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BIOHERBICIDE: SUSTAINABLE ALTERNATIVES TO CHEMICAL WEED MANAGEMENT

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ABSTRACT

Weeds are among the most serious biological constraints affecting global agricultural productivity and quality. They compete with crops for vital resources such as water, nutrients, and light, while also serving as alternate hosts for pests and pathogens. Conventional chemical herbicides have long been the dominant method of weed control due to their cost-effectiveness and reliability. However, the overdependence on these synthetic chemicals has led to severe ecological and agronomic problems, including environmental contamination, herbicide-resistant weed populations, and health risks to humans and non-target organisms. These challenges highlight the urgent need for sustainable, eco-friendly alternatives such as bioherbicides. Bioherbicides, derived from living organisms or natural metabolites, represent an emerging and environmentally compatible approach to weed management. They include products based on bacteria, fungi (mycoherbicides), plant-derived allelochemicals and essential oils, and plant viruses. Bacterial bioherbicides, such as *Xanthomonas campestris* and *Pseudomonas fluorescens*, suppress specific weed species by releasing phytotoxic metabolites. Fungal bioherbicides, especially those derived from *Colletotrichum*, *Alternaria*, and *Phoma*, act through infection and enzymatic degradation of plant tissues. Plant-based bioherbicides utilize allelochemicals and essential oils from species like *Sorghum bicolor*, *Juglans nigra*, *Eucalyptus globulus*, and *Ocimum basilicum* to inhibit weed germination and disrupt cellular metabolism. Viral bioherbicides, exemplified by Tobacco mild green mosaic virus (TMGMV), induce hypersensitive reactions in target weeds, leading to necrosis and death. Although more than 22 bioherbicidal products have been registered globally, their widespread adoption remains limited due to short shelf life, formulation instability, inconsistent field performance, and high production costs. Environmental factors such as humidity, temperature, and UV exposure further influence their efficacy. Additionally, complex regulatory frameworks and low awareness among farmers constrain their commercialization. Nevertheless, the growing global emphasis on sustainable agriculture and climate resilience presents new opportunities for bioherbicide development. Future research should focus on improving formulation technology, enhancing field consistency, identifying novel bioherbicidal strains, and integrating biological control into holistic weed management systems. Collaborative efforts among researchers, policymakers, and industry stakeholders are vital for overcoming economic and technical barriers. In conclusion, bioherbicides hold great promise as a sustainable, safe, and effective component of integrated weed management strategies, offering an environmentally responsible alternative to synthetic herbicides while supporting global goals for agricultural sustainability and food security.

Introduction

Weeds are among the most persistent biological constraints that reduce crop productivity and quality globally. They compete with crops for essential growth resources, such as water, light, nutrients, and space and can harbor numerous pests and pathogens that leads to more yield losses. Weeds are estimated to cause 30-40% yield reduction in major crops if left uncontrolled, resulting in billions of dollars in agricultural losses annually. Chemical herbicides have served as the primary and most effective method for weed suppression due to their rapid action, reliability, and ease of application. However, the excessive and repeated use of these synthetic herbicides has led to serious ecological, agronomic, and health-related challenges, including environmental pollution, herbicide-resistant weed biotypes, and contamination of food chains and groundwater. Eco-friendly weed management strategies that align with the principles of sustainable agriculture should have created for better future.

The world's population may reach about 9.2 billion by the year 2050, which means food production must increase by nearly 70% to feed everyone (Kagan, 2016). The Food and Agriculture Organization (FAO, 2001) says that almost half of the land suitable for farming is already being used for agriculture. Farmers face many problems in these fields such as weeds, insects, and plant diseases, but among these, weeds cause the biggest loss in yield (Curran 2016). Weeds compete with crops for water, sunlight, nutrients, and space, which can reduce crop yield by 20–50%, depending on how serious the infestation is (Kaur *et al.,* 2019).

To manage weeds, farmers use different methods like hand weeding, machines, or chemicals (Rose *et al.,* 2016). Out of these, chemical weed control has become the most common and effective because it saves time, reduces labor, and increases productivity at a lower cost (Sondhia, 2014; Janaki *et al.,* 2015). Today, herbicides are a key part of modern farming and are used widely to increase yields and keep fields weed-free (Cobb 2022). Around the world, about 4.1 million tons of pesticides are used every year herbicides make up almost 47.5%, followed by insecticides (29.5%), fungicides (17.5%), and other chemicals (5.5%) (Sharma *et al.,* 2019a; Riedo *et al.,* 2021). Since 1945, farmers in many countries have used more than 200 types of herbicide ingredients, which make up about 25% of total pesticide use in the past ten years (Green, 2014). This increase in chemical use has been linked to rapid economic and industrial growth, especially during the late 19th century (Sharma *et al.,* 2019a).

Herbicides play a major role in increasing crop yield and ensuring food security, they also pose risks to human health and the environment due to their presence in soil, air, and water (Fernandes *et al.,* 2020). When used in farms or other areas, herbicides can harm people, animals, insects, and aquatic life, especially when overused or handled improperly (Khan *et al.,* 2023; Sondhia, 2014). Their residues may remain in crops and soils, cause toxicity, create resistant weeds, and affect non-target organisms (Janaki *et al.,* 2015). Runoff, leaching, and air movement can spread these chemicals to other areas, increasing their environmental impact (Andreu and Picó 2004). Therefore, it is important to monitor herbicide residues and understand their behavior in the environment for safe and sustainable use (Meftaul *et al.,* 2020).

