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Bioherbicides: revolutionizing weed management for sustainable agriculture in the era of One-health

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A R T I C L E I N F O

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A B S T R A C T

The main objective of agricultural weed management is to increase crop productivity to maintain a delicate balance between food demand and supply for an increasing population and ensure food security globally. Agriculture plays a significant role in the social life and economy of many developed or developing countries. Blind use of chemical herbicides to maximize crop production exerts many negative environmental impacts and develops resistance among the weed biotypes against herbicides, even representing a high risk to the environment and human health. Thus, in the last few years, the research activities of scientists have increased to find alternative weed control methods. Bioherbicides or biological management of weeds is an emerging topic with decent potential for sustainable crop production. Biological management of weeds has numerous positive aspects and advantages over chemical control, such as being highly selective, specific toward targeted weeds, sustainable, and having minimize harmful effect on the main crop, environment, and humans. Several biological agents, such as bacteria, fungi and viruses, also plant extracts and essential oils, have been introduced, and their bioherbicidal potential has been explored in weed management. To develop an effective bioherbicide, specific and complex types of interaction have been developed between targeted weeds and biological agents. Whereas a limited number of bioherbicides have performed successfully under field conditions to control specific weeds, nonetheless, the efficiency of many other bioherbicidal agents is still inadequate due to many reasons, such as formulation, less persistence in the field as well as lack of host-agent interaction. This critical review paper discusses several different biological methods of weed management, their advantages and disadvantages, and the importance of bioherbicides as weed-controlling agents to achieve global sustainable crop production, in the era of One-health.

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1. Introduction

Wheat, cotton, rice, sugarcane, maize and vegetables are some basics crops for many agriculture-based countries; in addition, their cultivation area is continuously decreasing worldwide with high population pressure. With the advent of the 21st century, the agriculture sector is concerned more with enhancing crop production for food security (Khaliq et al., 2013). However, weeds, pathogens and insects are the major yield-limiting factors, as they compete for natural resources, damage crop plants, and deteriorate the quality of crop yields (Gharde et al., 2018). Globally, the annual worth of agrochemicals used for crop protection is expected to increase from $70.47 billion in 2024 to $75.3 billion in 2025 with growth rate of 6.3 % (Crop Protection Chemicals Global Market Report, 2025). Thus, the largest number of agrochemicals used in cereals and grain crops account for 47. 02 % of the overall crop protection agrochemicals of the market (Size, 2024)

Weeds are responsible for the loss of 25–40 percent of crop yields annually (Fahad et al., 2013). Weed is defined as any unwanted plant that grows in a field under cultivation and competes with the main crop for resources like space, light, water, and nutrients. Therefore, anything that reduces the vigor and growth of the main crop, like deep sowing, limited aeration, interrupted light, soil compaction, and nutrient deficiency will encourage the growth of weeds (Elmahdi, 2016). At the early stages due to the rapid growth, crops, especially cereals, are more sensitive to weed growth and infestation (Asghar and Kataoka, 2021). Crop yield reduction in the field because of weed infestation has been observed as low as up to 18 % and as high as up to 80 %. Among different factors, weed infestation is the most significant yield-reducing factor. Averagely, weed infestation could cause 25–40 % losses in grain yield and overall loss for all crops is from 20 to 76 % (Gharde, 2018, Asghar et al., 2024). Weeds could be managed by manual, cultural, mechanical, physical, chemical as well as biological methods. However, weed management methods have some limitations, as well as chemical methods, due to having the most drastic negative impact on the environment by their residues.

Cultural (stale seed bed and double seed rate) and mechanical/ manual control (hand hoeing, hand pulling, and bar harrowing) practices are sustainable weeds management techniques that can be easily operated in the field and subsequently boost the crop yield, whilst these are laborious, energy-intensive and inexpensive strategies (Jabran et al., 2012). Non-chemical weed control methods are discriminating and desirable due to their several ecological and economical attributes for organic food production.

