cotton planting model by incorporating peppers, leveraging cotton's advantages of flood resistance and tolerance to continuous cropping. The intercropping involves planting cotton in strips between rows of peppers. Specifically, garlic is planted in October of the first year, followed by cotton and chili peppers in April of the second year. Garlic and cotton coexist for approximately 1 month before the garlic is harvested in June. Cotton and peppers continue to grow together until late September or early October when they are harvested (Wang J. et al., 2021). The model can not only effectively mitigate the market risk following chili monoculture and prevent yield losses caused by flooding or disaster risks but also achieve "one fertilizer for dual use," "one water for dual use," "one film for dual use," and "one pesticide for dual use." This reduces the input of fertilizers, pesticides, and plastic films, lowers production costs, and increases per-hectare income to over 15 ten thousand yuan (Wang et al., 2007).

4.3 Short-season cotton light green filmless cultivation cotton system

The lack of freshwater resources in the Yellow River Delta cotton area and the traditional single-maturing planting pattern led to issues such as rotten bolls, severe early-season failure, scattered boll distribution, and difficulties in centralized harvesting. Therefore, the promotion and application of short-season cotton varieties have been prioritized, involving late spring sowing, reasonably dense planting, non-film cultivation, simplified pruning, and centralized boll formation, all of which constitute the core of the short-season cotton light green simplified non-film cultivation technology (Cui, 2011). This is conducive to realizing centralized boll maturity, laying the foundation for mechanized harvesting while effectively preventing residual film pollution (Xu et al., 2024a). At the same time, late spring sowing extends the cotton planting period, increasing the use of natural rainfall for cotton cultivation. This approach addresses the issues of saline soils in regions with freshwater scarcity, enabling moisture-free sowing and improving barren land conditions, thereby significantly increasing the potential for successful saline cotton cultivation (Wang et al., 2023).

4.4 Saline and alkaline cotton forage (green manure) two-crop combined with the use of cotton cropping system

North Shandong and Northwest Shandong, as saline-alkaline cotton-growing regions, face issues such as a low replanting index, poor overall efficiency, and winter land degradation. To address these challenges, it is essential to accelerate the promotion of a new planting model that integrates cotton with forage (or green manure) crops. Specifically, this involves planting winter crops (such as ryegrass, winter rape, hairy vetch, or alfalfa, among other suitable forage or green manure varieties) in November of the first year. These crops are harvested in the spring or early summer of the following year, after which the short-season cotton is directly sown into the stubble fields (Pemsl and Waibel, 2007; Zhang et al., 2021; Guo et al., 2023; Zhang et al., 2023b). This cropping system transforms the single spring cotton planting in saline land into a dual-crop rotation of pasture (green manure) and cotton, enabling the full utilization of winter and spring idle fields and significantly enhancing land use efficiency (Pemsl, 2006; Sun et al., 2022). If the winter crop is used as pasture, the average income of forage per acre of land can exceed 700 yuan. If the pasture market is unfavorable, it can be directly utilized as green manure and incorporated into the soil to improve soil fertility. This practice not only replaces part of the fertilizer required for the subsequent cotton crop but also enhances the physical and chemical properties of the soil while reducing fertilizer inputs and production costs (Zhang et al., 2022). The vigorous development of salt-tolerant cotton has been included in Shandong Province's "Ten Strong Industries" plan and was documented in the No. 1 Document of the Shandong Provincial Party Committee in 2022. Promoting the application of the cotton system contributes to the construction of the Yellow River Delta saline and alkaline high-quality cotton industry belt, which holds significant potential and promising prospects for future development (Wang D. et al., 2021).

4.5 Cotton peanut wide intercropping green cotton system

For Ruzhong, the East Lu hilly drylands, and sandy soils, issues such as low efficiency in cotton and peanut monoculture systems, peanut intolerance to heavy stubble, and other challenges have been addressed by accelerating the promotion and application of cotton–peanut alternate intercropping technology (Li et al., 2023). The technology has four significant features: First, the sowing widths for cotton and peanuts are equalized to facilitate rotational planting and mechanized operations in subsequent years minimizing crop interference and ensuring balanced and stable production; second, it fully leverages the lateral line effect of cotton, resulting in an average yield increase of 10–20% compared to monocropping under equivalent conditions; third, it enhances ventilation and light penetration within the third is to improve the ventilation and light penetration of cotton planting belt, reducing boll rot and promoting earlier fiber maturity, thereby improving fiber quality; fourth, it capitalizes on the nitrogen-fixing properties of the peanut root system. Through cotton–peanut rotation, it reduces nitrogen fertilizer application in the cotton planting belt by 20–30% in the following year without compromising cotton yield, achieving a reduction in input while maintaining output (Li L. et al., 2021). Field trials conducted in 2021 across cotton-growing regions, including Xiajin County in Dezhou, Dongping County in Taian, and Changyi City in Weifang, demonstrated that this intercropping system yielded 368 kg of sub-cotton per acre and 421 kg of peanut pods, significantly surpassing the yields of pure cropping systems (Li X.-F. et al., 2021). The yield of 421 kg of peanut pods is significantly higher than the economic benefits of pure cotton or pure peanut. This cropping system effectively leverages the complementary characteristics of cotton and peanuts, optimizing spatial utilization above ground, root system interactions below ground, and nutrient allocation throughout the growing season. By achieving high yields for both cotton and peanuts while reducing fertilizer and pesticide inputs, this system represents a novel approach to green and efficient crop production with significant potential for widespread adoption (Ma et al., 2024).

