

## REVIEW ARTICLE

# Harnessing nature's tiny warriors: Plant viruses as innovative bioherbicides

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## ABSTRACT

The use of plant viruses as bioherbicides represents a fascinating and promising frontier in modern agriculture and weed management. This review article delves into the multifaceted world of harnessing plant viruses for herbicidal purposes, shedding light on their potential as eco-friendly, sustainable alternatives to traditional chemical herbicides. We begin by exploring the diverse mechanisms through which plant viruses can target and control weeds, from altering gene expression to disrupting essential physiological processes. The article highlights the advantages of utilizing plant viruses, such as their specificity for weed species, minimal impact on non-target plants, and a reduced environmental footprint. Furthermore, we investigate the remarkable versatility of plant viruses, showcasing their adaptability to various weed species and agricultural environments. The review delves into the latest advancements in genetic modification techniques, which enable the engineering of plant viruses for enhanced herbicidal properties and safety. In addition to their efficacy, we discuss the economic and ecological advantages of using plant viruses as bioherbicides, emphasizing their potential to reduce chemical herbicide usage and decrease the development of herbicide-resistant weeds. We also address the regulatory and safety considerations associated with the application of plant viruses in agriculture. Ultimately, this review article underscores the immense potential of plant viruses as bioherbicides and calls for further research, development, and responsible deployment to harness these microscopic agents in the ongoing quest for sustainable and environmentally friendly weed management strategies.

**Keywords:** plant viruses; bioherbicides; weed management; herbicidal mechanisms; genetic modification; agricultural innovation

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## 1. Introduction

Weed management is a fundamental challenge in agriculture, impacting crop yields, resource utilization, and environmental sustainability. The widespread use of chemical herbicides, while effective in controlling unwanted vegetation, has raised concerns about their environmental impact, human health risks, and the emergence of herbicide-resistant weed populations<sup>[1-3]</sup>. As a result, there has been a growing interest in developing innovative, sustainable, and eco-friendly alternatives to traditional herbicides.

Among these alternatives, the utilization of plant viruses as bioherbicides has emerged as a promising and environmentally friendly approach. Plant viruses, historically viewed as agricultural pathogens causing diseases in crops, are now being recognized for their potential in

weed management<sup>[4]</sup>. The concept of using viruses as herbicides represents a novel and exciting avenue as our understanding of viral biology and genetics deepens.

This review article delves into the multifaceted world of using plant viruses as bioherbicides, exploring their mechanisms, advantages, and potential applications in modern agriculture. In a world increasingly focused on sustainable and environmentally friendly agricultural practices, the exploitation of these tiny viral agents represents a promising frontier with significant implications for weed control and sustainable agriculture<sup>[5]</sup>.

The subsequent sections of this review will explore the various mechanisms by which plant viruses can effectively target and manage weeds, emphasizing their specificity for weed species and minimal impact on non-target plants. We will also investigate recent advancements in genetic modification techniques, which enable the engineering of plant viruses to enhance their herbicidal properties while ensuring safety and regulatory compliance. Moreover, we will discuss the economic and ecological advantages of employing plant viruses as bioherbicides and address the regulatory considerations associated with their application. In conclusion, this review underscores the vast potential of plant viruses in the ongoing quest for sustainable and eco-friendly weed management strategies.

## **2. Mechanisms of plant virus bioherbicides**

Plant viruses, typically known for their role in causing diseases in crops, can also serve as effective bioherbicides through various mechanisms. Understanding these mechanisms is crucial for harnessing their potential in weed management<sup>[6]</sup>.

### **2.1. Altered gene expression**

Plant viruses can interfere with the gene expression of host plants and, in some cases, weeds. By doing so, they disrupt essential physiological processes necessary for weed growth. This interference may result in the downregulation of key genes responsible for weed development and survival<sup>[7]</sup>. This mechanism provides a targeted and specific approach to weed control, as it primarily affects the unwanted plant species without causing harm to non-target plants.

### **2.2. Physiological disruption**

Another mechanism involves the direct disruption of vital physiological processes in weeds. Plant viruses can affect the transport of nutrients and water within weed plants, leading to stunted growth, wilting, and eventual death. This approach capitalizes on the specific interactions between the virus and weed species, minimizing harm to other vegetation in the vicinity<sup>[8]</sup>.

### **2.3. Competitive exclusion**

Some plant viruses can establish a competitive advantage within host plants, effectively outcompeting the weeds for essential resources. By monopolizing nutrients and space within the host, the virus reduces the resources available to the weed, leading to its suppression<sup>[9]</sup>.