Those weeds that have developed resistance against chemical herbicides are an important concern nowadays (Heap, 2014). Thus, cultural and mechanical practices are, considering, cultural and mechanical practices, the best methods for their control (Farooq et al., 2011b); however, manual and mechanical weed control measures are less effective (Muhammad et al., 2018). Despite this, chemical control is still considered an quickest, effective and successful way to control weeds among all methods (Muhammad et al., 2018). Nevertheless, the uncontrolled use of chemical herbicides is also an expensive method and has an imbalance impact on air composition, causing pollution, soil erosion, human health problems and driving a disturbance in natural flora/fauna (Mir et al., 2015; Farooq et al., 2011a, Pati and Chowdhury, 2015). Synthetic chemical herbicide usage could be minimized by adopting biological control methods, through which microorganisms and/or biological agents are used for the management and control of weeds' population and their density.

Narrow and broad leave weeds that compete with the main crop are mainly wild oat (*Avena fatua* L.), common daisy (*Bellis Perennis* L.), lambs quarters (*Chenopodium album* L.), canary grass (*Avena fatua* L.), dandelion (*Taraxacum officinale* L.), field bindweed (*Convolvulus arvensis* L.), dock (Rumex obtusifolius L.), groundsel (Senecio vulgaris L.), cat weed (Hypochaeris radicata L.) and white clover (Trifolium repens L.). Regarding nutrient competition, crops-infested with weeds utilize 3 to 4 times more nitrogen (N), potassium (K), and magnesium (Mg) than weed-controlled crops (Reddy et al., 2003). Weeds infestation contributes more to an annual yield loss than the other losses observed under insect attacks (Shehzad et al., 2012). Weeds not only decline the yield but also degrade the quality of grains, so it reduces the market value of produce, drastically. Therefore, it is imperative to apply the best management practices of weed infestation control to maximize crop production.

Traditional methods for weed control are costly, time-consuming, less efficient, labor-intensive, and highly dependent on the weather conditions of an area (Cheema and Khaliq, 2000). Many researchers have explained a positive correlation between the best weed management practices and crop yield through a series of field trials. Meanwhile, the use of only one method for weed control, like chemical control, is not an economical and sustainable approach. About weeds resistance, indiscriminate application of chemical herbicides causes that some weeds are not more susceptible to these chemical herbicides over time (Ma, 2005). According to international surveys, about weed species out of 295 bio-types have developed resistance against different chemical herbicides (Mahmood et al., 2009).

Biological control of weeds, a natural and sustainable approach, is becoming the most suitable alternative and a viable tool for weed control; additionally, increasing crop yield within desired limits. Thus, supplementation of synthetic agrochemicals with biological weed control is a more effective and innovative management practice for sustainable agriculture.

Biological control of weeds using bacteria is a win-win situation (Li et al., 2003). Bacterial species can reduce the germination and growth of weeds; however, their potential is limited due to unfavorable environmental conditions in the field and nutrient deficiency in the soil (Li et al., 2003). Nutrients are the key elements that significantly improve the bacterial potential to suppress weeds' growth (Naik et al., 2019). Bacteria need optimum nutrients to express their maximum potential (Khan et al., 2022). A few plant extracts contain specific metabolites and these metabolites additionally contain allelochemicals that have been specifically used to suppress the growth and development of other plants, this phenomenon is known as allelopathy (Khan et al., 2016). Thus, the integrated application of bacteria in combination with allelochemicals would increase the bacterial efficiency to reduce the weeds' growth and development (Raza et al., 2021). Bacteria and allelopathic extract work synergistically to inhibit the growth of weeds and this effect is more than double as compared to the alone application of plant extract for weeds management. Bacterial culturing as biological control agents is a relatively simple technique (Li et al., 2003, Raza et al., 2021). Therefore, this review aims to discuss the importance of bioherbicides, novel bio-control methods of weed management practices, and their pros and cons to ensure sustainable crop production in the one-health era.

1.1. Importance of bioherbicides

Bioherbicide application is a sustainable, pollution-free strategy that leaves no chemical residual impact on the environment. Its mode of action is considered an important aspect during the research and development of bio-products. An Australian Ash (2010) reported that weeds have developed high resistance to chemical herbicides. In response to this challenge, an Australian weed scientist discovered that the fungus Plectosporium alismatis can be effectively used as a biocontrol agent in paddy fields to manage resistant weeds. Additionally, studies have demonstrated a synergistic interaction between P. alismatis and synthetic herbicides, where their combined application significantly reduces the required herbicide dosage while enhancing weed control efficacy. This integration of bioherbicides with synthetic herbicides not only improves weed suppression but also minimizes the likelihood of resistance development in target weed populations. The development of bioherbicides is a costly practice. Therefore, international organizations should play a major role in developing these bioherbicides. The main purpose of developing bioherbicides is to establish niche or non-cores among prevailing markets.

