DOI: 10.34101/ACTAAGRAR/1/12000

Biological potential of plant pathogenic fungi on weeds: A mini-review essay

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SUMMARY

The invasion of weeds into productive areas has substantial negative effects on native ecosystems as well as agricultural production systems globally. Consequently, the task of maintaining or restoring these systems will become increasingly challenging without consistent, ongoing management efforts. The intensifying emergence of herbicide resistance in numerous weed species, coupled with the unintended pollution caused by synthetic herbicides, underscores the growing necessity for alternative, environmentally friendly, and sustainable management techniques, such as the utilisation of bioherbicides. Plant pathogenic microbes play an important role in biologically management of weeds, with the utilization of plant pathogenic fungi emerging as a promising area of study for novel research trends aimed at weed management without reliance of herbicides and to mitigate environmental pollution. A potential solution to decreasing pesticide usage involves the development of bioherbicides containing fungal active ingredients. Among the most commonly utilised fungi in bioherbicides are genera like Alternaria, Colletotrichum, Cercospora, Fusarium, Phomopsis, Phytophthora, Phoma, and Puccinia. Increased weed resistance to herbicides has influenced new strategies for weed management, with some fungi from genera such as Colletotrichum and Phoma already employed for weed control. Nonetheless, it is evident from reviews that further research is imperative in this domain, with particular emphasis on analysing the efficacy of each plant pathogenic fungi.

Keywords: *phytopathogenic fungi; weeds; biological control; bioherbicide*

INTRODUCTION

The presence of weeds in agricultural and environmental settings poses significant threats to ecosystems globally, impacting both economic and environmental aspects (Chauhan, 2020; Qu et al., 2021). Undesirable vegetation can cause adverse effects in various scenarios, particularly when they vie with native plants and cultivated crops for essential resources like nutrients, sunlight, and water (Vila et al., 2004). Non-indigenous plant species that pose a threat to the human, animal, or plant health by causing economic or environmental damage are classified as invasive ones (Beck et al., 2008).

It is important to investigate phytopathogenic fungi and other microorganisms in weeds. Today, the main and most economically significant enemies in agriculture are weeds. Weeds are the main problem in both agricultural production and turfgrass management, causing yield- and quality reductions. In addition to being an annoyance, pollen can trigger allergic reactions (Stewart-Wade et al., 2002; Oerke, 2006; Gadermaier et al., 2014). As a result, to keep crops productive, weeds must be effectively controlled (Shahzad et al., 2016a, b).

Pesticides are used across the world, as all we know. Considering, fungicides and herbicides are the most often used chemical compounds in agriculture. Herbicides accounted for more than 40% of all pesticides used globally. Weeds are developing resistance to herbicides decreasing the effectiveness of weed control in agriculture across all primary modes of action and against chemicals. There are currently 530 biotypes of weeds resistant to herbicides documented globally (Heap, 2021). In this regard, alternative, eco-friendly and economically viable weed management strategies that target different aspects of a plant metabolism are urgently required (Bordin et al., 2021).

Any living organisms that has the ability to inhibit the growth of weeds is generally regarded as a biocontrol agent including agents like arthropods (insects, mites) and pathogens are more suitable and frequently utilized for targeted weed control (McFadyen, 1998; Charudattan, 2001; Schwarzländer et al., 2018).

Usually, diseased plants are found in the field or in greenhouses, and it is at this point that the process of isolating and identifying the causal agent starts. It is much more difficult to find living organisms for use as bioherbicides than it is to find artificial phytotoxins. Unique microbe-plant interactionsare presented using pathogens for weed management. In this regards bioherbicides contain microbial or phytotoxin agentthat can be applied on a weed to control or to cause its death (Pacanoski, 2015).

"Bioherbicide" refers to microorganisms (such as fungi, bacteria, viruses, and algae) or their products that have been utilized in the supplemental control of weed species. In the literature, the term 'Mycoherbicide' has been used to describe the direct application of weed control products containing pathogenic fungal organisms (as described by Hoagland in 1990). Fungal pathogens can indeed serve as biological agents in weed management.

The aim of this mini review was to give a worldwide overview of the subject of plant pathogen-based weed biocontrol and the advancements that have been realized. An overview of all pathogen introductions of biocontrol of weeds.