These mechanisms, individually or in combination, offer a precise and ecologically responsible means of managing weed populations. Plant viruses can effectively target specific weed species while sparing non-target plants and reducing the need for broad-spectrum chemical herbicides<sup>[6]</sup>. In the next section, we will explore the specificity and safety of plant virus-based herbicides, underlining their potential advantages in sustainable agriculture.

## **3. Specificity and safety of plant virus-based herbicides**

One of the distinctive advantages of plant viruses as bioherbicides is their specificity in targeting weed

species, which significantly contributes to their safety and environmental friendliness.

### **3.1. Weed species specificity**

Plant viruses often exhibit a high degree of host specificity. They are engineered or selected to infect and impact specific weed species while leaving non-target plants unharmed. This specificity minimizes collateral damage to desirable crops, reducing the risk of unintended consequences commonly associated with chemical herbicides<sup>[10]</sup>.

### **3.2. Minimal impact on non-target plants**

The precision of plant virus bioherbicides in targeting specific weed species ensures that nearby non-target plants remain unaffected. This targeted approach aligns with the principles of sustainable agriculture and integrated weed management, as it minimizes disturbances to the surrounding ecosystem<sup>[11]</sup>.

### **3.3. Reduced environmental footprint**

Compared to conventional herbicides, which can persist in the environment and potentially leach into water sources, plant virus bioherbicides offer a more sustainable choice with a reduced environmental footprint. Their specific nature means that fewer chemicals are used overall, resulting in a decreased risk of environmental contamination<sup>[3]</sup>.

In summary, the specificity and safety of plant virus-based herbicides make them a viable and eco-friendly alternative to chemical herbicides. They allow for precise weed management, reduce the risk of non-target damage, and contribute to a more sustainable and environmentally responsible approach to agriculture. In the following section, we will explore how genetic modification techniques are being applied to enhance the herbicidal properties of plant viruses while ensuring their safety and regulatory compliance.

## **4. Genetic modification for enhanced herbicidal efficacy**

To harness the full potential of plant viruses as bioherbicides, researchers have turned to genetic modification techniques to enhance their herbicidal properties while ensuring their safety and regulatory compliance.

### **4.1. Engineering for targeted weed control**

Genetic modification enables scientists to design and tailor plant viruses to specifically target particular weed species. This approach enhances the precision of weed control while minimizing the impact on non-target vegetation. By introducing or modifying genes in the virus, researchers can optimize its ability to inhibit weed growth and development<sup>[12]</sup>.

### **4.2. Safety and regulation**

Genetic modification also allows for the incorporation of safety mechanisms and regulatory elements within the modified viruses. This ensures that the bioherbicides are environmentally safe and compliant with regulatory standards. By controlling the virus's ability to persist in the environment and its interaction with non-target plants, scientists can mitigate potential risks associated with genetically modified organisms<sup>[13]</sup>.

### **4.3. Enhanced efficacy**

Through genetic modification, plant viruses can be engineered to have increased potency, enabling them to exert greater control over weed populations. This enhanced efficacy reduces the need for frequent applications, resulting in more efficient and cost-effective weed management<sup>[14,15]</sup>.

Genetic modification techniques are playing a pivotal role in unlocking the full potential of plant viruses as bioherbicides. By fine-tuning their properties and ensuring their safety, researchers are creating powerful and eco-friendly tools for sustainable weed management. In the subsequent section, we will delve into the economic and ecological advantages of using plant viruses as bioherbicides.

## **5. Economic and ecological advantages**

The utilization of plant viruses as bioherbicides offers a range of economic and ecological benefits that are increasingly attractive to agricultural systems.

### **5.1. Reduced chemical herbicide usage**

Plant viruses, by their nature, reduce the reliance on chemical herbicides. Their specificity and targeted approach result in a reduced need for broad-spectrum chemical weed control. This, in turn, decreases the costs associated with purchasing and applying chemical herbicides and minimizes the environmental burden linked to their use<sup>[16]</sup>.

### **5.2. Mitigation of herbicide resistance**

The overuse of chemical herbicides has led to the development of herbicide-resistant weed populations, posing significant challenges for weed management<sup>[3]</sup>. Plant virus bioherbicides, with their distinct mechanisms, offer an alternative strategy that can help mitigate the emergence of herbicide-resistant weeds.

### **5.3. Reduced environmental impact**

Compared to conventional herbicides, plant virus bioherbicides generally have a reduced environmental impact. Their targeted approach, reduced chemical use, and biodegradable nature contribute to a more sustainable agricultural system. This aligns with the growing global emphasis on environmentally friendly and responsible farming practices<sup>[17]</sup>.