Bioherbicides have gained importance in the organic food production market and reducing the consumption of synthetic herbicides (Stubbs and Kennedy, 2012). The bioherbicide market could grow much higher in response to the globalization of organic agriculture. Some parasitic weeds that cannot be controlled by chemical herbicides are efficiently overcome by bioherbicides due to the existence of a niche-system relationship (Hallett, 2005). Dodder species (*Cuscuta* spp.) are controlled by the fungal pathogen *Alternaria destruens*. In China, a bioherbicide with the name of Lubao II has been used to control dodder. In this regard, there is an urgent need to study the social, biological, and economic aspects of bioherbicide for their adoption and production (Bailey et al., 2010).

Bioherbicides, such as the *Colletotrichum* species, can live saprophytically without the plant host; thus, the inoculation of such fungi is of great importance in developing artificial cultural strategies (Bailey, 2014). Likewise, obligate fungal pathogens that proliferate directly on the host plants like yellow nutsedge (*Cyperus esculentus*), and rust fungus (*Puccinia canaliculata*), mass culture grow in greenhouses or small fields plots, where uredospores are vacuum-harvested and stored in bulk before preparing bioherbicides (Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983)(Phatak et al., 1983). Through center-pivot irrigation systems, these uredospores are used in the field for weed control systems. The sustainable bioherbicides can be used on stumps of tree species surrounded by weeds or wounded branches to stop the re-sprouting. Soil-borne fungal pathogens are considered important herbicidal agents that inhibit weed germination-growth on direct application to the soil by killing the weed's seedlings (Jones and Hancock, 1990). In composted chicken manure, *Trichoderma virens* were inoculated, which significantly reduced narrow and broad leaf weeds in horticultural crops (Héraux et al., 2005b). Plant pathogenic bacteria including, *Pseudomonas syringae* pv. tagetis, and *Xanthomonas campestris* pv. poannua (Xcp) were used as bioherbicidal agents to control Asteraceae weeds and annual bluegrass (Poa annua) For effective application, Camperico bioherbicide must be sprayed directly onto wounded grass tissues, allowing the bacterial suspension to invade and establish infection (Imaizumi et al., 1997). To enhance this process, organosilicon has been successfully tested as a bioherbicide, demonstrating its ability to increase bacterial infection efficiency in stem tissues and leaves upon disease onset (Zidack et al., 1992).

1.2. Significance of bioherbicide to address health challenges and solutions

Since the Green Revolution, as the agricultural system has modernized, the usage of herbicides for weed control has progressively increased. The use of herbicides began in numerous advanced countries in the 1940s but has increased dramatically in recent years (Huanga et al., 2017). This is a basic fact that chemical herbicides are used either yearly or periodically, their efficacy is limited, and they kill microorganisms. Besides, chemical pesticides do not readily biodegrade (Begum et al., 2017). As a result, they accumulate in water and plants, generating significant contamination in the atmosphere and, ultimately, posing serious threats to life hold. According to Aneja (2000), pesticide pollution causes around one million individuals to get sick each year. Furthermore, the continued use of 209 traditional pesticides has resulted in weed resistance (Perotti et al., 2020). Tolerance is an inherent characteristic of one species against herbicide. In addition, herbicide remains in food are becoming a major source of issue, posing a danger for long-term herbicide toxicity. These residues permanence is determined by a variety of mechanisms, including decomposition, volatilization, wind drift, runoff, chemical degradation, root uptake, leaching, and microbial degradation (Huang et al., 2017; Chawla et al., 2018). In past years, investigation has emphasized the neurotoxicity, genotoxicity, reproductive, and mutagenic effects of traditional herbicides, which cause an extensive number of ailments. Symptoms and conditions include headaches, exhaustion, nausea, skin irritation, respiratory illness, cardiovascular illness, gastroenteritis, and an increased risk of cancer and Parkinson's disease (Kim et al., 2017). Thus, it has demanded a thorough quest for innovative herbicides that are both effective against weeds and safe for the environment.

