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Development of transgenic herbicide-resistant crops

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Abstract
The development of transgenic herbicide-resistant crops has been a significant advancement in agricultural biotechnology. These crops have been genetically engineered to resist specific herbicides, allowing farmers to effectively control weeds while minimizing the negative impact on crop growth and yield. The introduction of transgenic herbicide-resistant crops, such as z effects on beneficial organisms and ecosystem functioning. It emphasizes the importance of regulatory oversight, risk assessments, and best management practices to ensure the safe and responsible use of these crops. Overall, the development of transgenic herbicide-resistant crops has provided farmers with effective weed control solutions, increased crop yields, and reduced environmental impacts.
However, it is essential to continue research, monitoring, and the implementation of integrated weed management strategies to address evolving challenges, such as herbicide resistance and ecological impacts.

Keywords: Transgenic herbicide, liberty-link crops, resistant, genetic engineering, IWM, ecological

Introduction

Transgenic herbicide-resistant crops, also known as genetically modified herbicide-resistant crops or biotech crops, are a significant advancement in agricultural biotechnology. These crops have been genetically engineered to resist specific herbicides, enabling farmers to effectively control weeds while minimizing the negative impact on crop growth and yield. The development of transgenic herbicide-resistant crops emerged as a solution to the challenges posed by weeds in agricultural systems. Weeds compete with crops for water, nutrients, and sunlight, reducing crop productivity. Traditional weed control methods, such as mechanical cultivation and chemical herbicides, have limitations and may have adverse environmental consequences. Schütte and Gesine. (2017) [18]. Transgenic herbicide-resistant crops were first introduced commercially in the 1990s and have since gained widespread adoption in several major crops, including soybeans, corn, cotton, and canola. These crops have been genetically modified by inserting specific genes that resist broad-spectrum herbicides or herbicides with particular modes of action. The most well-known example is the Roundup Ready system, developed by Monsanto (now Bayer), which introduced glyphosate herbicide tolerance in crops. This system enabled farmers to apply glyphosate-based herbicides, such as Roundup, to control weeds without causing harm to the transgenic crop. Similarly, other herbicide-resistant traits, such as glufosinate, dicamba, and 2,4-D resistance, have been incorporated into various crops to address specific weed control challenges. Developing and adopting transgenic herbicide-resistant crops have offered several benefits to farmers and the agricultural industry. These benefits include enhanced weed control, increased crop yield potential, reduced reliance on multiple herbicide applications, decreased labour and production costs, and improved efficiency in weed management. Furthermore, using herbicide-resistant crops has facilitated the adoption of conservation tillage practices, which help reduce soil erosion and improve soil health. Schütte and Gesine. (2017) [18].

However, deploying transgenic herbicide-resistant crops also raises concerns about environmental impact, herbicide resistance evolution, gene flow to related plant species, and potential effects on non-target organisms. These concerns have prompted extensive research and regulatory oversight to ensure these crops' safe and responsible use.

Overview of Herbicides and Herbicide Resistance

1. Different types and modes of action of herbicides

Herbicides are chemical substances specifically designed to control or eliminate weeds. They can be classified into different groups based on their chemical properties and modes of action. Some common types of herbicides include:

a. **Glyphosate**: A widely used broad-spectrum herbicide that inhibits the EPSP synthase enzyme, which is essential for synthesizing aromatic amino acids.
b. **Glufosinate:** A non-selective herbicide that inhibits glutamine synthetase, disrupting plant nitrogen metabolism.
c. **2,4-D (2,4-dichloro phenoxy acetic acid):** A synthetic auxin herbicide that mimics the plant hormone auxin, causing uncontrolled growth and, eventually, plant death.
d. **Atrazine:** A selective herbicide that inhibits photosynthesis by blocking the electron transport chain in chloroplasts.
e. **Imidazolinones:** A group of herbicides that inhibit the acetolactate synthase enzyme involved in branched- chain amino acid synthesis.
f. These are just a few examples, and many other herbicides are available with different modes of action. Pieterse. (2010) [14].

