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# Eco-Friendly Weed Control: The Science and Scope of Bioherbicides

*Varsha N, Karthika M, Dhanshree B.J., Joseph B and A.P.K. Reddy
School of Agriculture, Kaveri University, Telangana, India
*Corresponding Author's email: nvarsha68@gmail.com

Weeds pose a serious threat to agricultural productivity and farmers' economic stability. In India, the total estimated economic loss due to weeds in ten major crops is about USD 11 billion. Among these, rice accounts for losses of approximately USD 4,420 million, wheat for USD 3,376 million, and soybean for USD 1,559 million (Gharde *et al.*, 2018). In addition to yield reduction, weeds deteriorate product quality and contribute to health and environmental hazards. Herbicides have been widely adopted as an effective tool for weed control, either alone or integrated with physical, cultural, and biological methods. They constitute nearly 47.5% of the total global pesticide usage, which amounts to around 2 million tonnes annually. However, excessive dependence on herbicides has led to several negative consequences, including environmental pollution, harm to non-target organisms, and contamination of soil and water bodies. Moreover, the emergence of herbicide-resistant weeds has become a major concern. To date, weeds have developed resistance to 164 herbicides and 21 out of 31 known modes of action. Globally, 509 cases of herbicide resistance have been reported across 266 weed species (153 dicots and 113 monocots) in 95 crops across 71 countries (Heap, 2021; Choudhary, 2020). In this context, biological weed control has emerged as a sustainable alternative. It involves the use of natural enemies, bioactive compounds, or living organisms to suppress weed growth and reproduction to economically manageable levels. Bioherbicides, particularly those based on pathogenic fungi (mycoherbicides), are applied similarly to chemical herbicides, typically through spraying, where the pathogens infect and control target weeds.

Although bioherbicides are gaining recognition as an important component of weed management (Hoagland *et al.*, 2007), they are not considered a complete replacement for synthetic herbicides. Instead, they serve as an eco-friendly alternative that should be integrated with other weed management strategies. Sustainable weed management relies on a combination of approaches rather than a single method, making the integration of bioherbicides with cultural, mechanical, and biological practices essential for effective and long-term weed control (Singh et al., 2009). Bioherbicides are substances derived from biological sources that reduce weed populations through the action of living organisms such as microbes, pathogens, or their natural metabolites. They include plant-based natural products, pathogenic fungi, bacteria, and other microorganisms used for biological weed control. Despite being nature-derived, bioherbicides are not entirely harmless. Many plants naturally produce toxic compounds that can adversely affect non-target organisms in the environment. These toxins may also influence beneficial microorganisms such as bacteria, fungi, and viruses, potentially causing health issues in animals and humans (Sekhar, 2012). Therefore, careful management and application of these natural compounds are essential to avoid unintended damage to crops and beneficial biota (Duke, 2000). The development of bioherbicides dates back to the mid-1970s with the discovery of mycoherbicides (fungus-based herbicides). Since then, several bioherbicides have been developed, registered, and introduced into the global market (Zeng, 2020). One of the earliest bioherbicide approaches involved the use of the fungus *Fusarium oxysporum* against *Opuntia ficus-indica* (Pacanoski, 2015). Even earlier, in the 1950s, the parasitic weed *Cuscuta* spp. was successfully controlled using *Alternaria cuscutacidae*.

Subsequent research efforts expanded globally. In the late 1960s, extensive studies were conducted in the United States to identify pathogens for controlling *Rumex* spp., while similar work in Chile focused on *Rubus* spp. (Inman, 1971; Oehrens, 1977). Over time, the use of both registered and experimental bioherbicides has increased significantly. Plant extracts also play an important role in biological weed control. Many plants produce specific metabolites known as allelochemicals, which suppress the growth and development of neighboring plants—a phenomenon known as allelopathy (Khan et al., 2016). Recent studies suggest that combining allelopathic plant extracts with beneficial bacteria enhances weed suppression efficiency. This synergistic interaction can result in significantly greater weed inhibition compared to the use of plant extracts alone (Raza et al., 2021). Furthermore, the use of bacteria as biological control agents is relatively simple and cost-effective due to ease of culturing and application (Li et al., 2003; Raza et al., 2021). Such integrated approaches highlight the potential of bioherbicides as a sustainable component of modern weed management strategies.