Organic methods are being recognized as a substitute for chemical herbicides (Baker et al., 2020). Bioherbicides are typically generated through fermentation and consist of a naturally active component, a medium for growth, and supplements that can be added to broaden the scope of action. The fundamental nature of these biological products is determined by the microbe used; it must be assured that the number of spores available is adequate to have the intended impact on the plant, which occasionally fails to happen (Collinge et al., 2022). Bioherbicides can be both liquid (solution or liquid encapsulation) and solid (encapsulation in particles or adsorption on clay) (Kim et al., 2017). The most significant hazard for liquid (EO-based) bioherbicide happens during tank preparation and filling, followed by product application. In certain circumstances, bioherbicide will necessitate the addition of chemicals, hydrating substances, or encapsulating particles, and their harmful effects must be investigated.

Some potential health risks are posed to human health using bioherbicides. In vitro, some bioherbicides have been discovered to be harmful in Gram-positive and Gram-negative bacteria, deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) viruses, and fungi, including yeast (Sharma, 2022). Thus, several reaction modalities have been found, including membrane permeability, cytoplasmic coagulation, and lipid and protein destruction (Álvarez-Martínez et al., 2021). These actions cause macromolecular leaks and disintegration (Dhifi et al., 2016). In eukaryotic cells, mitochondrial membranes depolarize (affecting Ca^{++} cycling), triggering an event that results in cell death and demise (Duchen, 2000).

These impacts are primarily attributed to phenols, aldehydes, and alcohols (Lins et al., 2019). Though these impacts are utilized to defend humans, animals, and agriculture against diseases, the primary constituents of these bio-agents have been proven in vitro to cause cytotoxicity in mammalian cells by inducing apoptosis and necrosis. Unexpected DNA synthesis (UDS) tests, permitting detecting genotoxicity, were performed on some phenols and found that eugenol, isoeugenol, methyl eugenol, and safrole cause cytotoxicity along with genotoxicity in animal hepatic cells whereas estragole (main compound of *Artemisia dracunculus* essential oil and present in *Ocimum basilicum* causes UDS in animal's fibroblastic cells (Bakkali et al., 2008). In the investigation of oral administration of essential oils (Eos; a constituent of bioherbicides), a substantial dose (for example, 6–10 g of camphor) might be extremely harmful and cause coma (Maes et al., 2021). Yet less serious health problems are more prevalent, such as sensations of burning in the throat and mouth, nausea, vomiting, and diarrhea. These do not exclude essential oils from being utilized in the food industry at lower concentrations (1.5 mg/person/day for camphor) with no adverse effects. The highest oral and cutaneous dosages differ according to the EO's main components (Türkmenoğlu and Özmen, 2021). In contrast, some investigations found no harmful influence of EOs on allergic asthma.

The impact of bioherbicide on pregnancy is a very contentious issue. As previously indicated, the chemical makeup of bioherbicides varies based on several conditions, thus they seldom have the same effect on prenatal infants (Dhakad et al., 2018). When we look at the bioherbicide constituents separately, several have been proven to influence hormonal reproduction and exhibit fetotoxic, abortifacient, embryotoxic, and antigestational properties (Maes et al., 2021). By avoiding physical contact, solid encapsulation of EOs reduces exposure hazards significantly (Taban et al., 2020). Furthermore, the slower rate of release will result in lower volatility (Angelini et al., 2003). A further concern is the possibility of mutagenesis and/or cancer in the long-term. This is dependent on how much the person absorbs by respiration. Because these adverse effects were only demonstrated in vitro research (larger concentrations and direct exposure of cells to the substance), this amount is probably insufficient to create such a result (Pavela and Benelli, 2016).

To reduce the danger of long-term pesticide poisoning, the European Union's Good Agricultural Practice guideline now includes a maximum residue level (MRL) for all crops and pesticides (European Food Safety Authority, 2016). Most countries across the world employ MRLs to regulate pesticides, which include a critical reference dosage and an appropriate daily limit. They vary by country and are often lesser in Europe than in the United States (Handford et al., 2015). The key benefit of employing some organic constituents such as essential oils as bioherbicides is that, due to their instability, EO ingredient traces in food and soil are essentially non-existent. In contrast, this instability necessitates the application of a considerable amount of EOs, which can be harmful to the atmosphere and soil biodiversity. Encapsulation is an effective way to strike a compromise between bioherbicide efficacy and soil safety (Saha et al., 2023).