In recent years, agriculture has shifted towards high-input systems supported by new herbicides, genetically modified herbicide-tolerant crops, and improved weed management technologies (Beckie *et al.,* 2019). Systemic herbicides move inside plants to kill weeds effectively, while pre-emergence types prevent weed germination and reduce crop competition (Amna *et al.*, 2019; Oliveira *et al.,* 2020). Current trends show a move toward more targeted herbicide formulations that act on specific weeds and reduce chemical load in the environment (Damalas and Koutroubas, 2018).

Growing evidence of environmental and health risks highlights the need for eco-friendly and sustainable weed control approaches. Herbicides should be designed to break down safely after their intended use (Janaki *et al.,* 2015). However, information about their long-term effects and safe management is still limited. Hence, this review aims to summarize recent findings on herbicide use, resistance issues, new technologies, and sustainable strategies useful for farmers, policymakers, and researchers.

Herbicide Resistance in weeds and its mechanism

Weed resistance to herbicides is rapidly increasing worldwide and has become a serious concern for global food security (Délye *et al.,* 2013). Continuous use of the same herbicide with a similar mode of action causes weed populations to adapt and develop resistance (Qasem, 2011). For instance, the long-term use of glyphosate in genetically modified herbicide-resistant (HR) crops has led to the emergence of several resistant weed species (Gage *et al.,* 2019). Over time, these resistant weeds multiply and dominate the field population (Bo *et al.,* 2017).

Herbicide resistance depends on factors such as chemical structure, application frequency, and non-chemical conditions (Renton *et al.,* 2014). The first known case was reported in 1957, when wild carrot (*Daucus carota* L.) in Canada became resistant to 2,4-D. Since then, more than 200 weed species have evolved resistance to one or more herbicides globally (Délye *et al.,* 2013). The highest numbers are found in the USA, Australia, Canada, France, and China (Heap, 2014). Notable examples include wild radish (*Raphanus raphanistrum L.*) in Australia, prickly lettuce (*Lactuca serriola* L.) in the USA, and corn poppy (*Papaver rhoeas L.*) in Europe, all resistant to common herbicides (Busi *et al.,* 2018a).

Glyphosate-resistant (GR) crops were introduced in 1996, but continuous glyphosate use soon led to resistant species like *Lolium rigidum* (1996) and *Eleusine indica* (1997) (Heap, 2014; Fernández *et al.,* 2017). Today herbicide-resistant weeds continue to spread, threatening crop productivity and ecological balance worldwide (Peterson *et al.,* 2018)

In modern farming, herbicide resistance has become a serious problem, reducing the ability of herbicides to control weeds effectively (Peterson *et al.,* 2018). Research shows that weeds develop resistance through several biological mechanisms. One common type is target-site resistance, which happens when genetic changes occur in the part of the plant where the herbicide normally acts, such as ACCase, ALS, or PSII enzymes. These mutations make the herbicide less effective because it can no longer attach properly to its target site (Heap, 2014; Moss, 2017). Such changes can occur naturally or after repeated herbicide exposure. Target-site resistance may result from altered proteins, increased gene copies, or higher gene expression levels (Heap, 2014; Moss, 2017).

Another important mechanism is metabolic resistance, where the weed breaks down or detoxifies the herbicide before it can cause harm. This usually involves enzymes like cytochrome P450 monooxygenases, glutathione transferases, or esterases that help the weed neutralize the herbicide (Yu and Powles 2014). Some weeds also resist herbicides by reducing uptake or movement of the chemical inside the plant. This can happen due to changes in cell membranes, reduced permeability, or increased activity of efflux transporters that push the herbicide out of plant cells (Gressel, 2015; Busi *et al.,* 2018b).

In certain cases, weeds develop multiple resistance, where they survive several herbicides with different modes of action. This can occur when different resistance traits build up in a population or when genes are transferred between species (Busi *et al.,* 2017). Understanding these resistance mechanisms is essential for designing effective and sustainable weed management strategies.

Bioherbicides and Their Mechanism:

Bioherbicides are different from normal biological control methods because they use specially prepared formulations made from plant pathogens that can be produced in large quantities (Hershenhorn *et al*., 2016). These products are usually sprayed or applied as granules on weed surfaces, allowing the active organisms to enter the plant and start infection (Caldwell, 2012; Harding and Raizada, 2015). After getting inside, the pathogens release a mix of enzymes such as cellulase, amylase, ligninase, protease, and pectinase, which help soften and break the plant's cell walls and membranes (Xie *et al*., 2013). This breakdown makes it easier for the pathogen to spread through the weed tissues (Xie *et al*., 2013, Hoagland *et al*., 2007).

Along with this, the pathogens in bioherbicides also produce toxic compounds and small peptides that disrupt the normal working of plant cells. These substances can change the way plant genes function and affect their defence and metabolic systems (Vurro *et al*., 2009). As a result, several physiological changes happen in the weed, such as a drop in enzyme and hormone activity, lower nutrient uptake, disturbed photosynthesis, damage to membranes, lipid oxidation, and failure of seed germination and growth (Xie *et al*., 2013; Lee *et al*., 2015; Talukder *et al*., 2019).

Poor nutrient movement reduces chlorophyll formation and turns leaves yellow. Hormonal imbalance also increases compounds like abscisic acid, jasmonic acid, and salicylic acid while reducing gibberellin activity (Lee *et al*., 2015; Talukder *et al*., 2019. This chain of changes lowers photosynthetic efficiency, increases oxidative stress, and causes earlier aging in plants (Lee *et al*., 2015). However, the way bioherbicides act can vary, as different pathogens affect weeds in slightly different ways (Pugazhendhi *et al*., 2019).