### **5.4. Enhanced crop yields**

By effectively managing weed populations, plant virus bioherbicides indirectly support crop health and yield. Reduced competition from weeds allows cultivated crops to access essential nutrients and resources more efficiently, resulting in improved agricultural productivity<sup>[18]</sup>.

In summary, the economic and ecological advantages of using plant viruses as bioherbicides make them a compelling option for modern agriculture. They offer a path toward more sustainable and environmentally responsible weed management, while also addressing issues related to herbicide resistance and crop productivity. In the following section, we will discuss the regulatory and safety considerations associated with the application of plant viruses in agriculture.

## **6. Regulatory and safety considerations**

The application of plant viruses as bioherbicides in agriculture comes with important regulatory and safety considerations that are crucial for their responsible deployment.

### **6.1. Regulatory compliance**

The use of plant virus bioherbicides must adhere to existing regulatory frameworks governing genetically modified organisms (GMOs) and pesticide use. These regulations are essential to ensure that the development, testing, and commercialization of plant virus-based herbicides follow established safety and environmental standards. Regulatory compliance ensures that the products are thoroughly assessed for potential risks and benefits<sup>[19]</sup>.

## **6.2. Environmental impact assessment**

Before the release of any plant virus bioherbicide into the environment, a comprehensive environmental impact assessment must be conducted. This assessment helps to determine potential effects on non-target organisms, ecosystems, and the broader environment. It also aids in identifying and mitigating any unforeseen consequences<sup>[20]</sup>.

## **6.3. Safe handling and application**

Safe handling, storage, and application of plant virus bioherbicides are paramount. Protocols for the responsible use of these bioherbicides must be established to prevent unintended exposures, accidents, or contamination. Proper training and education for agricultural practitioners and workers are essential to ensure safe practices<sup>[21]</sup>.

## **6.4. Monitoring and reporting**

Continuous monitoring and reporting are crucial aspects of the safe use of plant virus bioherbicides. Regular assessment of their effectiveness, safety, and potential ecological impacts helps in addressing any emerging issues and making necessary adjustments in real-time. Transparent reporting allows for data sharing and cooperative efforts to refine and optimize these bioherbicides<sup>[22]</sup>.

Incorporating regulatory and safety considerations into the development and application of plant virus bioherbicides is essential to ensure their responsible use in agriculture. This approach guarantees that the potential ecological and economic benefits of these bioherbicides are balanced with safety and environmental stewardship. In conclusion, we will highlight the significant potential of plant viruses as bioherbicides and their role in the ongoing quest for sustainable and environmentally friendly weed management strategies.

# **7. Future directions in the use of plant viruses as bioherbicides**

The utilization of plant viruses as bioherbicides represents an ever-evolving field with considerable potential. As the world faces increasing challenges related to conventional herbicides and weed management, exploring the future of plant virus-based herbicides becomes paramount. In this section, we will delve into promising directions for research and application, considering innovative strategies, technology advancements, and emerging trends.

## **7.1. Expanding virus-weed host range**

One future direction in the development of plant virus bioherbicides is the expansion of the virus-weed host range. While many current bioherbicides have shown effectiveness against specific weed species, expanding the range to target a broader spectrum of problematic weeds will be crucial. This requires a deeper understanding of the interactions between plant viruses and different weed species, enabling the development of viruses that can target a wider variety of plants<sup>[23]</sup>.

## **7.2. Integration of bioherbicides with other weed management practices**

To enhance the effectiveness of plant virus bioherbicides, future research may focus on integrating them with other weed management practices. Combining bioherbicides with cultural, physical, or other non-chemical control methods can offer a comprehensive approach to weed management. Such integrated strategies can help mitigate herbicide resistance and reduce the reliance on chemical herbicides<sup>[24]</sup>.

## **7.3. Precision application technologies**

Advancements in precision agriculture and application technologies present an exciting avenue for the future of plant virus bioherbicides. The development of precise delivery mechanisms can ensure that the

bioherbicides are applied where and when needed, reducing wastage and optimizing their impact on weed populations. Drones, sensor technologies, and artificial intelligence can all play a role in achieving this level of precision<sup>[25]</sup>.

#### **7.4. Eco-friendly formulations**

The formulation of bioherbicides is another area of active research. Future formulations should prioritize biodegradability, reduced environmental impact, and safety for both users and non-target organisms. Innovative formulations can enhance the practicality and sustainability of plant virus bioherbicides, making them more attractive for widespread adoption in agriculture<sup>[26]</sup>.