2. Mechanisms of Herbicide Resistance in Weeds:

Herbicide resistance occurs when weeds develop the ability to survive and reproduce, even when exposed to once- effective herbicides. The evolution of herbicide resistance in weeds is a complex process that involves various mechanisms, including:

a. **Target-site resistance:** This occurs when the target site of the herbicide (such as an enzyme or protein) undergoes genetic changes, rendering it less sensitive or completely insensitive to the herbicide's action.
b. **Metabolic resistance:** Weeds can develop enhanced metabolic pathways that detoxify or degrade the herbicide before it can have a detrimental effect.
c. **Reduced herbicide absorption:** Weeds may develop thicker cuticles or altered cell wall structures that prevent the herbicide from entering and affecting the plant's vital tissues.
d. **Enhanced herbicide sequestration:** Weeds can produce proteins or enzymes that bind to and sequester herbicides, reducing their availability and efficacy.
e. **Enhanced herbicide efflux:** Weeds may develop transport proteins that actively pump herbicides out of their cells, reducing the herbicide concentration within the plant.
f. These mechanisms can act individually or in combination, leading to varying levels of herbicide resistance in weed populations. Gage. (2019) [4].

Herbicide Resistance Management Strategies

Several strategies and best management practices have been developed to combat herbicide resistance. These strategies aim to prolong the effectiveness of herbicides and minimize the evolution and spread of resistant weed populations. Key approaches include:

a. **Diverse herbicide modes of action:** Rotating or alternating different herbicides with distinct modes of action can reduce the selection pressure for resistance and prevent the dominance of resistant weed populations.
b. **Integrated weed management (IWM):** Utilizing cultural, mechanical, biological, and chemical control methods can effectively manage weeds while reducing reliance on herbicides.
c. **Herbicide mixtures and tank mixes:** Using herbicide mixtures or tank mixes that combine multiple active ingredients with different modes of action can improve weed control and reduce the likelihood of resistance development.
d. **Monitoring and early detection:** Regular monitoring of weed populations for herbicide resistance and adopting early detection methods can help identify resistant populations before they become widespread.
e. **Education and awareness:** Providing Education and training to farmers and agronomists on the importance of herbicide resistance management and promoting best management practices can contribute to more effective weed control and sustainable agriculture.

By implementing these strategies, it is possible to slow down the development and spread of herbicide resistance and maintain the long-term efficacy of herbicides in weed management. Continuous research and monitoring are essential to adapt and refine these strategies in response to evolving resistance issues. Beckie. (2006) [1].

Development of Transgenic Herbicide Resistance in Crops

Herbicide-resistant crops (HRCs) are a major component of modern agricultural production systems. The first HRCs, bromoxynil-resistant cotton and glyphosate-resistant canola, were commercialized in 1995. Since then, HRCs have been developed for a wide range of crops, including soybeans, corn, cotton, alfalfa, sugarbeets, and wheat. HRCs have had a significant impact on weed management, crop yields, and environmental quality.

The development of HRCs has been driven by the need for more effective and sustainable weed management practices. Herbicides are the most widely used pesticides in agriculture, and they are an essential component of integrated weed management systems. However, the use of herbicides can lead to the development of herbicide- resistant weeds. HRCs offer a way to manage herbicide-resistant weeds by providing crops with resistance to specific herbicides.

HRCs have had a number of benefits for farmers. They have allowed farmers to use herbicides more effectively, which has led to increased crop yields and reduced weed pressure. HRCs have also reduced the need for tillage, which has improved soil quality and reduced greenhouse gas emissions.

HRCs have also had a number of benefits for the environment. They have reduced the use of broad-spectrum herbicides, which can harm non-target organisms. HRCs have also reduced the need for tillage, which can improve water quality and reduce soil erosion. Duke and Cerdeira (2005) [3].