Bacteria

Bacteria-based bioherbicides have shown promising results in managing different types of weeds (Table 1). However, one of the biggest challenges in their development is finding and selecting the right bacterial strains that can directly attack and suppress specific weed species (Dumas *et al*., 1997). Recent studies have identified several bacterial strains with strong weed-suppressing ability (Table 1). Among them, *Xanthomonas campestris* pv. *poae* (JT-P482) and *X. campestris* (LVA-987) have been the most effective in reducing the growth of turf grass weeds. These strains were later developed into a commercial bioherbicide in Japan called Camperico™ (Halgren *et al*., 2013; Hussain *et al*., 2021; Charudattan *et al*., 1986).

Although Camperico™ has been successful in controlling certain weeds, its performance largely depends on environmental conditions. Research has shown that it needs a warm and humid environment, with around 25 °C and sufficient dew, to achieve more than 60% weed mortality. Therefore, future studies should focus on understanding how factors such as temperature, humidity, and climate influence the effectiveness of bacterial bioherbicides. Such information would be highly useful for land managers and farmers to ensure better and more consistent weed control results (Boyette *et al*., 2015).

Apart from the *Xanthomonas* strains, several other bacterial species have also been reported to possess weed-suppressing potenti. These include *Curtobacterium* sp. (MA01) (Harding, 2015), *Pseudomonas fluorescens* (strains D7, WH6, and BRG100), and *Pseudomonas viridiflava* (CDRTC14) (Samad *et al*., 2017). Each of these bacteria has demonstrated effective inhibition of various weed species, indicating their possible use as bioherbicides. However, compared with synthetic herbicides, bacterial bioherbicides generally act more slowly in reducing weed populations (Kennedy, 2018). For instance, *P. fluorescens* may require nearly five to seven years to fully suppress an infested area, making the process time-consuming and expensive. Moreover, in some cases, it has also negatively affected nearby native grass species. Therefore, its practical application as a commercial bioherbicide remains limited unless improvements are made in terms of cost-effectiveness, time efficiency, and environmental safety.

Integrating bacterial bioherbicides with other weed control measures such as burning, grazing, or manual removal could enhance their effectiveness. However, this approach may not always result in satisfactory weed suppression. For example, Pyke *et al.,* reported that using a *P. fluorescens*-based bioherbicide in combination with post-fire native grass sowing failed to control *Bromus tectorum* (cheatgrass). Despite such limitations, further research is needed to better understand how different combinations of bioherbicides and management strategies interact. Such studies could contribute significantly to developing sustainable and long-term weed management programs (Halgren, 2013).

Fungi (Mycoherbicides)

The use of fungi as bioherbicides, commonly termed *mycoherbicides*, has gained significant attention due to their effectiveness against a wide range of weed species (Table 2) (Bailey *et al*., 2010 ; Cordeau *et al*., 2016; Charudattan *et al*., 1986; Dumas *et al*., 1997; Boyette *et al*., 2019; Nandhini *et al*., 2019; Galea 2021). The concept dates back to the 1950s when Russian researchers successfully developed and mass-produced spores of *Alternaria cuscutacidae* for controlling the parasitic weed *Cuscuta* spp. (dodder) (Kaur *et al*., 2019). Since then, several fungal bioherbicides have been developed and commercialized in countries such as Australia, Canada, China, South Africa, the Netherlands, and the USA (Bailey *et al*., 2010 ; Cordeau *et al*., 2016; Charudattan *et al*., 1986; Dumas *et al*., 1997; Boyette *et al*., 2019; Nandhini *et al*., 2019; Galea 2021; Morris *et al*., 1999; Butt and Copping, 2000; Green, 2003)

Among the commercially available products, BioChon™, Chontrol™/Ecoclear™, Myco-Tech™, and Stumpout® have been effectively used to manage woody weeds (Table 2) (Bailey *et al*., 2010; Dumas *et al*., 1997; Morris *et al*., 1999; Green, 2003; Charudattan, 2005). These formulations typically consist of fungal mycelia applied as a paste to the freshly cut stumps of target plants. Once applied, the fungal mycelium invades the vascular tissues, obstructs nutrient transport, prevents resprouting, and accelerates the decay of plant tissues (Bailey *et al*., 2010; Charudattan, 2005; Bailey, 2014; Vieira *et al*., 2018). However, this method requires prior mechanical cutting of plants close to the ground, which can be labor-intensive and expensive when treating extensive infestations (Bailey *et al*., 2010; Cordeau *et al*., 2016).

To overcome these limitations, a more efficient approach using capsule-based, stem-injected mycoherbicides has recently been developed. This technique allows fungal capsules to be drilled directly into the stems of target plants, eliminating the need for cutting and reducing operator exposure to potential hazards (Galea, 2021). The product Di-Bak Parkinsonia™, containing *Lasiodiplodia pseudotheobromae*, *Macrophomina phaseolina*, and *Neoscytalidium novaehollandiae*, has demonstrated excellent control of *Parkinsonia aculeata* L. (parkinsonia) (Galea, 2021). Beyond killing existing plants, this formulation has shown the ability to spread through *P. aculeata* populations and suppress seedbank recruitment, providing long-term weed management (Galea, 2021).

Future studies should explore the potential of similar capsule-injection mycoherbicides for other woody weeds. The main challenge in such applications will be identifying fungal strains that are host-specific and do not harm neighboring native vegetation.

Among the fungi evaluated for bioherbicidal potential, species belonging to the genus *Colletotrichum* have been the most extensively studied and utilized in mycoherbicide formulations (Butt, 2000; Andersen *et al*., 1985; Bowers, 1986; Mortensen, 1988; Vieira *et al*., 2018; Fernando *et al*., 1993; Fernando *et al*., 1994; Fernando *et al*., 1996; Bowers, 1986). Numerous research efforts involving this genus have led to the development of several mycoherbicidal products (Table 2), including BioMal® (derived from *C. gloeosporioides* f. sp. *malvae*) (Bowers, 1986; Mortensen, 1988; Boyetchko *et al*., 2007), Collego™/LockDown™ (formulated from *C. gloeosporioides* f. sp. *aeschynomene*) (Boyette *et al*., 2019; Bowers, 1986), Lubao 1 and Lubao 2 (based on *C. gloeosporioides*) (Nandhini *et al*., 2019), Velgo® (sourced from *C. coccodes*) (Andersen *et al*., 1985), and *C. truncatum*, which has shown promise but is yet to be commercialized (Vieira *et al*., 2018).