1.3. Diversity of weeds and their competition with crops

Weeds belong to various families of kingdom plantae, but some families, such as Asteraceae, Brassicaceae, Fabaceae, and Poaceae contribute to the major components of weed flora worldwide (Marwat et al., 2009). Worldwide, about 30,000 species of weeds spread widely over the soil, and out of these only 45 to 200 are mostly causing significant harm to the major crops (Mahmood et al., 2013). It is estimated that about 250 species of weeds are commonly competing with crops, globally.

According to (Marwat et al., 2013) different narrow and broad leaved competitive weeds compete with main crop for natural resources are mainly canarygrass (*Avena fatua* L.) and field bind weed (*Convolvulusarvensis* L.), Piazi (*Asphodelus tenuifolius* Cav.), Jangli jai (*Avena fetua* L.), Pohli (*Carthamus oxycantha* L.), Bathu (*Chenopodium album* L.), Karund (*Chenopodium murale* L.), Kasni (*Cichorium intybus* L.), Leh (*Cirsium arvense* L.), Lehli (*Convolvulus arvensis* L.), Jangli halon (*Coronopus didymus* L.), Khabbal (*Cynodon dactylon* L.), Dudhi (*Euphorbia helioscopia* L.), Shahtra (*Fumaria indica* L.), Warribooti (*Galium aparine* L.), Dokanni (*Lathyrus aphaca* L.), Chraal, kasseri (*Lathyrus sativus* L.), Halon (*Lepidium sativum* L.), Sonchal (*Malva parviflora* L.), Maina (*Medicago polymorpha* L.), Sufaid senji (*Melilotus alba* L.), Zard senji (*Melilotus indica* L.), Zard senji (*Melilotus indica* (L.), Dumbi sittee (*Avena fatua* L.), Dranak, hazardani (*Polygonum plebejum* R.), Lomar ghas (*Polypogon monspeliensis* L.), Jangli palak(*Rumex dentatus* L.), Takla (*Saponaria vaccaria* L.), Khoob kalan (*Sisymbrio irio* L.), Kandiali, dodhak (*Sonchus asper* L.), Kalri booti (*Spergula arvensis* L.), and Revari, Choti phalli (*Vicia sativa* L.).

Among all the growth-reducing factors, weed infestation is the most damaging cause that reduces the growth as well as yield of the main crop. The reduction is due to the competition of weeds for inputs (nutrients, water, space, light) and releasing (phytotoxic compounds) allelochemicals (Gupta, 2020). Cereals at early growth stages are more sensitive to weed competition. Weeds have more competition with the main crop for nutrition at early growth stages and significantly decrease the crop yield. However, some weeds emerge late, and their seedlings face tough competition with fast-growing crops for their survival (Rao et al., 2007). Among different yield-reducing factors, on average weeds infestation caused 25–40 % losses in grain yield (Ahmad and Shaikh, 2003). Weeds serve as an obstacle during different cultural practices like harvesting and plowing. Contaminated grains also act as an obstacle during milling and other processes. According to European food standards, grain commodities are not accepted if they contain more than 3 % impurities (Thomas et al., 1999). Seed regulation confined the contamination of weed seeds that are seed in the market for sale. Heavy infestation of weeds in the field like perennial weeds could make agriculture land less suitable for cultivation and land monetary value decreases under severe infestation.

1.4. Weeds as the source of pest

Weed infestation also increases the cost of controlling insects, pests, and diseases. Insects and pathogens always require the host to cause diseases and these weeds serve as a medium of alternate host for the survival of pathogens, pests, and disease-causing agents (Dangwal et al., 2010). Weeds are an important resource for insects because they feed on weeds and have both positive/negative effects on crop growth and productivity (Hobbs, 2007). Some weeds are similar to crop plants and mostly play a role in the survival of insects to attack crops (Capinera, 2005).