4.6 Efficient cropping system and business system fit supporting

Implementing an appropriate cropping system and a large-scale mechanized production and management system is the fundamental solution for developing cotton production in Shandong Province (Zhi et al., 2019). Based on research conducted at the Lijin County Chunxi Agricultural Machinery Farmers' Cooperative (saline cotton), Wudi County Green Wind Agricultural Company (saline cotton feeding two-maturing cropping system), and other cotton planting entities covering over 1,000 acres, it has been demonstrated that the entire lifecycle of cotton—from sowing, field management to harvesting—has achieved near-complete mechanization. The average cost of materials and chemicals per hectare is 3,735 yuan, representing a 48.1% reduction compared to traditional small-scale farming practices (Jayakumar and Surendran, 2017). The labor cost is 3,375 yuan per hectare, which reflects a 66.2% decrease in labor costs compared to small-scale farmers. Overall, mechanized production and operation systems result in cost savings and efficiency gains exceeding 10,000 yuan per hectare (Singh et al., 2015).

In the concurrent development of the cotton system and business system, emphasis should be placed on enhancing the quality of cotton throughout the production process. Pre-production should prioritize the genetic quality of cotton by selecting high-quality varieties with fiber lengths of at least 30 mm and strength reaching over 30cN/tex (Lv et al., 2023). During production, the focus should be on improving production quality through large-scale mechanized and standardized planting to enhance the consistency of fiber quality. Post-production should emphasize processing quality by implementing categorized picking, drying, sales, and collections to prevent mixing grades and prices while advocating for pricing based on quality.

5 Shandong cotton system reform policy recommendations

As a critical agricultural product, cotton has consistently received support at the national level (Cerasoli et al., 2021). At present, the cotton production support policy in Shandong's cotton-growing regions primarily originates from the national government. In 2017, the State Council issued the "Guiding Opinions on Establishing Grain Production Functional Areas and Important Agricultural Production Protection Zones." Subsequently, in 2020, both the state and provincial governments introduced policies aimed at ensuring the supply of key agricultural products (Meng, 2022). Shandong has delineated a 4-million-acre cotton production protection zone, proposing a series of supporting policies and measures. However, there is currently no specific financial support policy. The cotton production support policy issued by the Ministry of Agriculture and Rural Affairs and the Ministry of Finance in 2021 (covering the period 2020–2022) is nearing expiration. Therefore, it is recommended that the continuity, stability, and timeliness of the cotton production support policy be maintained, and preliminary research on the policy and plan accordingly should be conducted as early as possible (Meng and Yuhua, 2025). Early release of the policy will ensure seamless integration between the old and new policies thereby further boosting the confidence of cotton farmers planting cotton and promoting the restorative growth of cotton production and high-quality development. In terms of prioritizing support, it is recommended to focus on the following key directions (Jain and Jain, 2020):

5.1 Support for new cotton cropping system and large-scale business model fit supporting

For the distinct characteristics of the three major cotton-growing regions in Shandong, it is essential to enhance policy guidance. This includes promoting the integration and innovation of new cotton technologies through intensive efforts, as well as advancing their application. In addition, there should be a focus on strengthening the mechanization of cotton planting techniques, particularly by increasing R&D and promoting cotton pickers suitable for small-and medium-scale operations in Shandong. Furthermore, large-scale cotton farming should be encouraged. To accelerate progress, the construction of the cotton area, combining land consolidation with agricultural and mechanical technologies, should be prioritized. This will facilitate the alignment of cropping systems and business models, ultimately fostering a new type of efficient cotton production and operation system.