Although *Colletotrichum*-based mycoherbicides have demonstrated successful weed control across different regions, their widespread adoption has been limited by several factors. These include their higher production cost compared to synthetic herbicides, lower consistency in field performance, and narrow host range, which restrict their use to specific weed species (Zimdahl, 2018; Osadebe *et al*., 2021). Consequently, these constraints have reduced the market demand and practical application of many fungal bioherbicides (Zimdahl, 2018; Osadebe *et al*., 2021).

Similar challenges have also been reported for other fungal-based bioherbicides such as Casst™ (from *Alternaria cassiae*) (Anese *et al*., 2015), DeVine® (from *Phytophthora palmivora*) (Tigre *et al*., 2015), Dr. Biosedge® (from *Puccinia canaliculata*) (Cheng *et al*., 2021), Sarritor™ (from *Sclerotinia minor*) (Bailey *et al*., 2010; Mortensen, 1988), Smolder® (from *Alternaria destruens*) (Bailey *et al*., 2010; Cordeau *et al*., 2016), and Woad Warrior® (from *Puccinia thlaspeos*) (Table 2).

To ensure the sustainable and economical use of mycoherbicides in weed management, future research should focus on:

(i) reducing the production and formulation costs for large-scale deployment;

(ii) enhancing awareness and adoption among landmanagers;

(iii) minimizing non-target effects on native vegetation; and

(iv) improving the field performance and persistence of existing products

Recent investigations have also revealed several promising fungal species with potential for future commercialization (Table 2). These include *Albifimbria verrucaria* (formerly *Myrothecium verrucaria*) *Fusarium oxysporum* f. sp, *Gibbago trianthemae*, *Phoma chenopodicola*, *Phoma macrostoma* Montagne 94-44B *Pseudolagarobasidium acaciicola*, *Trichoderma koningiopsis*, and *Trichoderma polysporum*. These fungi represent valuable candidates for further study, with potential to broaden the range of effective and eco-friendly mycoherbicides available for integrated weed management programs.

Plant Extracts (Allelochemicals and Essential Oils)

Plant-derived phytotoxins mainly allelochemicals and essential oils have demonstrated significant potential and efficiency in managing a wide range of weeds (Table 3). These compounds offer several advantages over conventional synthetic herbicides because they are biodegradable, exhibit diverse modes of action, and are generally non-toxic to humans and non-target organisms.

Among these natural compounds, allelochemicals have attracted particular interest. They are secondary metabolites produced by certain plants that, when released into the environment or applied to other plants, disrupt vital physiological and biochemical functions. Specifically, allelochemicals can alter enzymatic activity, gene expression, hormonal balance, and metabolic pathways, which results in stress, growth inhibition, and eventually, plant death.

Research and experimental studies have identified numerous allelopathic plant sources with potential for bioherbicide formulation (Table 3). These include *Canavalia ensiformis* de Candolle (jack bean) extract (50 g L^{-1}), *Cirsium setosum* L. (HL-1 isolate) (Anwar *et al*., 2021), *Cynara cardunculus* L. (artichoke thistle) ethanol and lyophilized leaf extracts *Juglans nigra* L. (black walnut) (>42.9% concentration), *Lantana camara* L. (Lantana), *Ocimum basilicum* L. (sweet basil), and *Sorghum bicolor* L. (great millet).

While these plant extracts have shown promising results in suppressing various weed species, long-term and repeated-use studies are still required to determine their effects in both agricultural and natural ecosystems. Future investigations into allelochemicals should focus on understanding (i) their phytotoxic efficiency, (ii) their impact on surrounding flora, (iii) chemical composition and structural activity relationships, (iv) their mechanism of action, and (v) their potential for safe and sustainable commercialization

In addition to allelochemicals, essential oils extracted from plants have also proven effective as bioherbicidal agents against numerous weed species (Table 3) Essential oils can be obtained from different plant parts, including bark, flowers, fruits, leaves, roots, or even the whole plant. They typically act by damaging the target plant’s DNA, enzymatic systems, and cellular functions, leading to disruption of physiological processes and subsequent death

Since 2020, several commercial bioherbicides containing essential oils as active ingredients have entered the market. Examples include Avenger Weed Killer® (70% d-limonene), GreenMatch® (55% d-limonene), GreenMatchEX® (50% lemongrass oil), Weed Slayer® (6% eugenol), WeedZap® (45% clove oil and 45% cinnamon oil), and Bioweed™ (10% pine oil + sugar)

A more recent development is Weed Lock®, a non-selective bioherbicide formulated in Malaysia for managing a broad spectrum of weed species This product acts through foliar absorption, inducing chlorosis and wilting in the target plants within a few hours of application. Despite its effectiveness, Weed Lock® is currently available only in small, ready-to-use formulations, which limits its practicality and cost-effectiveness for large-scale weed management Therefore, further optimization and upscaling of its production process are necessary to make it feasible for extensive agricultural use.