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Fungi as biological control of weeds

Agriculture in modern days is always changing and developing. The widespread use of chemical fertilizers and pesticides enabled a significant increase in agricultural outputs in the century 20th. Innovative farming techniques and the emergence of biotechnologies are being utilized (Montagu, 2019). To control weeds, biological control agents are used to control weed infections and these agents can not completely eradicate the weed population (Yandoc-Ables et al., 2007). In the past five decades, this area of research has increasingly concentrated on potential solutions for managing weeds and other invasive plant species using of fungi and bacteria (Li et al., 2003).

Biological weed control involves an ecological understanding of interactions between weeds, plants, and the environment. There are numerous organic factors that prevent weeds from growing like as insects, seed damage in the soil, allelo-chemicals, pathogens, and competition with other plant species (Radócz, 2013).

Exserohilum fusiforme and *Colletotrichum graminicola* were utilized in studies in Vietnam, Australia, and South Korea to biologically control *Echinochloa crus-galli* and other *Echinochloa* species in rice paddies by preventing their reproduction during the rice plant's growth stages (Johanson et al., 2003).

It is important to preserve the environment during cultivation, or the idea to use products that are environmentally friendly. Bioherbicides based on fungi (Mycoherbicide) have been increasingly successful in controlling a variety of weeds (Bailey et al., 2010; Cordeu et al., 2016; Dumas et al., 1997; Boyette et al., 2019; Nandhini et al., 2019). Russian scientists made significant progress in this area in the 1950s by mass-producing and formulating *Alternaria cuscutacidae* spores to control holoparasite dodder (*Cuscuta* sp.) species. Nearly as old as the study of plant pathology itself is the concept of employing plant pathogens to manage weeds (Wilson, 1969). The source of bioherbicides may come from fungi and their metabolites. Since fungi and their metabolites are challenging to use, this alternative is not trouble-free, but significant advancements have been made, and the findings are encouraging. However, this strategy based on the use of fungal bioherbicides cannot be used alone and must instead be combined with other complementary strategies. Integrated pest management (IPM) is based on alternative solutions (Triolet, 2019). In plant fitness and plant–microbe interactions, both plant fitness and plant-microbe interactions, fungal endophytes play key roles. (Shahrtash and Brown, 2020). In pathogen protection, the plant microbiome can play positive in acquiring nutrients and improve stress tolerance (Bulgarelli et al., 2013; Berg et al., 2014; Christian et al., 2017).

The suspected pathogen first must be isolated and grown in pure culture as directed by the plan for pathology procedures (Stevens, 1981). Secondary metabolites are used by plant-pathogenic fungi to increase the virulence of the generating strain, which is required for weed control (Graupner et al., 2003).

Puccinia chondrillina, in 1971, was the first introduction of a fungus or traditional plant biocontrol method to control *Chondrilla juncea* (Julien and Griffiths, 1998; Barton, 2004) in Australia.

In India, a *Phoma* sp. strain's anthraquinone pigment has been isolated, and studies have revealed that it has herbicidal effects on several significant weeds in Central India (Quereshi et al., 2011). Additionally, *Phoma chenopodicola* has been researched as a potential lamb's quarters weed management agent (*Chenopodium album)* (Cimmino et al., 2013). *Phoma chenopodiicola* produced phytotoxins have been recommended as fungal pathogen products for *Chenopodium album* biocontrol (Evidente et al., 2015).

Also, the other important fungal pathogens were determined on common weed species: *Peronospora farinosa* on *Chenopodium album*. *Septoria convolvuli*, *Erysiphe convolvuli*, and *Puccinia punctiformis* on *Convolvulus arvensis*. These fungal pathogenswere observed mainly on the weeds located at the edge of fields (Kadioğlu et al., 2010).

Based on (Iffat et al., 2010) *Alternaria alternata* can be used as a potential biological control agent for the management of *Rumex dentatus* in wheat. While *Alternaria* spp. as, *Alternaria alternata*, *Alternaria solani*, *Cladosporium cladosporioides*, *Cladosporium herbarum*, and *Fusarium sambucinum*, were dominant fungi on redroot pigweed plants (Mazur et al., 2015).