Transgenic herbicide-resistant crops are developed through genetic engineering techniques that introduce specific genes into crop plants to confer herbicide resistance. This allows farmers to effectively control weeds while minimizing the negative impact on crop growth and yield. The development process includes several key steps, as outlined below:

3. Genetic engineering techniques

a. **Gene Isolation:** The first step is to identify and isolate the gene responsible for herbicide resistance from a known resistant source, such as a naturally occurring herbicide-resistant plant or a microorganism.

b. **Gene Cloning:** Once the resistance gene is isolated, it is cloned using molecular biology techniques to obtain multiple copies of the gene for further manipulation.
c. **Gene Modification:** Genetic modification techniques, such as site-directed mutagenesis or gene editing technologies (e.g., CRISPR-Cas9), can be employed to modify the gene to enhance its expression or optimize its function in the crop plant.
d. **Gene Expression Regulation:** Promoters and regulatory elements are incorporated to ensure the herbicide resistance gene is expressed in the desired plant tissues and at the appropriate levels.

Selection and characterization of herbicide resistance genes

a. **Screening Herbicide Resistance Genes:** Various molecular and functional assays are employed to identify and select the specific herbicide resistance genes that effectively confer resistance to the target herbicide.
b. **Characterization of Resistance Mechanism:** The mechanism of action of the selected resistance gene is studied to understand how it confers herbicide resistance at the molecular and physiological levels. This helps in assessing the gene's suitability for transfer to crop plants. Kumar. (2020) [8].

Transformation Methods and Gene Transfer Technologies

a. **Agrobacterium-Mediated Transformation:** Agrobacterium tumefaciens is commonly used as a vector to transfer the herbicide resistance gene into the target crop plant. The resistance gene is inserted into the Ti plasmid of Agrobacterium, which then transfers the gene into the plant cells during infection.
b. **Biolistic or Particle Bombardment:** In this method, microscopic particles coated with the herbicide resistance gene are shot into plant tissues using a gene gun or particle bombardment device. The particles penetrate the plant cells and deliver the gene into the genome.
c. **Protoplast Transformation:** Protoplasts, plant cells with their cell walls removed, can be transformed with the herbicide resistance gene using various methods such as electroporation or polyethene glycol (PEG) treatment. Once transformed, the protoplasts can be regenerated into whole plants.
d. **CRISPR-Cas9-Mediated Genome Editing:** The CRISPR-Cas9 system allows for precise gene editing by introducing targeted changes in the plant's genome. This technology can insert, delete, or modify specific DNA sequences, including the herbicide resistance gene.

These techniques enable the successful transfer and integration of the herbicide resistance gene into the crop plant's genome. Once the transgenic plants are obtained, they undergo rigorous testing and evaluation for herbicide resistance, agronomic performance, and safety considerations before commercialization.

It is important to note that the specific techniques and methods used may vary depending on the crop species and the herbicide resistance gene of interest. Genetic engineering and biotechnology advances continue to expand the repertoire of tools available for developing transgenic herbicide-resistant crops. Yu. (2016) [21].

- **Major transgenic herbicide-resistant crops**

Transgenic herbicide-resistant crops have been commercially developed and widely adopted in agriculture, offering effective weed control solutions. Here are two prominent examples of commercially available transgenic herbicide-resistant crops, along with their agronomic performance, economic benefits, and impact on weed control practices:

Roundup Ready Crops

a. Roundup Ready crops, developed by Monsanto (now Bayer), are genetically modified to tolerate the herbicide glyphosate, commonly known as Roundup.
b. Roundup Ready crops include soybeans, corn, cotton, and canola.
c.
d. **Agronomic Performance:** Roundup Ready crops have demonstrated improved weed control and reduced crop yield loss due to weed competition. They provide flexibility in weed management timing and allow for effective post-emergence weed control.
e.
f. **Economic Benefits:** Adopting Roundup Ready crops has provided significant economic benefits for farmers. It has simplified weed management practices, reduced labour and machinery costs associated with mechanical weed control, and increased yields by minimizing weed competition.
g.
h. **Impact on Weed Control Practices:** Roundup Ready crops have greatly influenced weed control practices.
Glyphosate, a broad-spectrum herbicide, allowed farmers to shift from multiple herbicide applications to a single herbicide, simplifying weed control programs. However, the extensive use of glyphosate has led to the emergence of glyphosate-resistant weeds, necessitating the adoption of integrated weed management strategies. Herbicides. (United States Environmental Protection Agency.)