Other plant-derived essential oils have also demonstrated considerable potential for use as natural bioherbicides. Notably, oils obtained from Corymbia citriodora Hooker (formerly *Eucalyptus citriodora*, lemon-scented gum) and *Eucalyptus globulus* Labillardière (blue gum) have exhibited strong phytotoxic properties against various weed species. Similarly, manuka oil, extracted from *Leptospermum scoparium* Forster (manuka tree), and pine oil (10% concentration combined with sugar) have also shown effective weed suppression (Table 3)

Additionally, several compounds present in the essential oils of citronella, clove, lemongrass, orange, pine, thyme, and other *Eucalyptus* species have been reported to possess significant bioherbicidal activity against a broad spectrum of plant species To enhance the applicability of these natural compounds, future research should focus on optimizing their formulations and determining the specific weed species most susceptible to each essential oil when used as a bioherbicidal agent.

Virus-Based Bioherbicides

Bioherbicides developed using viral pathogens have shown mixed levels of success in managing different weed species (Table 4). Among these, one of the most promising and well-studied examples is the Tobacco mild green mosaic virus (TMGMV) This virus has been highly effective in controlling *Solanum viarum* Dunal (tropical soda apple) in Florida, USA, by inducing necrotic spots and hypersensitive reactions that eventually cause plant death within 20 to 50 days.

Because viral particles contain nucleic acids (DNA or RNA), they must enter living plant cells through small wounds or openings to initiate infection. For this reason, TMGMV is typically formulated with carborundum and an organosilicon adjuvant to help the virus penetrate plant tissues. It can be applied through methods such as abrade-and-spray treatment, high-pressure spraying (over 80 psi), or wiper applications. Interestingly, TMGMV remains active even when mixed with some synthetic herbicides, suggesting that combining it with chemical herbicides could improve its weed control efficiency.

Another virus, the Araujia mosaic virus (AMV), has shown potential in controlling *Araujia hortorum* Brotero (moth plant) in New Zealand AMV causes leaf distortion and mosaic symptoms that eventually kill the plant. However, its use as a bioherbicide is limited because it can also infect and harm plant species that serve as host plants for the Monarch butterfly (*Danaus plexippus* L.), posing a risk to biodiversity. To make AMV a safer bioherbicide, genetic modification may be required to restrict its transmission to non-target plants, but such work is costly and not widely supported

Other plant viruses such as Tobacco rattle-like virus, Pepper mosaic virus (Óbuda Pepper Virus), and Pepino mosaic virus have also shown potential in suppressing certain weeds when tested in bioherbicidal formulations (Table 4) However, to enable their successful and reliable use, further research is needed to understand their formulation, application methods, and host specificity.

Plant extract bioherbicides

Plant extract-based bioherbicides are obtained from different plant parts such as leaves, roots, and seeds, which naturally contain compounds with herbicidal activity. These extracts utilize the bioactive substances present in plants to interfere with weed growth, physiology, and metabolic functions. Examples include extracts from neem (*Azadirachta indica*), clove (*Syzygium aromaticum*), cinnamon (*Cinnamomum verum*), parthenium (*Parthenium hysterophorus*), and even natural vinegar, all of which have shown strong weed-suppressing abilities A notable instance is the phytotoxic water extract derived from *Sorghum bicolor*, which effectively suppresses weeds without affecting crop yield. Application of sorghum water extract has been reported to decrease the biomass of *Echinochloa crus-galli* by nearly 40%, leading to an 18% enhancement in rice yield.

Biochemical Bioherbicides

Biochemical bioherbicides are developed from naturally derived or biologically synthesized compounds that disrupt the physiological and biochemical pathways of weeds, ultimately suppressing their growth and development. These compounds may include plant hormones, enzymes, or secondary metabolites with proven herbicidal activity. For instance, a byproduct obtained from ethanol manufacturing has been shown to effectively control *Stellaria media* L. and *Poa annua*, while also reducing the germination of *Oxalis corniculata* L. Similarly, corn gluten meal (CGM) a residue produced during the wet-milling of maize has long been recognized for its natural herbicidal potential.

Seed-Based Bioherbicides

Seed-based bioherbicides are applied directly to seeds prior to sowing to suppress weed emergence during crop germination and early seedling stages. This approach shields young crops from early weed competition, facilitating better establishment and vigor of the desired plants These bioherbicides represent an eco-friendly and adaptable strategy for weed management, employing natural organisms or their bioactive compounds that act through multiple mechanisms. For effective and sustainable outcomes, their selection and application must consider weed species, environmental conditions, and method of use. With growing emphasis on sustainable agriculture, seed-based bioherbicides are anticipated to become an increasingly important component of integrated weed management systems in both agricultural and natural ecosystems.

Achievements, Developments and Future Challenges

Significant progress has been made in the development and use of bioherbicides in recent years. At present, more than 22 bioherbicidal products have been officially registered and are available commercially for weed management (Table 5). Apart from these, several additional formulations are either under development or have been tested earlier but could not reach the market due to limited farmer acceptance and the high cost of production (Tables 1–3).

According to global market estimates, the bioherbicide industry was valued at approximately USD 1.28 billion in 2016, and with ongoing research and technological innovations, it is projected to grow to around USD 4.14 billion by 2024. This trend reflects the increasing interest in sustainable weed management and eco-friendly alternatives to chemical herbicides.

However, despite these encouraging advancements, several technical, economic, and regulatory challenges still restrict the widespread commercialization of bioherbicides. Issues such as short shelf life, formulation stability, inconsistent field performance, and limited awareness among end users remain major obstacles. Addressing these barriers is essential to make bioherbicides economically feasible and commercially successful in the long run.

