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Resolved concerns after 28 years of *Bt* cotton in China

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Abstract

Bacillus thuringiensis Berliner (*Bt*) cotton was widely grown in China from 1997. Since then, it has resulted in many misunderstandings and concerns about *Bt* cotton. However, extensive research and practical experience over the past 28 years in China have led to the resolution of many of these concerns. This short review explores how the concerns has been resolved, and provides valuable insights for the future utilization of genetically modified products.

Keywords *Bt* cotton, Concerns, Resolution

Bacillus thuringiensis Berliner (*Bt*) cotton has been widely grown in China Since 1997, with a significant increase in adoption over the years. It reached 3.8 million ha in 2007, accounting for 69% of the national cotton planting area (Ho et al., 2009), while 95% of the total cotton area was covered with *Bt* cotton in 2018 (Lu, 2019). Since 1997, genetically modified organisms (GMO) have attracted much attention and controversy, especially many misunderstandings and concerns about *Bt* cotton. Key concerns and misunderstandings surrounding *Bt* cotton mainly include variability in efficacy, susceptibility to premature senescence, pest resistance, yield disadvantage, and impacts on non-target pests. Extensive research and practical experience over the past 28 years in China have led to the resolution of many of these initial concerns and misunderstandings. This short review aims to explore the evolution of concerns and misunderstandings surrounding *Bt* cotton, drawing upon a thorough examination of relevant literature from both domestic and international sources. By synthesizing existing knowledge and insights, this review seeks to provide a comprehensive overview of the issues at hand and offer valuable insights for the future utilization and management of genetically modified (GM) products. Additionally, the review will highlight both the challenges faced and the solutions developed in the cultivation of *Bt* cotton, serving as a valuable resource for informing best practices moving forward.

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Variability in *Bt* cotton efficacy

The efficacy of transgenic *Bt* cotton against target pests varies with plant age, plant part, and even under different environmental conditions (Dong et al., 2007). This spatiotemporal variability in *Bt* cotton efficacy can potentially precipitate outbreaks of bollworm and other target pests, leading to great loss of yield and benefits. However, the 28-year observation of Bt cotton cultivation in China has indicated that there are indeed spatiotemporal variations in Bt cotton efficacy to target pests, but there have never been serious problems or losses due to the variability in cotton production in China. This resilience can be attributed to several key factors: first, the implementation of tailored chemical control strategies specific to *Bt* cotton in China's cultivation regions; second, the sustained efficacy through long-term genetic selection, ensuring a relatively stable expression of *Bt* cotton's effectiveness against insect pests; and third, the inherent compensatory growth capacity of cotton plants, which can mitigate losses in fruiting sites caused by pests (Zhang et al., 2022).

Yield disadvantage of *Bt* cotton

In China, transgenic *Bt* cotton stands as the primary GM crop cultivated on a large commercial scale. Field trials and surveys across various provinces have demonstrated that *Bt* cotton varieties contribute to significant net revenue gains for farmers by lowering production costs. However, the observed yield increment compared with non-*Bt* cotton varieties, when coupled with effective management practices and pesticide applications, has been found to be marginal (Dong et al., 2004). This initial understanding was subsequently challenged by the introduction of high-yielding *Bt* cotton varieties developed through genetic breeding efforts. Recent field trials conducted in 2021 and 2022 illustrated that prominent *Bt* cotton varieties such as SCRC28 and K836 exhibited a 53.4% and 58.3% increase in lint yield compared with earlier *B*t cotton varieties DP 33B and a 45.7% and 50.2% increase over SGK 321 (Table 1). The substantial enhancement in lint yield of these contemporary *Bt* cotton varieties can be attributed to notable improvements in boll weight (15.4%–29%), boll density (11.2%–19.9%), and lint percentage (4.9%–9.9%). These findings underscore that the yield potential of *Bt* cotton is not unduly constrained by the presence of the *Bt* gene. By leveraging genetic enhancements to simultaneously enhance yield, quality, and pest resistance, the continuous improvement of *Bt* cotton's agronomic traits remains entirely feasible.

Furthermore, over the past 28 years since the introduction of *Bt* cotton, there has been a substantial increase in average yields. In 1996, before the adoption of *Bt* cotton, the average lint yield of the nation was approximately 890.1 kg·ha^{-1}. By 2023, it had impressively risen to 2 014.9 kg·ha^{-1}, representing a 1.26-fold increase (Feng et al., 2022). The widespread adoption of *Bt* cotton has likely played a significant role in the substantial yield increase of cotton, providing indirect evidence to refute arguments claiming a yield disadvantage of *Bt* cotton.