Liberty Link Crops

a. Liberty Link crops, developed by Bayer, are genetically modified to tolerate the herbicide glufosinate (e.g., Liberty herbicide).
b. Liberty Link crops include soybeans, corn, cotton, and canola.
c. Agronomic Performance: Liberty Link crops provide an effective alternative for weed control, particularly against glyphosate-resistant weeds. Glufosinate has a different mode of action than glyphosate, allowing for effective weed control in resistant populations.
d. Economic Benefits: Adopting Liberty Link crops offers economic benefits by reducing yield losses due to weed competition and providing flexibility in weed management. It also allows farmers to diversify their herbicide options and manage herbicide resistance more effectively.
e. Impact on Weed Control Practices: Liberty-Link crops have expanded weed control options, particularly in areas with prevalent glyphosate resistance. They have enabled farmers to employ different herbicides, rotate herbicide modes of action, and implement integrated weed management practices to combat herbicide-resistant weeds.

It is important to note that adopting transgenic herbicide-resistant crops has advantages and challenges. While they provide adequate weed control and economic benefits, overreliance on a single herbicide or mode of action can lead to the evolution of herbicide-resistant weed populations. Thus, integrated weed management approaches that combine various control methods and herbicide rotations are necessary for long-term sustainable weed control.

The commercialization of transgenic herbicide-resistant crops has revolutionized weed management practices, improved crop productivity, and provided farmers with valuable tools for sustainable agriculture. Continuous research and monitoring are essential to address evolving challenges such as herbicide resistance and to develop innovative weed control strategies. Owen. (2005) [13].

Environmental and ecological considerations

Transgenic herbicide-resistant crops have significantly changed agricultural practices and raised important ecological considerations. Here are some key points regarding the ecological risks and benefits associated with these crops, potential gene flow, and non-target effects on beneficial organisms and ecosystem functioning.

Ecological Risks and Benefits

a. **Risks:** There are concerns that the widespread adoption of transgenic herbicide-resistant crops could lead to the emergence and spread of herbicide-resistant weed populations. Overreliance on a single herbicide or mode of action may result in selection pressure favouring resistant weeds' evolution. This can reduce herbicides' effectiveness and increase weed management strategies' complexity.

b. **Benefits:** Transgenic herbicide-resistant crops can contribute to sustainable agriculture by reducing the need for multiple herbicide applications, thereby decreasing the environmental impact of chemical weed control. They can also enable the adoption of conservation tillage practices, which help reduce soil erosion and improve soil health. Green. (2011) [6].

Potential Gene Flow and Biodiversity

a. **Gene Flow:** Gene flow refers to transferring genes from genetically modified crops to wild or weedy relatives through pollination. It is a concern because it can spread transgenes and associated traits into non- target plant populations.

b. **Biodiversity Implications:** Gene flow from transgenic herbicide-resistant crops to wild or weedy relatives may result in the hybridization and introgression of transgenes into wild populations. This can have implications for biodiversity conservation, mainly if the transgenes confer herbicide-resistance traits that enhance the fitness of the recipient plants. Shi. (2008) [19].