Environmental Challenges and Future Considerations for Bioherbicides

A major limitation in the effective use of bioherbicides is their sensitivity to environmental conditions Factors such as humidity, soil type, temperature, UV radiation, and the availability and quality of water have been shown to significantly affect bioherbicide performance. These variables can influence both the formulation process and the field efficiency of bioherbicides, sometimes reducing their effectiveness when applied directly to target plants

Furthermore, climate change is expected to introduce additional challenges. Rising temperatures and atmospheric CO_2 concentrations are predicted to alter weed population dynamics and increase the frequency of herbicide-resistant species. Such shifts suggest that current weed management strategies may become insufficient under future climate scenarios, highlighting the need for more adaptive approaches, including the use of bioherbicides.

Given these uncertainties, a variety of questions are likely to emerge regarding the efficacy and mode of action of bioherbicides, as weeds may undergo structural, physiological, and evolutionary changes in response to changing environmental conditions This emphasizes the importance of a multidisciplinary research approach to evaluate bioherbicide performance under diverse and changing climates. Future studies should focus on understanding how predicted climatic variations affect bioherbicide effectiveness, ensuring their reliable application in future weed management programs.

Formulation and Commercialization Challenges of Bioherbicides

Another key limitation affecting the success of bioherbicides lies in their formulation and commercialization. Since bioherbicides contain living organisms, maintaining their viability and stability throughout production, storage, and application is critical. Ensuring that these biological agents remain active over the entire period from development to field use requires careful attention to optimal storage conditions, which can vary significantly depending on the specific bioherbicidal agent.

Economic and Regulatory Barriers to Bioherbicide Use

In addition to formulation challenges, the high production and commercialization costs of bioherbicides pose a significant barrier to their widespread adoption, particularly for large-scale applications. These costs could be mitigated through increased awareness and education about the benefits of bioherbicides, as well as by incorporating technological innovations such as precision or smart spray systems

Regulatory requirements also limit the use of bioherbicides. In many countries, these products must undergo formal registration with agencies such as the Environmental Protection Agency (EPA) before commercialization. This process is often expensive and time-consuming, and requirements can vary widely between countries. For example, investment and use of bioherbicides in Australia, Canada, and the USA are significantly higher than in many European nations The limited development and adoption in some regions are partly due to uncertainties and caution regarding the use of living biological agents in agricultural or natural ecosystems

To address these challenges, it is recommended that governmental and non-governmental organizations collaborate to identify priority areas where research and information are urgently needed. Such efforts would support the safe, effective, and long-term use of bioherbicides for weed management

Conclusions

Despite significant progress in the development of biological control as a dependable strategy for weed suppression, its practical implementation in agroecosystems particularly within complex cropping systems remains limited. There is a growing need for efficient bioherbicidal strategies capable of targeting multiple weed species simultaneously. Achieving this goal may involve identifying and utilizing several “core strains” of bioagents that are well adapted to the soils and climatic conditions of specific regions and possess the ability to suppress dominant local weed flora.

For successful adoption, it is essential to integrate biological control methods into existing weed management practices, allowing the efficacy and reliability of bioherbicides to be demonstrated under field conditions. In the near term, bioherbicides developed for niche applications and sustainable farming systems are expected to show the greatest potential for effective biological weed control. Such targeted success can provide momentum for the discovery and large-scale development of new bioherbicides.

From a broader weed management perspective, combining multiple strategies such as diverse bioherbicides and biologically based approaches can enhance both the stability and long-term efficiency of weed control programs (Cardina, 1995). Integrating biological control into current systems also provides a valuable supplementary option, especially as chemical herbicide use faces increasing restrictions. Continuous reliance on single chemical herbicides often leads to the evolution of resistant weed populations and further degradation of conventional cropping systems. In contrast, employing bioherbicides within integrated and diversified weed management frameworks can help restore soil fertility, maintain productivity, and prevent the spread of herbicide-resistant and invasive weeds. Moreover, the inclusion of bioherbicides in agricultural and ecological restoration programs plays a crucial role in reclaiming degraded lands and reviving biodiversity within ecosystems affected by intensive conventional farming.

Despite these benefits, bioherbicides remain an emerging technology that requires further research to overcome several challenges. Future work should focus on:

1. Improving commercialization and formulation processes to ensure economic viability and stability.
2. Identifying and developing new bioherbicidal sources from bacteria, fungi, plant extracts, or viruses.
3. Elucidating the specific modes of action for different classes of bioherbicides.
4. Assessing the influence of environmental conditions on their effectiveness in diverse agricultural and natural ecosystems.

Addressing these areas in a coordinated manner will be crucial to enhance the efficiency, reliability, and long-term adoption of bioherbicides in sustainable weed management programs.

Table 1 : Bacterial bioherbicides and their impacts on targeted weeds.

Bacterial Source	Target Weed(s)	Effect / Mode of Action
*Curtobacterium*sp. MA01	*Petunia* spp.	Alters enzymatic and metabolic reactions, including the degradation of protein synthesis and lipid peroxidation.
Pseudomonas fluorescens D7	*Aegilops cylindrica* (jointed goatgrass); *Bromus tectorum* (downy brome); *Taeniatherum caput-medusae* (medusa-head)	Colonizes root structures and interferes with enzymes that use pyridoxal phosphate as a cofactor.
Pseudomonas fluorescens D7	*Bromus tectorum* (cheatgrass)	Inhibits growth and disrupts plant metabolic functions.
Pseudomonas fluorescens BRG100	*Setaria viridis* (green foxtail)	Interferes with plant hormones and metabolism, inhibiting roots and shoots.
Pseudomonas viridiflava CDRTC14	*Lepidium draba* (hoary cress)	Alters plant hormones and metabolism.
Xanthomonas campestris pv. *poae* (JT-P482)	*Poa annua* (annual bluegrass); *Poa attenuata* (meadow-grass)	Suppresses growth and causes black rot disease.
Xanthomonas campestris (LVA-987)	*Ambrosia artemisiifolia* (common ragweed); *Ambrosia trifida* (giant ragweed); *Conyza canadensis* (marestail); *Xanthium strumarium* (common cocklebur)	Suppresses growth and causes black rot disease.