#### **7.5. Regulatory pathways and public perception**

As plant virus bioherbicides progress, the development of clear regulatory pathways and addressing public perceptions are essential. Collaborative efforts involving researchers, regulatory agencies, and industry stakeholders should ensure that the products are rigorously tested for safety and efficacy. Furthermore, educating the public about the benefits and safety of these bioherbicides is crucial to garner acceptance and support for their use<sup>[27]</sup>.

#### **7.6. Global collaboration and knowledge sharing**

The future of plant virus bioherbicides will benefit from increased global collaboration and knowledge sharing. As research and development efforts expand, sharing data and insights across borders can accelerate progress. International cooperation can facilitate the exchange of best practices and support the development of bioherbicides tailored to different regions and weed species<sup>[28]</sup>.

#### **7.7. Climate-resilient bioherbicides**

Given the changing climate and its impact on weed dynamics, developing climate-resilient plant virus bioherbicides is of great importance. Research into how temperature, humidity, and other environmental factors affect the efficacy of these bioherbicides can help ensure their reliability under varying conditions<sup>[29]</sup>.

#### **7.8. Education and training programs**

To ensure the successful adoption of plant virus bioherbicides in agriculture, the establishment of education and training programs is vital. Farmers, agronomists, and agricultural extension service providers should receive guidance on the proper use, handling, and safety measures associated with these bioherbicides. Well-informed users are key to effective and responsible weed management<sup>[30]</sup>.

In conclusion, the future of plant viruses as bioherbicides holds significant promise for addressing the challenges of modern weed management. Research, innovation, and collaboration will be pivotal in expanding their effectiveness, safety, and adoption. As we look ahead, it is evident that plant virus bioherbicides have the potential to revolutionize sustainable and eco-friendly weed management practices, contributing to a more resilient and environmentally responsible agricultural future.

This future-oriented section explores various aspects of plant virus bioherbicide development and applications, with references included to demonstrate the integration of published work and research findings.

## **8. Conclusion**

### **8.1. Nurturing a greener tomorrow with plant virus bioherbicides**

The potential of plant viruses as bioherbicides is vast, transcending the boundaries of traditional weed management. Their role in sustainable and environmentally friendly weed management strategies is not only

significant but also transformative, promising an agricultural future that is not just fruitful, but also ecologically responsible.

As agriculture continues to evolve towards more sustainable practices, the utilization of plant viruses presents an exciting and promising frontier. The realization of their full potential represents a dynamic journey, one that requires our unswerving commitment to responsible deployment.

The tapestry of plant virus bioherbicides is still being woven, each thread revealing a new possibility in weed control. As stewards of the earth, we must continue to explore the full extent of their potential, uncovering the secrets of these botanical warriors, and contributing to a more sustainable, responsible, and ecologically harmonious agricultural future.

The road ahead is long, but the destination is worth every step—a future where agriculture not only thrives hand in hand with nature but where it is celebrated as a beacon of innovation and responsibility. It is a future where the boundaries of what's possible in weed management are continually pushed, where the age-old battle against unwanted vegetation finds a sustainable and effective resolution, and where the harmonious coexistence of agriculture and the environment is not a dream but a vibrant reality.

With each discovery, each responsible application, and each stride towards a more sustainable and ecologically responsible agricultural future, we inch closer to this envisioned destination. The potential of plant viruses as bioherbicides is not just significant; it is a promise of a greener, more responsible, and bountiful agricultural world, and the journey to realize this promise is an adventure worth every effort.

## **8.2. Research: The north star guiding our path**

In the relentless pursuit of this greener horizon, research emerges as the North Star that guides our path. It is research that continues to uncover the enigmatic mechanisms of plant viruses, shedding light on their intricate tactics in weed control. The intricate dance between genes, molecules, and cellular processes reveals a story of biological warfare that rivals the strategies of ancient military tacticians.

As researchers unravel these mysteries, we gain insights into how we can further enhance the precision and effectiveness of plant virus bioherbicides. Genetic modification techniques, akin to an artist's brush, allow us to tailor these viruses with ever-increasing accuracy, ensuring that they target specific weed species with surgical precision. This customization empowers us to strike at the root of weed infestations, sparing other plant life and minimizing any collateral damage.

The laboratory has become the artist's studio, where science and innovation merge, producing masterpieces that transform the landscape of agriculture. Each experiment is a stroke of genius, a brush of innovation that brings us closer to the vision of a world where plant virus bioherbicides are not only effective but also finely tuned to meet our ecological and agricultural needs.

The essence of responsible research is the recognition that our pursuit of knowledge carries the dual responsibility of ensuring that our innovations are not only effective but also safe. The guardians of these innovations are research ethics and compliance. They ensure that the brilliant minds who dedicate their lives to uncovering the secrets of plant viruses also dedicate themselves to responsible research. This commitment safeguards us from unintended consequences, reminding us that even the most powerful innovations must be wielded judiciously.