Purple nutsedge can grow more slowly when *Dactylaria higginsii* is present, which includes a reduction in shoot biomass and the number of tubers (Kadir et al., 2000).

The fungus *Phyllosticta cirsii* has been evaluated as another possible biocontrol agent of *Canadian thistle* (Berestetskiy et al., 2005), additionally, when cultivated in liquid cultures, *Phyllosticta cirsii*, a fungal pathogen that was discovered infected *Cirsium arvense* leaves and is being investigated as a biocontrol agent of this noxious perennial plant, produces various phytotoxic compounds that have potential herbicidal activity. (Evidente et al., 2008).

Mira et al. (2021) have verified to be pathogenic on its native hosts: *Alternaria thunbergiae*, *Nigrospora sphaerica*, *Colletotrichum cigarro*, *Epicoccum draconis*, and *Didymella rumicicola* on *Thunbergia alata*; *Bipolaris* sp. on *Digitaria horizontalis; Bipolaris zeicola*, *Phialemoniopsis curvata*, and *Stemphylium beticola* on *Persicaria nepalensis* and, *Alternaria thunbergiae* and *Nigrospora sphaerica* on *Thunbergia alata*. Except for *Alternaria thunbergiae* and *Bipolaris* sp., these could fairly be regarded as the first reports of such interactions ever publishedin the entire world.

Table 1 presents fungi with strong herbicidal activity, indicating their potential as candidates for biological herbicides.

DOI: 10.34101/ACTAAGRAR/1/12000

Table 1. **Identification of some important fungi from weeds**

Pathogen	Target weed(s)	Reference
Colletotrichum graminicola **and** ***Exserohilum fusiforme***	*Echinochloa crus-galli* *Echinochloa* spp.	Johanson et al., 2003
Phoma chenopodicola	*Chenopodium album*	Evidente et al., 2015; Cimmino et al., 2013
Dactylaria higginsii	*Cyperus rotundus*	Kadir et al., 2000
Alternaria sp.	*Rumex dentatus*	Iffat et al., 2010
Phyllosticta cirsii	*Cirsium arvense*	Berestetskiy et al., 2005; Evidente et al., 2008
Puccinia punctiformis	*Convolvulus arvensis*	Kadioğlu et al., 2010

Bioherbicides based on fungi (Mycoherbicide)

For environmentally sustainable weed control, "bioherbicides" are formulated from naturally occurring living organisms or their metabolites (Hoagland et al., 2007; Bailey, 2014). These substances, derived from nature, serve as effective tools for weed management. They formulations that include living microorganisms together with auxiliary elements such as surfactants, adjuvants, preservation agents, water-holding additives, inert fillers, etc. Formulations for weed control that are based on fungi are known as mycoherbicides (Bailey, 2014). Within the scope of IPM, in conventional agriculture, weeds are controlled by screening viable microorganisms and their natural products as potential biocontrol candidates (Zimdahl, 2011; Hinz et al., 2014).

The importance of biological controls using advantageous microbes has increased significantly (Lahlali et al., 2022).

The first step in the creation of bioherbicides is the isolation of microorganisms linked to weeds that pose a serious management issue locally for some crops (Charudattan and Dinoor, 2000; Ray and Vijayachandran, 2013; Tehranchian et al., 2014; Mazur et al., 2015).

Plant-pathogenic viruses, bacteria and fungi are frequently detected in weed species. The category of "fungi against weeds" appears to be the most promising biological agents. Following extensive *in vitro* propagation process, plant pathogenic fungi are used as classical pesticides. Classical bio-herbicide application is the name of this technique (Radócz, 2013). With the discovery of mycoherbicides in the middle of the 1970s, the first documented bioherbicide development was observed. Since then, many bioherbicides have been authorized and made available on the international market (*Table 2*) (Zeng, 2020).