Non-target Effects on Beneficial Organisms and Ecosystem Functioning

a. **Beneficial Organisms:** Transgenic herbicide-resistant crops and associated herbicides can have unintended effects on non-target organisms, including beneficial insects, soil microorganisms, and wildlife. For example, the broad-spectrum nature of certain herbicides may negatively impact pollinators and natural enemies of pests.

b. **Ecosystem Functioning:** Changes in weed management practices associated with transgenic herbicide- resistant crops can influence ecological interactions and ecosystem functioning. For instance, alterations in weed communities may affect soil nutrient cycling, plant competition dynamics, and wildlife habitat.

Regulatory frameworks and best management practices have been developed to address these environmental and ecological considerations. These include rigorous risk assessments, gene flow monitoring, establishing refuge areas with non-transgenic crops, and implementing integrated pest management strategies. Ongoing research, surveillance, and adaptive management approaches are crucial for assessing the long-term impacts and sustainability of transgenic herbicide-resistant crops in the context of ecological systems.

It is important to note that the specific environmental and ecological impacts can vary depending on the crop, the herbicide used, and the local environmental context. Hence, a case-by-case approach is necessary to evaluate and mitigate potential risks associated with transgenic herbicide-resistant crops. Lehman. (1950) [11].

- **Herbicide resistance evolution and management**

Dynamics and evolution of herbicide resistance in weed populations

a. **Selection Pressure:** Continuous and intensive use of herbicides creates intense selection pressure on weed populations, favouring individuals with natural or induced resistance traits.

b.

c. **Genetic Variation:** Weed populations exhibit genetic variation, allowing for the presence of individuals with inherent or acquired herbicide resistance traits.

d.

e. **Fitness Cost:** Herbicide resistance in weeds often comes with a fitness cost, meaning resistant individuals may have reduced fitness compared to susceptible individuals without herbicide pressure.

f.

g. **Evolutionary Processes:** Over time, repeated herbicide exposure can lead to the accumulation and dominance of herbicide-resistant individuals within weed populations through natural selection, genetic drift, and gene flow.

Strategies to Mitigate the Development and Spread of Herbicide Resistance

a. **Diverse Herbicide Modes of Action:** Using a diverse range of herbicides with different modes of action helps prevent or delay the emergence of herbicide-resistant weed populations. Rotating or alternating herbicides with different modes of action is essential.

b. **Herbicide Mixing and Sequencing:** Mixing or sequencing multiple herbicides with different modes of action can provide effective control while reducing the selection pressure for resistance.

c. **Effective Herbicide Application:** Following recommended herbicide rates, application timings, and proper spray coverage can maximize herbicide efficacy and minimize the survival and selection of resistant weed individuals.

d. **Integrated Weed Management (IWM):** IWM combines multiple control methods, such as cultural practices (crop rotation, cover cropping), mechanical methods (tillage, hand-weeding), biological controls (biocontrol agents), and chemical controls (herbicides), to reduce reliance on herbicides and manage weed populations more sustainably.

e. **Monitoring and Early Detection:** Regular monitoring of weed populations for herbicide resistance is crucial. Early detection of resistant individuals allows for timely intervention and the implementation of appropriate management strategies.
f. **Education and Awareness:** Educating farmers, agronomists, and stakeholders about herbicide resistance management and promoting best practices is essential for effective resistance management. Reddy. (2016) [15].

Integrated Weed Management Approaches for Sustainable Herbicide Use

a. **Crop Rotation:** Rotating different crops helps disrupt weed life cycles, reduces weed species diversity, and allows for using herbicides with different modes of action.
b. **Cover Crops:** Planting cover crops can suppress weed growth, enhance soil health, and reduce reliance on herbicides.
c. **Mechanical Weed Control:** Practices such as tillage, mowing, hand-weeding, and mechanical cultivation can physically remove weeds and reduce the reliance on herbicides.
d. **Biological Control:** Utilizing natural enemies, such as insects, pathogens, and herbivores, can effectively suppress weed and reduce herbicide use.
e. **Site-Specific Weed Management:** Employing precision agriculture technologies, such as remote sensing and variable rate application, allows for targeted herbicide application only where needed, reducing overall herbicide use.

