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Biotechnological Innovations Shaping the Future of Insect-Resistant Crop Development

S Kingslee Sujan[1], Shashikala B[2], Sachin R Kondaguri[3], Girish Patidar[4] and Sanjana Tagde[5]

Abstract: -

Biotechnological crops, particularly those genetically modified (GM) with *Bacillus thuringiensis* (Bt) endotoxins for insect resistance, have been commercially cultivated and increasingly adopted across numerous countries over the past 14 years. This review highlights the current status of insect-resistant transgenic crops and addresses common concerns regarding their durability and potential loss of effectiveness due to the evolution of insect resistance. The discussion covers both the currently deployed Bt crops and new candidates progressing from research and development toward commercial approval. Future directions and prospects for biotechnology-based insect management are also explored, including the use of stacked resistance genes, modified Bt toxins, vegetative insecticidal proteins, lectins, and intrinsic plant defense mechanisms, along with emerging innovative strategies. Furthermore, the review evaluates the benefits and potential risks of GM insect-resistant crop adoption, particularly focusing on implications for developing nations and resource-limited smallholder farmers.

Introduction:

Beyond genetically modified (GM) crops, the term "biotech crops" encompasses all plants developed using modern biotechnological tools, including mutagenesis and marker-assisted breeding. However, in this review, the term specifically refers to GM

S Kingslee Sujan[1], Shashikala B[2], Sachin R Kondaguri[3], Girish Patidar[4] and Sanjana Tagde[5]

[1]M.Sc. Scholar, Department of Molecular Biology and Biotechnology, National Institute for Plant Biotechnology, Indian Agricultural Research institute

[2]Ph.D Research Scholar, Division of Entomology, ICAR-IARI, New Delhi

[3]M.Sc. Scholar, Department of Plant Pathology College of Agriculture, Mandya, University of Agricultural Sciences, Bangalore

[4]Assistant Professor, Faculty of Agriculture, Medicaps University, Indore

[5]M.Sc. Scholar, Department of Biochemistry, College of Basic Science and Humanities, Punjab Agricultural University, Ludhiana

crops. To meet the growing global demand for food and feed in the coming decades, it is essential to substantially increase agricultural productivity, particularly in developing regions such as Asia, Africa, and Latin America. Achieving this goal in an environmentally sustainable and economically viable manner requires enhancing yields primarily on existing farmlands. One of the most effective strategies to raise yields is by reducing pest-related losses, which currently account for an estimated 14–25% of total global agricultural production. These losses are especially severe in food crops due to less effective pest management compared to cash crops. In 2003, pest-induced yield reductions were reported as 37% in rice, 40% in potatoes, 31% in maize, 26% in soybean, and 28% in wheat. Additionally, pesticide usage costs exceed US $10 billion annually, and their negative impacts such as effects on non-target species and harmful chemical residues further underscore the need for more sustainable crop protection strategies.

GLOBAL STATUS OF BIOTECH CROPS

Commercial cultivation of biotech crops began in 1996, and by 2009, their global production area had expanded to 134 million hectares across 25 countries. Although nine industrialized nations continued to cultivate a larger share of genetically modified (GM) crops compared to the 16 developing countries, the gap was steadily narrowing as more farmers in developing regions began to experience the direct advantages of adopting biotech crops. This trend made biotech crops the most rapidly adopted agricultural technology in history, with an average annual growth rate of around 8%.

The widespread adoption can be attributed to the significant economic and environmental benefits reported by farmers in both developed and developing nations. According to James (2009), by that year, 725 approvals for commercial cultivation had been issued for 155 biotech events spanning 24 different crops. Of the approximately 14 million farmers growing biotech crops globally, over 90% were small-scale, resource-poor farmers most of whom cultivated *Bacillus thuringiensis* (Bt) cotton, followed by Bt maize.

Adoption of Bt Crops in developing countries

In India, *Bacillus thuringiensis* (Bt) cotton was introduced in 2002, when about 54,000 farmers cultivated it on 50,000 hectares (James, 2003). By 2009, the area under Bt cotton had expanded dramatically to 8.4 million hectares, grown by 5.6 million small and resource-poor farmers. Notably, 90% of these farmers replanted Bt cotton, which accounted for approximately 87% of the country's total cotton area. A comparable trend was observed in China, where 7.1 million farmers cultivated Bt cotton on 3.8 million hectares, representing 69% of the nation's total cotton production area in 2008. On average, Bt cotton growers achieved a 10% increase in yield, reduced pesticide applications by 60%, and earned an additional $220 per hectare. In Argentina and Brazil, biotech adoption was largely focused on herbicide-tolerant soybean. However, Argentina also cultivated Bt maize and Bt cotton on 2.8 million hectares (valued at $482 million) and 0.4 million hectares (earning $19.7 million), respectively, while Brazil planted Bt cotton on approximately 0.5 million hectares, primarily on large-scale farms.

In South Africa, both Bt cotton and Bt maize are widely cultivated, with Bt cotton accounting for over 85% of the national crop. Uniquely, South Africa also grows white Bt maize for food about 0.9 million hectares, representing 67% of the country's total maize area. By the end of 2009, China had also approved Bt rice and genetically modified (GM) phytase maize for commercial cultivation. These publicly developed crops are expected to have significant future impacts on China's food security, livestock nutrition, and national policies concerning GM crops.