2. Biological methods of weed control

The continuous use of traditional herbicides for weed control increases the cost of crop production with many negative impacts on health and the environment. Several types of chemical herbicides e.g., glyphosate, Atlantis (Mesosulfuron Methyl 3 % + Iodosulfuron Methyl Sodium 0.6), Dicamba (3,6-dichloro-2-methoxybenzoic acid), and 2,4-D, have been widely used for the management of weed germination and growth, but their long-time application does not effectively control weeds, nonetheless, develop resistance in weeds against the herbicides. Furthermore, chemical herbicides also pollute our air, water, and soil, and pose many toxic effects on living communities, including microorganisms, plants, animals, and humans (Boyce, 2010). Ultimately, crop productivity is reduced due to the development of resistance in weeds against weedicides. This is one of the utmost reasons that there have been no new herbicides commercialized with a novel target site during the last two decades. To avoid the negative impact of synthetic herbicides on the environment, scientists tried to introduce biological agent-based bioherbicide which is an alternate successful way to control weeds (Duke et al., 2002). So, new weeds controlling methods with environmentally friendly characteristics are required (Duke, 2012). Organic farming is an alternative method in which weeds are managed without using chemicals, hence weeds become unable to develop resistance against commonly used herbicides and global interest in organic farming is increasing several times. Recently, several biological agents have been used in weed management globally (Cordeau et al., 2016).

Nature is a big source of many new compounds and a large number of bacteria, plants, fungi, lichens, and insects that provide many new and natural bio-active compounds having germination and inhibitory effects (Da Mastro et al., 2006). Biological control is defined as the use of living agents such as insects, bacteria, nematodes, or fungi alone or in a complex form to suppress the growing weeds. All the forms which involve the application of microbes or living organisms are classified as biological control. Examples of agents that suppress weed growth biologically include arthropods (mites and insects), pathogens (bacteria, fungi, viruses, and nematodes), birds, fish, and other animals. Weed management through biological means may also involve modification of genes, genetic mechanisms, and gene products. In nature, plants can be controlled by naturally occurring organisms, so, bioherbicides are a combination of naturally occurring products that originate either from living organisms or from their primary and secondary metabolites which were fatherly used for controlling germination as well as weed growth without harming their surroundings (Bailey and Falk, 2011).

Biological-based herbicides have been further classified as host-specific or non-host-specific methods of weed management. Many species of bacteria and fungi have been developed and shown bioherbicidal properties against many vulnerable weeds (Hoagland, 2007). The target specificity bio-herbicide products are gaining more attention for the formulation of alternative commercial herbicidal products rather than chemicals-based herbicides (Cordeau et al., 2016). Biological agent-based herbicide (Bio-herbicide) was first introduced as a commercial product to farmers in the USA, Europe, Canada, and Ukraine, respectively (Cordeau et al., 2016). Non-chemical (bioherbicides based) weed-controlling methods are becoming more attractive in many countries. Different kinds of plant extracts and microbes were tested in lab research and applied in the field trials successfully, however, due to a lesser success rate only limited products are available in ago-markets to the farmers (Cordeau et al., 2016). Allelochemicals of plants naturally suppress the germination capabilities of weed seeds and their growth. For example, tomato plants release two types of allelochemicals named tomatine and tomatidine which suppress the germination of the weed, in some crop plants and hinder the pathogenic fungi (Hoagland, 2009). Recently, meta-genomics and chromatic techniques were used to study the phytotoxic activities of such bio-active compounds of plants (Kao-Kniffin et al., 2013). Many research studies have concluded that bacteria such as plant growth-promoting rhizobacteria (PGPR), fungi, and plant water extract effectively reduce weed seed germination and drastically control the growth of weed plants (Harding and Raizada, 2015, Dhanasekaran et al., 2017).