Table 2 : Fungal bioherbicides and their impacts on targeted weeds.

Bacterial Source	Target Weed(s)	Effect / Mode of Action
Alternaria cassiae	*Cassia obtusifolia* (sicklepod), *Cassia occidentalis* (coffee senna), *Crotalaria spectabilis* (showy crotalaria)	Causes parasitic leaf blight and tissue damage.
Alternaria destruens	*Cuscuta* spp. (dodder)	Inhibits plant growth and development.
Albifimbria verrucaria (syn. *Myrothecium verrucaria*)	*Pueraria lobata* (kudzu)	Inhibits seed germination and early plant growth.
Chondrostereum purpureum	*Prunus serotina* (black cherry), hardwoods, and deciduous trees	Causes stump decay, prevents resprouting, and promotes woody tissue decomposition.
Colletotrichum coccodes	*Abutilon theophrasti* (velvetleaf)	Causes inoculation damage, leaf lesions, and inhibits growth.
Colletotrichum gloeosporioides	*Echinochloa crus-galli* (barnyard grass), *Cuscuta chinensis* (Chinese dodder), *Cuscuta australis* (Australian dodder)	Causes severe infection and leaf spot disease.
C. gloeosporioides f. sp. *aeschynomene*	*Aeschynomene virginica* (jointvetch), *A. indica* (Indian jointvetch), *Sesbania exaltata* (hemp sesbania)	Induces anthracnose lesions on stems and leaves.
C. gloeosporioides f. sp. *malvae*	*Malva pusilla* (round-leaved mallow)	Causes lesions on leaves, flowers, and stems.
Colletotrichum truncatum	*Bidens pilosa* (beggartick)	Inhibits seed germination and plant growth.
Cylindrobasidium laeve	*Acacia mearnsii* (black wattle), *A. pycnantha* (golden wattle), *Poa annua* (winter grass)	Accelerates decomposition of stumps and roots.
Fusarium oxysporum f. sp. *orthoceras*	*Orobanche* spp. (broomrape)	Causes leaf lesions and wilting.
Fusarium fujikuroi	*Cucumis sativus* (cucumber), *Sorghum bicolor* (great millet)	Induces chlorosis and necrosis.
Gibbago trianthemae	*Trianthema portulacastrum* (horse purslane)	Causes stem blight and leaf spot disease.
Lasiodiplodia pseudotheobromae, *Macrophomina phaseolina*, *Neoscytalidium novaehollandiae*	*Parkinsonia aculeata* (parkinsonia)	Produces toxins and enzymes that degrade plant tissues and defenses.

Phoma chenopodicola	*Chenopodium album* (lamb's quarter)	Causes extensive necrotic lesions.
Phoma macrostoma	Broadleaf weeds such as *Taraxacum officinale* (dandelion)	Colonizes roots and obstructs nutrient uptake through mycelial growth.
Phytophthora palmivora	*Morrenia odorata* (milkweed vine)	Causes root infection leading to plant death.
Pseudolagarobasidium acaciicola	*Acacia cyclops* (coastal wattle)	Causes seed mortality and plant death.
Puccinia canaliculata	*Cyperus esculentus* (yellow nutsedge)	Inhibits reproductive processes and seed germination.
Puccinia thalaspeos	*Isatis tinctoria* (dyer's woad)	Infects first-year plants and reduces flowering and seed formation.
Sclerotinia minor	*Taraxacum officinale* (dandelion), broadleaf weeds	Absorbs plant tissue and causes decay.
Trichoderma koningiopsis	*Euphorbia heterophylla* (Mexican fire plant)	Increases cellulase and lipase activity, leading to tissue degradation.
Trichoderma polysporum	*Avena fatua* (wild oats), *Chenopodium album* (goosefoot), *Elsholtzia densa* (dense Himalayan mint), *Lepyrodiclis holosteoides* (false chickweed), *Polygonum aviculare* (common knotgrass), *P. lapathifolium* (pale persicaria)	Produces secondary metabolites with antifungal activity that inhibit growth and germination.

Table 3 : Plant-sourced bioherbicides and their impacts on targeted weeds.