## Importance of bioherbicides

The application of bioherbicides represents a sustainable and environmentally friendly approach to weed management, as it leaves minimal or no harmful chemical residues in the ecosystem. Understanding the mode of action of bioherbicides is a crucial aspect in their research and development, as it determines their effectiveness, specificity, and safety. Integration of bioherbicides with synthetic herbicides has shown promising results, as it enhances overall weed suppression while reducing the risk of herbicide resistance development in weed populations. This integrated approach supports sustainable agriculture by lowering dependence on chemical inputs. However, the development and commercialization of bioherbicides are often costly and require significant investment in research, production, and regulatory approval. Therefore, international organizations and research institutions should play a key role in supporting the development and dissemination of these eco-friendly products. One of the primary objectives behind bioherbicide development is to target niche or less competitive segments within the existing agrochemical market.

**Table: Types of Bioherbicides and Their Characteristics:**

| Category | Agents/Examples | Target Weeds | Mode of Action | Key Features |
|---|---|---|---|---|
| Fungal Pathogens (Mycoherbicides) | *Alternaria*, *Phoma*, *Sclerotinia*, *Dactylaria higginsii*, *Phomopsis amaranthicola*, *Chondrostereum purpureum* | *Chenopodium album*, *Cirsium arvense*, *Cyperus rotundus*, *Amaranthus spp.* | Produce phytotoxins, cause leaf spots, blight, root/stem rot | Host-specific, long persistence, most effective bioherbicides |
| | *Sclerotinia minor*, *S. sclerotiorum* | Dandelion, creeping thistle | Release oxalic acid inhibiting plant defense enzymes | Strong phytotoxic effect |
| | *Alternaria destruens* (Smolder) | *Cuscuta spp.* | Infects and destroys parasitic weeds | Commercially available |
| | *Phytophthora palmivora* (DeVine) | *Morrenia odorata* | Causes disease in weed plant | Used in citrus orchards |
| Viruses | Tobacco Mosaic Virus (TMV) | *Solanum viarum* | Infects plant cells causing death | Less specific, high variability, limited use |

| | | | | |
|---|---|---|---|---|
| Bacteria | *Pseudomonas fluorescens* | Multiple monocots & dicots | Suppresses seed germination | Easy to culture, eco-friendly |
| | *Xanthomonas campestris* (Camperico) | *Poa annua* (annual bluegrass) | Infects and reduces weed growth | Can be genetically improved |
| Plant-Based Bioherbicides | Plant extracts, essential oils, allelochemicals | Various weeds | Inhibit germination and growth | Natural, biodegradable |
| | Secondary metabolites (alkaloids, terpenoids, peptides) | Broad spectrum | Interfere with physiological processes | Used in organic farming |

## Formulation of Bioherbicide

The formulation of bioherbicides is a critical step in ensuring their effectiveness in field conditions. Many fungal pathogens that infect leaves and stems depend on specific humidity levels and suitable temperatures to perform optimally. This creates a need for specialized formulations that help maintain their activity after application. According to Boyetchko *et al.* (1998), bioherbicide formulation technology must address several key factors to preserve or enhance the efficacy of the biocontrol agent while also ensuring compatibility with standard field application methods. Common formulation types include emulsions, organosilicone surfactants, hydrophilic polymers, and encapsulated granules made from materials like alginate, starch, or cellulose. Each of these has its own benefits and limitations in terms of improving pathogen virulence, overall effectiveness, and ease of use (Charudattan, 2001; Hallett, 2005). Overall, an effective formulation should help make the target weed more susceptible to infection, protect the pathogen from environmental stresses, and support the development of disease for successful weed control.

## Potential Areas for the Use of Bioherbicides

Bioherbicides have significant potential across a range of agricultural situations, particularly where conventional weed control methods face limitations.

1. In conventional cropping systems, bioherbicides can be especially useful under several conditions: when weeds develop resistance to broad-spectrum herbicides; when high doses of herbicides are required to control specific weeds; when parasitic weeds cannot be managed due to a lack of selective herbicides; when chemical herbicide use is restricted by cost or environmental concerns; and when invasive weed species establish in areas with limited control options.
2. As herbicide resistance continues to increase among major weed species, bioherbicides are likely to play a growing role in maintaining effective weed management in conventional agriculture.
3. Changes in cropping practices, such as reduced tillage, often lead to shifts in weed populations particularly an increase in perennial weeds. Bioherbicides offer a way to manage these emerging weeds before they become economically significant.
4. In many regions, parasitic weeds cause severe crop losses and are difficult to control due to the absence of selective herbicides. Bioherbicides show strong potential for targeted control of such weeds.
5. Bioherbicides are most effective when used as part of an integrated weed management (IWM) approach, which combines multiple strategies such as tillage, cultural practices, chemical herbicides, allelopathy, and biological control. Rather than acting alone, bioherbicides contribute best within a broader, long-term weed control program.
6. Since most biological control agents are highly specific to individual weed species, combining bioherbicides with selective herbicides can improve overall weed control. Using reduced herbicide doses alongside bioherbicides can also enhance their effectiveness, particularly in the case of mycoherbicides.