Integrated weed management approaches combine various control methods to reduce herbicide reliance, diversify weed control tactics, and manage weed populations effectively while minimizing the risk of herbicide resistance development and spread.

Implementing a holistic approach to herbicide resistance management is crucial, considering both short-term weed control goals and long-term sustainability. Regular monitoring, adaptive management, and collaboration among researchers, farmers, and industry stakeholders are vital for effective and sustainable weed management practices. Upadhyay. (2006) [20].

Regulatory and Societal Aspects

Regulatory frameworks for transgenic herbicide-resistant crops

a. **Regulatory Authorities:** Each country has its regulatory authorities responsible for evaluating and approving transgenic crops, including those with herbicide resistance traits. Examples include the United States Department of Agriculture (USDA), the European Food Safety Authority (EFSA), and the Food Standards Australia New Zealand (FSANZ).
b. **Safety Assessments:** Regulatory frameworks typically require comprehensive safety assessments of transgenic crops, including evaluating potential risks to human health, the environment, and biodiversity. These assessments involve rigorous scientific scrutiny of the crops' characteristics, including their gene source, the introduced traits, and potential effects on non-target organisms.
c. **Environmental Release and Market Approval**: Transgenic herbicide-resistant crops must undergo field trials to evaluate their agronomic performance, environmental impact, and herbicide resistance management strategies. Commercial release and market access are approved after meeting the regulatory requirements. Green. (2007) [5].
d. **Public Perception, Acceptance, and Ethical Concerns:**
e. **Public Perception:** Public opinion on genetically modified organisms (GMOs), including transgenic herbicide-resistant crops, varies worldwide. Views are influenced by knowledge, cultural values, perceptions of risks and benefits, and trust in regulatory systems.
f. **Acceptance and Ethical Concerns:** Some concerns related to transgenic herbicide-resistant crops include potential environmental risks, the dominance of large agrochemical corporations, seed patenting, and potential impacts on traditional farming practices. Ethical concerns may also arise regarding modifying organisms and potential effects on biodiversity and human health. Lucht. (2015) [12].

Intellectual Property Rights and Patent Issues

a. **Patent Protection:** Companies that develop transgenic herbicide-resistant crops often seek patent protection for their inventions. Patents grant exclusive rights to the inventors, allowing them to control transgenic crop use, production, and commercialization.

b.

c. **Licensing and Access:** Intellectual property rights can impact the availability and access to transgenic crops. Licensing agreements between companies and farmers may govern the use and sale of transgenic seeds, including restrictions on seed saving and replanting.

Farmer's Rights and Seed Sovereignty: Some concerns exist regarding the implications of patenting and intellectual property rights on farmers' rights and seed sovereignty. Debates continue to strike a balance between protecting innovation and ensuring fair access and benefits for farmers.

Governments, regulatory bodies, and international organizations are actively addressing regulatory, public perception, acceptance, and ethical concerns related to transgenic herbicide-resistant crops. This includes promoting transparency, conducting public consultations, fostering dialogue, and implementing measures to ensure the safe use and appropriate management of transgenic crops.

It is important to note that regulations, public opinion, and intellectual property rights can differ across countries and regions. Ongoing discussions, stakeholder engagement, and continuous evaluation of regulatory frameworks are necessary to ensure effective and responsible management of transgenic herbicide-resistant crops in light of societal concerns. Lakshmikumaran. (2019) [9].

Future Perspectives and Challenges

Advances in Biotechnology and Genetic Engineering

Novel Herbicide Resistance Traits: Advances in biotechnology and genetic engineering hold the potential to develop novel herbicide resistance traits beyond the existing glyphosate and glufosinate resistance traits. Researchers are exploring new resistance mechanisms and engineering crops to tolerate alternative herbicides or herbicide combinations, expanding the options for effective weed management.