Table 2. **Some widely used bioherbicides in the world**

Product name	Registration		Active ingredient	Target weed (s)
	Year	Country		
Di-Bak® Parkinsonia	2018	Australia	*Lasiodiplodia pseudotheobromae, Neoscytalidium novaehollandiae, Macrophomina phaseolina*	*Parkinsonia aculeata*
Bio-Phoma™	2016	Canada	*Phoma macrostoma*	Numerous broad-leaved weeds
Phoma™	2012	USA		
Sarritor®	2009	Canada	*Sclerotinia minor*	*Taraxacum officinale* and other broad-leaved weeds
Collego™	1982	USA	*Colletotrichum gloeosporioides* f. sp. *Aeschynomene*	*Aeschynomene virginica*
LockDown™	2006			
Chontrol™	2004	Canada, USA	*Chondrostereum purpureum*	*Populus* and *Alnus* spp.
DeVine™	1981, 2006	USA	*Phytophthora palmivora*	*Morrenia odorata*

Note: Morin L., 2020. Biological weed control using plant pathogens.

Bioherbicide adoption is on the rise in other countries as an alternative to replace chemical herbicides. Only a small number of the microbes and plant products that have successfully undergone laboratory testing and field trials – 9 fungi, 3 bacteria, and 1 plant extract – are currently sold commercially (Cordeau et al., 2016).

Bioherbicide based on fungus that was registered in (1981) in USA Devine™ was produced by Abott Laboratories. It contains *Phytophthora palmivora* strain MVW, which was approved to control the weed

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Morrenia odorata in citrus crops (Kenney, 1986). In 1986 in USA Collego™ was produced by Upjohn Co (Bowers, 1986). This bioherbicide targets *Aeschynomene virginica* by strain of *Colletotrichum gloeosporioides*. According to more contemporary standards, in 1997, the Environment Protection Agency (EPA) reassessed the strain ATCC 20358 of *Colletotrichum gloeosporioides* f.sp. *aeschynomene*. Collego™ changed to LockDown® in 2006.

The active ingredient in the bioherbicide BioMal® is *Colletotrichum gloeosporioides* f.sp. *malvae* ATCC 20767 is used to control *Malva pusilla* in arable crops (Boyetchko et al., 2007).

To control sprouts from *Prunus serotine* stumps and *Populus euramericana* in the sandy soils of conifer forests, the fungus *Chondrostereum purpureum* was used to create the bioherbicides MycotechTM and Chontrol® pastes. *Chondrostereum pupureum* strain HQ1 under the name of Mycotech™ was registered by Myco-Forestis Corporation in 2002 in Canada and 2005 in the USA and in 2004 Chontrol® Pastes was introduced from strain PFC 2139 of the fungus *C. purpureum* (Hintz, 2007).

The plant pathogen of the *Cuscuta* genus, *Alternaria destruens* strain 059, is found in Smoulder®. Loveland Products Inc. (Greely, Colorado) and Sylvan Bio Inc. (Kittanning, Pennsylvania) developed and registered this bioherbicide, which was approved by the EPA in 2005 (Bailey, 2014).

Sarritor® is a bioherbicide composed of the fungus *Sclerotinia minor*. Biological management for dandelion in turfgrass was done by using the *Sclerotinia minor* strain (IMI 344141) (Abu-Dieyeh, and Watson, 2007).

Camperico® is a bioherbicide whose active agent is the bacterial strain of *Xanthomonas campestris* JTP482 to control *Poa annua* in turf. Developed by the Japan Tobacco Inc. (Tateno, 2000).

Organo-Sol® contains *Lactobacillus casei* (strain LTP-111) *Lactobacillus rhamnous* (strain LTP-21) *Lactobacillus lactis* ssp. *lactis* (strain LL64/CSL), *Lactobacillus lactis* ssp. *lactis* (strain LL102/CSL), *Lactobacillus lactis* ssp. *cremoris* (strain M11/CSL) in 2010 which was authorized in Canada, and AEF Global presently sells this product under the brand KonaTM to manage lawn-established *Trifolium repens* and *Trifolium pratense*, *Lotus corniculatus*, *Medicago lupulina* and *Oxalis acetosella* (www.aefglobal.com).

And Beloukha®, a new bioherbicide, was given permission to enter the European market in 2015 as a plant protection product (Nguyen et al., 2013).