7. Managing weed seed banks and preventing seed germination are essential for long-term weed control. Bioherbicides can target seeds and seedlings before they compete with crops. Approaches include applying microbial agents to soil, crop residues, or crop seeds, and integrating treatments with techniques like soil solarization or germination-stimulating agrochemicals to eliminate emerging weed seeds.
8. Farming systems that limit or avoid chemical herbicides, such as organic, ecological, and sustainable agriculture are well-suited for the adoption of bioherbicides. These systems provide valuable opportunities to develop and refine biologically based weed management strategies for wider application.

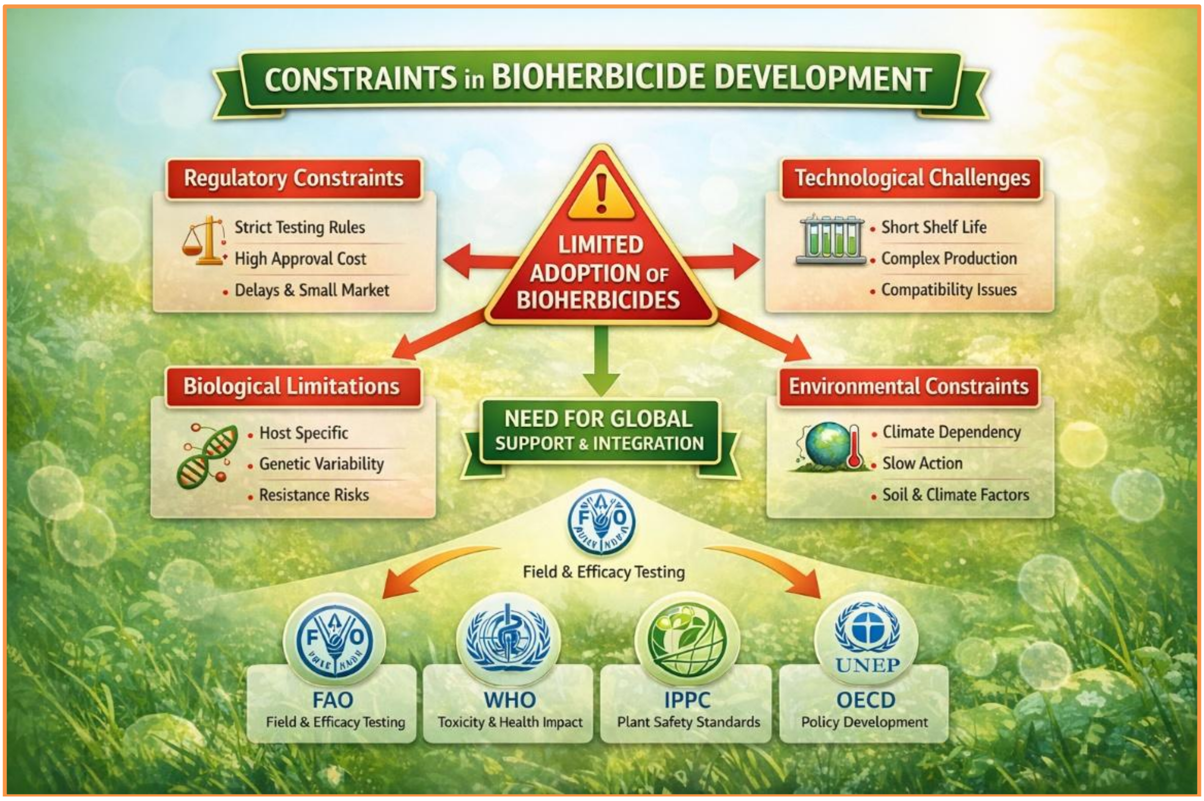


**Fig: Constraints in using bioherbicides development**

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