Benefits from Bt crops

To date, more than 200 distinct *Bacillus thuringiensis* (Bt) proteins have been identified across different bacterial strains, each exhibiting varying toxicity levels toward specific insect species. Bt proteins have been utilized as safe biopesticides for over four decades; although relatively expensive, they are highly specific to target pests and non-toxic to vertebrates, unlike synthetic chemical pesticides. Bt transgenic crops share this selectivity, effectively targeting only specific insect pests without harming beneficial organisms. In contrast, synthetic insecticides often kill both pests and their natural predators. Bt crops are particularly advantageous for smallholder farmers because they require minimal equipment, technical expertise, and pesticide handling, thereby reducing farmers' exposure to toxic chemicals, especially in cases where manual sprayers are used. For example, Bt maize has significantly reduced losses caused by rootworms and stem borers without relying on hazardous organophosphate insecticides. It is estimated that Bt maize can replace 40–50% of the insecticides currently used on conventional maize. Similarly, while conventional cotton may require 2–30 pesticide applications per season, Bt cotton drastically reduces this need, improving environmental safety and reducing health risks for farm laborers particularly in developing countries such as China, where pesticides are frequently applied using knapsack sprayers. Another notable benefit of

Bt maize is its reduced accumulation of mycotoxins produced by opportunistic fungi that infect insect damaged kernels. Since Bt maize produces healthier, undamaged cobs, it is less susceptible to fungal infection and mycotoxin contamination, which can be harmful or even fatal to humans and livestock. The improved yield and quality of Bt crops result in higher farm incomes for both smallholders and large-scale producers. Importantly, extensive studies have reported no evidence of adverse effects on non-target insect populations in Bt crop fields.

Insect resistance to Bt toxins

The extensive cultivation of Bt crops inevitably heightens the risk of target insect populations developing resistance. Interestingly, Bt technology has remained effective longer than expected when compared to the typical timeframe in which resistance emerges against conventional neurotoxic insecticides. This durability persists despite Bt crops exerting one of the strongest known selection pressures for resistance. Several factors explain this delayed resistance development: (i) resistant individuals, particularly those identified under laboratory conditions, often exhibit reduced fitness and fail to survive in the field; (ii) the frequency of resistance alleles within insect populations is initially very low; (iii) resistant alleles are diluted through mating with susceptible insects from non-Bt fields or alternate host plants; and (iv) commercial Bt crops deliver a sufficiently high toxin dose to eliminate most heterozygous individuals before they can reproduce. To further delay resistance development, the "refuge strategy" has been implemented either by maintaining designated non Bt refuges on large commercial farms or through natural refuges in smallholder systems where intercropping and mixed cropping are common. Another effective approach involves pyramiding multiple *Cry* genes within a single crop, providing protection against a wider range of insect species. For instance, Bt cotton expressing both *Cry1Ac* and *Cry2Ab* confers resistance to *Helicoverpa zea*, *Spodoptera frugiperda*, and *Spodoptera exigua*, as these toxins bind to different receptors, requiring multiple genetic mutations for insects to develop resistance.

Nevertheless, since 2005, field cases of resistance have begun to surface. The fall armyworm (*S. frugiperda*) developed resistance to *Cry1F* maize in Puerto Rico, leading to the voluntary withdrawal of this product. In the United States, reports suggest that the cotton bollworm (*H. zea*) is showing early signs of resistance to *Cry1Ac* in both cotton and maize. Although these instances remain isolated, they suggest that widespread resistance to single-gene Bt crops may emerge in the near future. Laboratory studies have also demonstrated that *Heliothis virescens* can develop resistance to multiple *Cry* proteins. However, such laboratory findings often fail to translate directly to real-world conditions, as field environments impose additional ecological and fitness constraints that are difficult to replicate in controlled experiments.

Future Prospects of Genetically Modified (GM) Pest Control

The future of GM pest control lies in developing more sophisticated, sustainable, and integrated biotechnological strategies to manage insect pests while minimizing environmental and health risks. Advances in molecular biology, genomics, and synthetic biology are paving the way for next-generation pest-resistant crops that go beyond the traditional *Bacillus thuringiensis* (Bt) systems. Future approaches may include stacking multiple resistance genes, utilizing novel insecticidal proteins, and employing RNA interference (RNAi) based technologies that specifically silence vital pest genes without harming beneficial organisms. Genome editing tools such as CRISPR/Cas systems are expected to play a significant role in engineering precise and durable pest resistance by modifying plant genomes or disrupting pest reproductive and developmental pathways. Additionally, gene drive technologies are being explored to control pest populations directly by spreading resistance-suppressing or fertility-reducing genes through natural pest populations. Integration of GM pest control with ecological pest management practices such as biological control, habitat management, and precision agriculture will further enhance sustainability. Moreover, bioinformatics, machine learning, and big data analytics will help predict pest evolution and resistance dynamics, allowing for proactive resistance management. Overall, the future of GM pest control is moving toward more targeted, environmentally sound, and durable solutions that support global food security while reducing reliance on chemical pesticides.

Conclusion

Bt technologies have continued to demonstrate effectiveness and relevance even more than a decade after the introduction of the first genetically modified (GM) crops. Continuous innovation and the development of new strategies have helped maintain their efficacy. These technologies offer well-established economic and environmental advantages, along with significant future potential. However, in many developing countries, broader acceptance and support are essential. A shift in perception among governments, non-governmental organizations, and the general public is crucial to ensure that insect-resistant transgenic crops can deliver their benefits equitably, reaching all populations rather than being limited to a select few.

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