Plant Source	Target Weed(s)	Effect / Mode of Action
Canavalia ensiformis extract	*Commelina benghalensis* (Benghal dayflower), *Ipomoea grandifolia* (little bell)	Causes inhibition of plant growth and development.
Cirsium setosum (HL-1 isolate)	*Chenopodium album* (goosefoot), *Galium aparine* (cleavers), *Malva crispa* (Chinese mallow), *Polygonum lapathifolium* (pale knotweed)	Produces phytotoxins that inhibit seed germination and plant growth.
Cynara cardunculus (ethanol and lyophilized leaf extracts)	*Amaranthus retroflexus* (redroot pigweed), *Anagallis arvensis* (scarlet pimpernel), *Phalaris minor* (little seed canary grass), *Portulaca oleracea* (little hogweed), *Stellaria media* (chickweed), *Silybum marianum* (milk thistle), *Trifolium incarnatum* (crimson clover)	Induces oxidative stress and disrupts physiological and biochemical processes in plant cells.
Juglans nigra (black walnut) extracts	*Convolvulus arvensis* (field bindweed), *Conyza bonariensis* (hairy fleabane), *Conyza canadensis* (horseweed), *Echinochloa crus-galli* (barnyard grass), *Ipomoea purpurea* (tall morning glory), *Portulaca oleracea* (common purslane), *Solanum nigrum* (black nightshade)	Inhibits H^+-ATPase activity, reduces photosynthesis, and suppresses root and leaf development.
Lantana camara (cold and hot extracts)	*Avena fatua* (wild oats), *Euphorbia helioscopia* (sun spurge), *Phalaris minor* (little seed canary grass), *Rumex dentatus* (toothed dock)	Contains aromatic allelochemicals that suppress seed germination and plant growth.
Ocimum basilicum extracts	*Amaranthus* spp., *Portulaca* spp.	Inhibits germination, growth, and root/shoot elongation.
Sorghum bicolor (great millet)	*Amaranthus retroflexus* (redroot pigweed), *Ambrosia artemisiifolia* (common ragweed), *Cassia obtusifolia* (sicklepod), *Coronopus didymus* (lesser swinecress), *Cyperus rotundus* (purple nutsedge), *Phalaris minor* (little seed canary grass), *Solanum nigrum* (black nightshade)	Inhibits photosynthetic processes by altering solute and water uptake.
Corymbia citriodora (lemon-scented gum) oil (0.03%)	*Avena fatua* (wild oats), *Sinapis arvensis* (charlock), *Sonchus oleraceus* (sowthistle)	Disrupts chlorophyll and cell membranes, leading to cell damage.
Corymbia citriodora oil (0.06%)	*Amaranthus viridis* (slender amaranth), *Bidens pilosa* (blackjack), *Leucaena leucocephala* (lead tree), *Rumex nepalensis* (Nepal dock)	Inhibits germination and growth by affecting photosynthetic and respiratory metabolism.

Table 4 : Viral bioherbicides and their impacts on targeted weeds.

Virus Source	Target Weed(s)	Effect / Mode of Action
Araujia mosaic virus	*Araujia hortorum* (moth plant)	Causes mosaic symptoms and leaf distortion in the plant.
Pepper mosaic virus (*Óbuda pepper virus*)	*Solanum nigrum* (black nightshade)	Reduces biomass and increases seed dormancy.
Tobacco rattle-like virus	*Impatiens glandulifera* (Himalayan balsam)	Produces necrotic spots on leaves and stems.
Tobacco mild green mosaic virus	*Solanum viarum* (tropical soda apple)	Triggers a hypersensitive response and induces necrotic local lesions.

Table 5 : Currently available bioherbicides for weed control worldwide.

Commercial Name	Active Constituents	Use / Target Plant(s)	Country Available	Year Released
Avenger Organic Weed Killer®	*d*-Limonene and castor oil	Controls grass and broadleaf weeds	USA	N/A
Barrier H®	22.9% citronella oil	Targets ragwort	Europe, Japan, USA	2015
Beloukha®/ Scythe®	Rapeseed oil, nonanoic acid, pelargonic acid	Non-selective control of seedlings and young weeds	Australia, USA	N/A
Bialaphos®	*Streptomyces hygroscopicus*	Broad-spectrum post-emergence bioherbicide	Eastern Asia	2016
Bioweed™	Pine oil (10%) and sugar	Controls herbaceous and grassy weeds	Australia	N/A
Camperico™	*Xanthomonas campestris* pv. *poae* (JT-P482)	Turf grass weeds	Japan	1997
Di-Bak Parkinsonia™	*Lasiodiplodia pseudotheobromae*, *Macrophomina phaseolina*, *Neoscytalidium novaehollandiae*	*Parkinsonia aculeata* (parkinsonia)	Australia	2013
GreenMatch®	Lemongrass oil	Broadleaf and grassy weeds	USA	2008
Katana®	Pelargonic acid	Broadleaf and grassy weeds	USA	2016
Lockdown® / Collego™	Flumioxazin and *Colletotrichum gloeosporioides* f. sp. *aeschynomene*	Residual control of broadleaf weeds	USA	N/A
Matratec®	Clove oil, lactic acid, lecithin, *n*-butyl ester, wintergreen oil	Broad-spectrum, non-selective herbicide	USA	N/A
Myco-Tech® / Chontrol® / EcoClear™	Acetic acid, citric acid, *Chondrostereum purpureum*	Non-selective against green foliage and deciduous trees/shrubs	Belgium, Canada, Netherlands	2005
Opportune™	*Streptomyces* strain RL-110 T	Pre- and post-emergence herbicide (broadleaf and sedges)	USA	2013
Organic Interceptor®	Pine oil	Knockdown and pre-emergent herbicide	New Zealand	N/A
Organo-Sol® / Kona™ / Bioprotec™	Lactic acid, citric acid, *Lactobacillus rhamnosus* (LPT–21), *L. casei* (LPT–111), *L. lactis* ssp. *cremoris* (M11/CSL), *L. lactis* ssp. *lactis* (LL64/CSL, LL102/CSL)	Non-selective, post-emergent herbicide	Canada	2010
Phoma®	*Phoma macrostoma* 94–44B (Macrocidins A, B)	Broad-spectrum control of broadleaf weeds	Canada, USA	2016

Sarritor®	Flumetsulam and *Sclerotinia minor*	Broadleaf weeds	Australia, Canada	2007
SolviNix™ LC and WP	Tobacco mild green mosaic virus (*Tobamovirus cepa* U2)	*Solanum viarum* (tropical soda apple)	USA	N/A
Stump Out™	Sodium bicarbonate and *Cylindrobasidium laeve*	*Acacia* and *Poa* species	South Africa	1997
Weed Slayer®	Eugenol, clove oil, molasses	Grassy weeds	USA	N/A
WeedZap®	Cinnamon oil, clove oil, lactose, and water	Non-selective, controls small broadleaf and grassy weeds	USA	N/A
WoadWarrior®	*Puccinia thlaspeos*	*Isatis tinctoria* (dyer's woad)	USA	2002

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