Susceptibility of *Bt* cotton to premature senescence

Premature senescence is a process in which the life of a whole or partial plant terminates prematurely within the available growing season, which usually causes great cotton yield loss ranging from 10% to 30%. Premature senescence had been occurring on an increasing scale since *Bt* cotton was introduced for commercial production in China. Initially, it was believed that premature senescence was an inherent characteristic of *Bt* cotton, possibly linked to the *Bt* gene. Moreover, *Bt* cotton is sensitive to potassium deficiency, and the Bt toxin proteins may affect its potassium uptake (Tian et al., 2008). However, subsequent research and practice have shown that the number of squares and young bolls lost due to pests in Bt cotton has been greatly reduced relative to those in non-Bt cotton (Chen et al., 2016). A recent study has shown that the introduction of *Bacillus thuringiensis* gene doesn't necessarily hinder the potassium use efficiency (Wang et al., 2022). The imbalance between sink and source, caused by *Bt* cotton carrying too many bolls, ultimately leads to premature senescence. Moreover, it has been found that removing early fruiting branches in *Bt* cotton delays leaf senescence (Chen et al., 2018). Therefore, the susceptibility of *Bt* cotton to premature senescence is not directly caused by the introduction of *Bt* genes, and it is not an inherent characteristic of *Bt* cotton. Many new *Bt* cotton cultivars that are less prone to premature senescence have been developed, further clarifying this traditional misconception.

Table 1 Yield and yield components of *Bt* cotton varieties bred at different time points

Variety	Boll density /(m^{-2})	Boll weight /g	Lint percentage /%	Seedcotton yield /(kg·ha^{-1})	Lint yield /(kg·ha^{-1})
DP33B[a]	79.18b	4.51d	37.5c	3 571c	1 339d
SGK321	74.83b	4.82c	39.1b	3 607c	1 410c
SCRC21	89.49a	5.28b	40.8ab	4 725b	1 928b
SCRC28	89.69a	5.56ab	41.2a	4 987ab	2 055ab
K836	88.76a	5.82a	41.0a	5 166a	2 118a
Source of variance					
Year (Y)	0.005 0	0.045 0	ns	0.035 0	0.021 5
Variety (V)	< 0.000 1	< 0.000 1	< 0.000 1	0.025 0	0.001 5
Y×V	ns	ns	ns	ns	ns

[a] DP33B, developed by the USA Delta and Pine Land Company in 1993, incorporates the *Bt* gene for pest resistance. SGK321, SCRC21, SCRC28, and K836 are *Bt* cotton varieties bred in China in 2002, 2005, 2007, and 2012, respectively. The field trials were conducted in Linqing City, Shandong Province, with a planting density of 60 000 plants per hectare and following standard local agronomic practices

Resistance of target pests to *Bt* cotton

The continuous large-scale planting of *Bt* cotton has created strong selection pressure on target pests, which would gradually induce resistance and threaten the sustainable utilization of Bt cotton (Xiao et al., 2019). Long-term monitoring has shown that the sensitivity of cotton bollworm populations in cotton fields in China to *Cry1Ac* has decreased, leading to early resistance (Tabashnik et al., 2013). However, no failure of *Bt* cotton in controlling cotton bollworm has been found in practice (Zhang et al., 2019). At present, *Bt* cotton still maintains a high level of insect resistance efficiency, and there has been no failure in the control of *Bt* cotton target pests in production. This is thanks to the intercropping or adjacent planting of cotton with corn, peanuts, soybeans, or vegetables. These host crops have played a natural shelter role, delaying the growth of *Bt* resistance to cotton bollworm in the field (Quan et al., 2023). The *Cry1Ac* transgenic cotton has been applied in China for more than 28 years and still dominates in planting area and continue to play a role.

Outbreaks of non-target pests

There are over 300 types of pests identified in the cotton field. The adoption of *Bt* cotton has proven effective in controlling Lepidoptera target pests like the cotton bollworm. However, a significant reduction of more than 50% in pesticide has been observed in cotton fields (Wu et al., 2018). This reduction has resulted in a notable increase in the occurrence of non-target pests, such as stink bugs (Zhang et al., 2018). Initially, this rise in non-target pests posed a major concern for cotton pest control in China. Fortunately, the reduction in pesticide use in cotton fields has also increased the number of natural enemies in the field, suppressing the population occurrence of non-target pests such as cotton aphids (Wu et al., 2018). Additionally, Chinese scientists have also established a technology for blind stink bug control by luring and killing adults of blind stink bug and cutting off seasonal host transfer pathways, effectively controlling the occurrence the non-target pests (Jiang et al., 2015). Although concerns regarding the damage caused by non-target pests were initially raised, they are alleviated by the combination of increased natural enemies and targeted pest control strategies.

In summary, the successful 28-year application of *Bt* cotton in China has addressed concerns and provided references for other GM crops. However, controversies surrounding *Bt* cotton and GMOs have been fueled by a lack of understanding and misinformation. Objective assessment of GMO technology benefits and risks, along with transparent communication and education, is crucial for informed decision-making and policy development.

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