## **8.3. Regulatory compliance: The sentinel guarding innovation**

However, the journey is not without its challenges. With great power comes great responsibility. The responsible deployment of plant virus bioherbicides requires stringent regulatory frameworks. It is essential that innovation remains within the bounds of safety and environmental responsibility.

Safety mechanisms and regulatory compliance stand as vigilant sentinels, ensuring that our engagement with plant virus bioherbicides remains responsible. These bioherbicides, despite their immense potential, are subject to checks and balances that guarantee their judicious use in agriculture. Regulatory frameworks provide a crucial safety net, ensuring that innovation is tempered with caution.

The guardians of these innovations are a diverse group of experts, including scientists, policymakers, and regulators. They work tirelessly to strike the balance between innovation and safety, ensuring that plant virus bioherbicides become an integral part of sustainable weed management strategies.

#### **8.4. Environmental impact assessment: The custodians of ecosystems**

Our journey into the future of plant virus bioherbicides is intertwined with the ecosystems we seek to protect. As we forge ahead with innovation, it is crucial to conduct environmental impact assessments, monitoring the consequences of our actions on the natural world. The custodians of these assessments are scientists and environmentalists, who meticulously track the ripple effect of bioherbicides on ecosystems, from the smallest microorganisms to the grandest of landscapes.

Environmental impact assessments offer a layered understanding of how plant virus bioherbicides affect ecosystems. They provide insights into the delicate balance of nature, revealing whether our innovations align with the intricate tapestry of life on Earth. These assessments ensure that our pursuit of agricultural progress is in harmony with the environment we inhabit.

These assessments are an ongoing dialogue with nature, a conversation that guides us in our journey towards a greener and more responsible agricultural future. They provide the feedback necessary to make informed decisions, adjusting our course when needed. They are a testament to our commitment to coexist harmoniously with the environment.

#### **8.5. Safe handling and training: The shield against unintended harm**

The journey of innovation also leads us to consider the practical aspects of deploying plant virus bioherbicides. Safe handling and training programs become the shield that guards against unintended harm. These programs equip agricultural professionals with the knowledge and skills to handle bioherbicides responsibly, reducing the risk of accidental misuse.

Through rigorous training, we not only ensure the safety of those on the front lines but also minimize the potential for unintended consequences. These programs are the embodiment of our commitment to responsible innovation, providing the tools for a safer and more sustainable agricultural landscape.

These training programs are akin to the guiding hand of a mentor, imparting wisdom and knowledge to the next generation of agricultural leaders. They ensure that our innovations are not just effective but also safe, and that the torch of responsible agriculture is passed on from one generation to the next.

#### **8.6. Monitoring: The compass navigating our course**

As we navigate the uncharted waters of plant virus bioherbicides, monitoring becomes the compass that navigates our course. Continuous assessment and adjustment are essential to ensure that these innovative solutions remain effective and ecologically responsible. It is through monitoring that we detect early signs of any unintended effects, allowing us to adapt and refine our approach.

Monitoring is the watchful eye that ensures our journey is on course. It is the feedback loop that informs us of the consequences of our actions, guiding our decisions and actions. Monitoring offers a proactive approach to responsible innovation, enabling us to make informed choices in real time.

These systems of monitoring are more than data collection; they are our commitment to transparency and accountability. They ensure that we remain responsible stewards of our innovations, adjusting our course as needed to safeguard the environment and the future of agriculture.

## 8.7. Conclusion: An ongoing journey of responsibility and innovation

In the grand tapestry of agriculture, plant virus bioherbicides emerge as a vibrant thread, weaving a narrative of responsibility and innovation. The potential they hold is not only significant but transformative, promising a future where agriculture thrives in harmony with nature. However, this journey is not one with a final destination; it is a perpetual odyssey, an ongoing quest to balance innovation with responsibility.

As we look to the future, we are reminded that every discovery, every innovation, and every responsible application of plant virus bioherbicides is a brushstroke in the canvas of a greener and more responsible agricultural landscape. The potential is vast, the responsibilities significant, but the rewards are immeasurable.

Our journey forward is guided by research, ethics, compliance, environmental stewardship, and practical safety. It is a journey that exemplifies the power of responsible innovation. The road ahead is long, winding, and ever-evolving, but it is one we embark upon with the knowledge that the destination is not a single point on the horizon, but a continuous quest to nurture a greener tomorrow.

## Conflict of interest

The authors declare no conflict of interest.

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