5.2 Support non-cereal cultivated land suitable for cotton planting industrial zone construction

In the context of the national "stable grain and oil" policy, cotton should be fully utilized for its drought-resistant and saline-alkaline-resistant characteristics, and cotton production should be concentrated in non-grain-field areas through policy guidance and institutional innovation. At the same time, the construction of a high-quality cotton industry belt with special characteristics in the Yellow River Delta was initiated, and a management system integrating agricultural machinery and agronomy should be explored, thus promoting the sustainable development of cotton production (Ruis and Blanco-Canqui, 2017). "Hidden cotton in the land" can effectively stabilize the cotton planting area, enhance cotton production, and provide robust support for stabilizing the supply of key agricultural products. This approach also contributes to the ecological protection and high-quality development of the Yellow River Basin (Jaworski et al., 2023).

5.3 Support cotton regional income insurance and catastrophe insurance

With reference to the research findings of relevant domestic experts and scholars, combined with the issues identified in the pilot cotton target price insurance in Shandong Province, it is recommended to draw on the U.S. experience. First, regional income insurance should be implemented at the county level to support the protection of cotton planting (Chen et al., 2021). Regional income insurance can effectively address the diversified risk protection needs of cotton farmers, reduce the costs of investigation and loss determination, minimize moral hazards, alleviate financial burdens, and ensure that farmers easily understand and accept the mechanism, thereby enhancing its feasibility (Abalos et al., 2022). Second, a catastrophe risk dispersion mechanism should be established. Given the natural risks associated with Shandong's cotton-growing areas, a comprehensive catastrophe risk dispersion mechanism should be developed, comprising reinsurance, catastrophe risk reserves held by insurance companies, and government-supported catastrophe risk funds. This approach will resolve the issue of agricultural insurers being unable to afford payouts after a catastrophe, ensuring the sustainability of agricultural insurance programs (Qin et al., 2022).

6 Conclusion

Shandong, as one of the key cotton-producing regions in China, faces a continuous decline in cotton production. Reforming the traditional cotton cropping system to stabilize cotton production is of great significance. Promoting the cotton crop system reform should adopt a connotative development path focused on quality improvement while maintaining scale. In terms of basic principles, it is essential to adhere to adopting measures to local conditions, prioritizing benefits, balancing quantity and quality, integrating nutritional complementarities, leveraging complementary advantages (constructing a plant type of "one tall and one short," root systems of "one deep and one shallow," adaptability to "one yin and one yang," and fertility for "one early and one late" group structures), and upholding sustainable development. Regarding regional layout and primary directions, the southwestern Shandong cotton region should fully utilize its regional light and heat resource advantages, optimize the traditional cotton and garlic (wheat) two-maturing technology process, and steadily expand the planting area of stubble-followed short-season cotton; the northern Shandong cotton region (Yellow River Delta cotton area) should leverage Yellow River Delta, Bohai Bay saline and alkaline resources to construct a high-quality cotton industry belt and strengthen the demonstration of no-film double-cropping cotton with cotton straw returning to fields and cotton feed (green manure); the northwestern Shandong cotton region should take advantage of sandy and alkaline land along the Yellow River, dryland resources, and comparative efficiency advantages for cotton planting thus accelerating the expansion of double-cropping areas for cotton and peanuts (yam, green manure); other central and eastern Shandong cotton regions should expand dry and thin, sandy cotton peanut double-cropping areas. In the context of policy support, while maintaining policy stability and continuity, emphasis will be placed on supporting the integrated innovation and demonstration in cotton cropping systems, the development of high-quality cotton industry belts in saline-alkali regions, as well as regional income insurance and catastrophe insurance for cotton.

In general, Shandong has a relatively diversified planting system (such as cotton and garlic, cotton–green manure, and cotton–peanut rotation), as well as adaptable farming management agronomic system; especially in the saline and alkaline land, sand and other marginal land on the efficient use of resources has accumulated rich experience. These technologies and systems are not only effective in guaranteeing stable yields, improving cotton quality, and promoting green and sustainable development but also have good replicability and popularization. With the accelerated process of agricultural modernization, Shandong's cotton production technology system can provide useful reference for China's other cotton areas, especially in improving land use efficiency, the development of composite planting patterns, and promote mechanization and intelligent management has a wide range of promotional value. At the same time, it also provides

Chinese experience and development paths for other cotton growing areas in the world that also face challenges such as limited land resources or saline and alkaline land management and contributes to the green transformation and high-quality development of global cotton industry.

Author contributions

YS: Formal analysis, Methodology, Data curation, Writing – original draft. XW: Investigation, Data curation, Writing – original draft, Formal analysis. ZW: Writing – original draft, Supervision, Data curation, Formal analysis. LG: Validation, Writing – review & editing, Conceptualization, Funding acquisition. ZZ: Visualization, Conceptualization, Validation, Writing – review & editing, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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