Table 3. **Fungi potentially available to be formulated as a mycoherbicide**

Fungal Source	Target Weed(s)	Commercial status
Albifimbria verrucaria, formally Myrothecium verrucaria	*Pueraria lobata*	X
Fusarium oxysporum* f. sp. *Orthoceras	*Orobanche* spp.	X
Gibbago trianthemae	*Trianthema portulacastrum*	X
Phoma chenopodicola	*Chenopodium album*	X
Phoma macrostoma	*Taraxacum officinale*	X
Trichoderma koningiopsis	*Euphorbia heterophylla*	X
Trichoderma polysporum	*Avena fatua* *Chenopodium album* *Elsholtzia densa* *Lepyrodiclis holosteoides* *Polygonum aviculare* *Polygonum lapathifolium*	X

X = not commercially available

There are several additional sources of fungi that may be used to create a mycoherbicide, but they have not yet been made accessible for commercial usage (*Table 3*). They include some fungi, for example *Fusarium oxysporum* f. sp. *Orthoceras* (Kakhaki et al., 2017), *Albifimbria verrucaria*, (formally *Myrothecium verrucaria*) (Hoagland et al., 2007; Weaver et al., 2021), *Gibbago trianthemae* (Félix-Gastélumet et al., 2021), *Phoma chenopodicola* (Cimmino et al., 2013), *Phoma macrostoma* (Rai et al., 2021; Hynes, 2018; Todero et al., 2018), *Trichoderma koningiopsis* (Junior et al., 2019) and *Trichoderma polysporum* (Zhu et al., 2020).

As possible mycoherbicides, several *Colletotrichum* species have been researched (Chakraborty and Ray., 2021; Jayawardena et al., 2016; Nandhini et al., 2019), as well based on Gu et al., 2023) this species has been shown to be successful in the control of Barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.). As a potential bioherbicide of *Albifimbria verrucaria* (Formerly *Myrothecium verrucaria*) shown effect on some herbicide-resistant weeds like as *Conyza canadensis* (Hoagland et al., 2023).

Action mechanisms of bioherbicides

Weed plants prevented from growing by fungi through a variety of mechanisms. The compatibility

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between plants and microorganisms was linked to the bioherbicidal activity of microorganisms. During this infection process, many virulence factors are directly involved. First, enzymes that break down the cytomembrane make it easier for such substances to penetrate and contribute to microorganism infection and phytotoxic effectiveness. Most plant entrance points are through the degradation of cell walls and lipid membranes by enzymes such as cellulases and lipases (Ghorbani et al., 2005; Cordeau et al., 2016). Pathogenic fungi produce various substances to inhibit weed growth and germination, such as tenuazonic acid, isotenuazonic acid, N2-β Dglucopyranoside, trans−4-amino-D-proline, cercosporin, beticolin, Nep1, trichothecene, β−1,4-exoglucanase, glucosidase, xylanase, β−1,4-endoglucanase and other organic acids which fungi are produced to control the development and germination of weeds (Motlagh, 2012).

Each fungus produces several cell wall-degrading enzymes (CWDE) with slightly different properties, which gives ecological flexibility. The cell membrane may be damaged by CWDE, but based on other research, cell membrane is usually attacked by lipid-degrading enzymes such as phospholipases of fungal origin. Membranes are mainly targeted by toxins. In several cases toxins have been classified as a strong pathogenic factor that induce infection and increase the severity of the infection, the case of toxins produced by *Alternaria* pathotypes (Hasan & Ayres, 1990). The fungal phytotoxin that was identified from *Alternaria* species was called tentoxin. According to Duke and Lyndon (1987), the application of tentoxin against Johnson grass (*Sorghum halapense*) in a maize and broad- and narrow-leaved weeds in a soy bean resulted in notable weed control activity.

CONCLUSIONS

Weeds represent one of the most accurate concerns in global plant protection discussions. It is estimated that work still needs to be done in weed studies in various aspects, particularly in fungal studies. This review concentrates on the use of fungi as biological agents for weed management, highlighting its promising potential and characteristics of biological weed control methods based on existing literature, emphasizing the utilization of fungi-derived bioherbicides for weed eradication. Evidently, this field has raised significant interest from a diverse spectrum of researchers. Future developments will make it possible for green agricultural practices and environmentally friendly weed control to spread more widely in the world's agriculture.

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