Stackable Traits: Future developments may focus on combining multiple herbicide resistance traits in a single crop, creating stackable characteristics that resist various herbicides or modes of action. This approach can enhance the flexibility and durability of weed control strategies Sangeetha (2020) [16].

Potential applications of genome editing technologies

a. **CRISPR-Cas9 and Other Tools:** Genome editing technologies, such as CRISPR-Cas9, offer precise and efficient methods for modifying specific genes. They can potentially engineer herbicide resistance traits directly into crop genomes or introduce targeted mutations in weed populations to disrupt resistance mechanisms.
b. **Non-Transgenic Approaches:** Genome editing allows the development of herbicide-resistant crops without introducing foreign DNA, which may address some public concerns associated with transgenic crops. However, regulatory frameworks and public acceptance of genome-edited crops are still evolving Zhang. (2020) [22].

Sustainable Strategies for Long-Term Weed Control

a. **Integrated Weed Management (IWM):** IWM approaches that combine various weed control methods, including cultural, mechanical, biological, and chemical controls, will continue to play a crucial role in sustainable weed management. IWM reduces herbicide reliance, diversifies control tactics, and targets multiple points in the weed life cycle.
b. **Precision Weed Management:** Advances in precision agriculture technologies, such as remote sensing, robotics, and machine learning, offer opportunities for site-specific weed management. These technologies enable targeted herbicide application, minimizing environmental impact and optimizing weed control.
c. **Resilience and Adaptive Management:** Developing resilient weed management strategies that account for the potential evolution of herbicide resistance is critical. Adaptive management approaches involve monitoring weed populations, implementing resistance prevention and detection measures, and adjusting management practices. Hussain. (2021) [7].

Challenges

a. **Herbicide Resistance Management:** The evolution and spread of herbicide resistance remain ongoing challenges. As new herbicide resistance traits are developed, it is essential to incorporate resistance management strategies from the outset to ensure their long-term effectiveness.
b. **Public Acceptance and Regulatory Considerations:** Public perception, acceptance, and regulatory frameworks surrounding transgenic crops and genome editing technologies continue to evolve. Addressing societal concerns, promoting transparency, and fostering stakeholder dialogue will be essential.
c. **Environmental and Ecological Impacts:** Continued research is necessary to understand the potential environmental and ecological impacts of transgenic herbicide-resistant crops, including gene flow, non- target effects, and long-term ecosystem consequences. Mitigation measures and monitoring programs should be in place to minimize unintended effects.

As biotechnology and agricultural practices evolve, ongoing research, collaboration among scientists, farmers, regulators, and stakeholders, and adaptive management approaches will be crucial for developing sustainable strategies to address weed management challenges in the context of transgenic herbicide-resistant crops.

References

1. Beckie HJ. Herbicide-resistant weeds: Management tactics and practices. Weed Technology. 2006;20(3):793-814. doi:10.1614/WT-05-084R1.1
2. Brookes G. Weed control changes and genetically modified herbicide tolerant crops in the USA 1996–2012. GM Crops and Food. 2014 Oct;5(4):321–332. doi:10.4161/21645698.2014.958930
3. Duke SO, Cerdeira AL. Transgenic herbicide-resistant crops: Current status and potential for the future. Pest Management Science. 2005;61(10):1113-1124.
4. Gage KL, Krausz RF, Walters SA. Emerging challenges for weed management in herbicide-resistant crops. Agriculture. 2019;9(8):8. doi:10.3390/AGRICULTURE9080180
5. Green JM. Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. Weed Technology. 2007;21(2):547–558. doi:10.1614/WT-06-004.1
6. Green JM, Owen MD. Herbicide-resistant crops: Utilities and limitations for herbicide-resistant weed management. Journal of Agricultural and Food Chemistry. 2011;59(11):5819-5829. DOI:10.1021/JF101286H
7. Hussain MI, Abideen Z, Danish S, Asghar MA, Iqbal K. Sustainable Agriculture Reviews. 2021;52:367-393. doi:10.1007/978-3-030-73245-5_11
8. Kumar K, Gambhir G, Dass A, Tripathi AK, Singh A, Jha AK, *et al*. Genetically modified crops: Current status and future prospects. Planta. 2020;251(4):91–91. doi:10.1007/S00425-020-03372-8
9. Lakshmikumaran M. Genetically modified plants: The IP and regulatory concerns in India. In K. C. Liu & U. 2019.
10. Racherla S. (Eds.), Innovation, economic development, and intellectual property in India and China. ARCIALA series on intellectual assets and law in Asia, 367–386. Singapore: Springer. doi:10.1007/978-981-13-8102-7_16
11. Lehman AJ. Effects on beneficial forms of life, crops and soil and residue hazards. JAMA. 1950;144(2):108-108. doi:10.1001/JAMA.1950.62920020005008D
12. Lucht JM. Public acceptance of plant biotechnology and GM crops. Viruses. 2015 July;7(8):4254–4281. doi:10.3390/v7082819, PubMed: 26264020, PubMed Central: PMC4576180
13. Owen MDK, Zelaya IA. Herbicide-resistant crops and weed resistance to herbicides. Pest Management Science. 2005;61(3):301–311. doi:10.1002/PS.1015

14. Pieterse PJ. Herbicide resistance in weeds – A threat to effective chemical weed control in South Africa. South African Journal of Plant and Soil. 2010;27(1):66-73. doi:10.1080/02571862.2010.10639971
15. Reddy KN, Jha P. Herbicide-resistant weeds: Management strategies and upcoming technologies. Indian Journal of Weed Science. 2016;48(2):108-111. doi:10.5958/0974-8164.2016.00029.0
16. Sangeetha J, *et al*. Tawaha, Abdel Rahman and Thangadurai, Devarajan and Jahan, Nusrat & Islam, Saher & Sundaram, Lalitha and Nosratti, Iraj and Jadav, Mulji and Arakera, Suresh and Rajendran, Santhakumari and Hospet, Ravichandra and Subramaniyam, Nithyapriya. Genetic Engineering for Developing Herbicide Resistance in Rice Crops. 2020. DOI:10.1007/978-981-15-5337-0_10.
17. Sangeetha Jeyabalan, Al Tawaha, Abdel Rahman, Thangadurai Devarajan, Jahan, Nusrat, *et al*. Genetic Engineering for Developing Herbicide Resistance in Rice Crops; c2020. 10.1007/978-981-15-5337-0_10.
18. Schütte G, Eckerstorfer M, Rastelli V, Reichenbecher W, Restrepo-Vassalli S, Ruohonen-Lehto M, *et al*. Herbicide resistance and biodiversity: Agronomic and environmental aspects of genetically modified herbicide-resistant plants. Environmental Sciences Europe. 2017;29(1):5–5. DOI:10.1186/S12302-016-0100-Y
19. Shi Y, Wang T, Li Y, Darmency H. Impact of transgene inheritance on the mitigation of gene flow between crops and their wild relatives: The example of foxtail millet. Genetics. 2008;180(2):969–975. doi:10.1534/GENETICS.108.092809
20. Upadhyay BM, Smith EG, Clayton GW, Harker KN, Blackshaw RE. Economics of integrated weed management in herbicide-resistant canola. Weed Science. 2006;54(1):138–147. DOI:10.1614/WS-05-050R1.1
21. Yu W, Yau YY, Birchler JA. Plant artificial chromosome technology and its potential application in genetic engineering. Plant Biotechnology Journal. 2016;14(5);1175-1182. doi:10.1111/PBI.12466
22. Zhang Y, Showalter AM. CRISPR/Cas9 Genome Editing Technology: A Valuable Tool for Understanding Plant Cell Wall Biosynthesis and Function. Frontiers in Plant Science. 2020, Nov 20;11:589517. doi:10.3389/fpls.2020.589517, PubMed: 33329650, PubMed Central: PMC7714752