2.1. Fungi as biological weed control agent

Various studies have revealed effective weed control through sustainable and novel fungi product application (Table 1). Biological weed control products are commercially manufactured in North America primarily based on formulation, composition, and fungal species. Many of these products have proven to be effective in long-term applications. For instance, *Collego*, a fungal formulation of *Colletotrichum gloeosporioides* f.sp. *aeschynomene*, was commercially introduced to control *Aeschynomene virginica* (Menaria, 2007). Similarly, *BioMal*, a formulation of *Colletotrichum gloeosporioides* f.sp. *malvae*, was developed for the control of *Malva pusilla* (Menaria, 2007; Harding and Raizada, 2015). Similarly, a fungal formulation was introduced against white clover and broad-leaf plantain (Sindhu et al., 2018), and several species belonging to the genus *Colletotrichum* have been investigated against different weeds, such as *C. truncatum* has been applied against *Sesbania exaltata* (Schisler et al., 1991). A few species from the genus *Phoma* (*Phoma chenopodicola* and *P. herbarum*) have been reported as potential biological weed-controlling agents against *Chenopodium album* (Cimmino et al., 2013). Another fungal formulation, *Puccinia thlaspeos*, was introduced to control Dyer's woad (*Isatis tinctoria*) (Thomas, 2008), under the product name Woad Warrior (EPA Registration Number 73,417- 1). In 2005, another fungal formulation *Alternaria destruens* strain 059 was registered with EPA (Reg. Nos. 34,704–825/824; Harding and Raizada, 2015). This bio-product was extracted from the fungi *Cuscuta gronovii,* which intended to control *Cuscuta* spp. (Cook et al., 2009). Another bioherbicide was the formulated by fungus *Phytophthora palmivora* and registered in 1981 and 2006 (EPA Reg No. 73,049–9) to control strangler vine in citrus orchards (Harding and Raizada, 2015). (Johnson, 1994) reported that *Phoma proboscis, Microsphaeropsis amaranth* and *Colletotrichum capsica* were found effective in controlling bindweed (*Convolvulus arvensis*), pigweed (*Amaranthus*) species and morning glory (*Ipomoea* spp.), respectively. To manage Canada thistle (*Cirsium arvense*), dandelion (*Taraxacum officinale*), scentless chamomile (*Matricaria perforata*), and chickweed (*Stellaria medium*), researchers (Bailey et al., 2011) investigated and successfully applied the naturally occurring fungus *Phoma macrostoma.*

In Hawaii a biological control program was launched, and a smut fungus (*Entyloma ageratinae* sp.) was used to cope with mysterious weed mist flowers (*Conoclinium coelestinum*) (Fowler et al., 1999). Another rust fungus was successfully used against a rush skeleton, and rust fungus imported from Turkey was also successfully used to control musk thistle (*Carduus thoermeri*). In 2003, a rust fungus was imported from Turkey and Bulgaria and used as a biological control agent for yellow star thistle (*Centaurea solstitialis* L), and extensively tested to determine the host range (Fisher et al., 2011, Bruckart III, 2006). In china, C. *gloeosporioides* was registered with the trade name 'Lubao No. I' which was used to control the dodder weed (Mortensen, 1998). The *Chondrostereum purpureum* and basidiomycetous fungus were found to be more potential bioherbicides against black cherry, red alder, aspen, and white birch (Becker et al., 1999).

Colletotrichum coccodes (Wallr.) has been introduced as a biological agent to control Velvetleaf (*Abutilon theophrasti* Medic.) by Watson (1989). *P. amaranthicola* and spore suspensions of *M. amaranthi* significantly decreased the biomass of pigweed in pumpkin, soybean, and

Table 1
Summary of fungus-based bioherbicides for the control of weeds.

Fungal bioherbicide agent	Target weed control	References
C. gloeosporioides f.sp. *aeschynomene*	Northern joint vetch (*Aeschynomene virginica* L.)	(Menaria, 2007)
Sclerotinia minor (Sarritor)	Dandelion (*Taraxacum officinale*), white clover (*Trifolium repens* L.), and broad-leaf plantain in turf (*Taraxacum officinale, Trifolium repens and Plantago major*) L.)	(Sindhu et al., 2018)
Colletotrichum gloeosporioides f.sp. *malvae*	Round leaf mallow (*Malva pusilla*)	(Harding and Raizada, 2015)
Phoma genus species	*P. herbarum*	(Sumampong et al., 2008)
C. orbiculare	Spiny cocklebur (*XanthiumXantium spinosum* L.)	Auld et al., 1988, 1990)
Puccinia thlaspeos	Dyer's woad (*Isatis tinctoria*) L.)	(Thomas, 2008)
Alternaria destruens strain 059	Dodder species (*Cuscuta campestris* L.) species	(Cook et al., 2009)
Microsphaeropsis amaranthi	Pigweed species (*Amaranthus*) *retroflexus* L.) species	(Johnson, 1994)
Phoma macrostoma	Dandelion (*Taraxacum officinale*), Canada thistle (*Cirsium arvense* L.), chickweed (*Stellaria media* L.) and scentless chamomile (*Taraxacum officinale, Cirsium arvense, Stellaria media, and Matricaria perforate, Tripleurospermum inodorum* L.)	(Bailey et al., 2011)
Trichoderma virens	Redroot pigweed (*Amaranthus retroflexus* L.)	(Héraux et al., 2005a)
Puccinia chondrillina	*Rush skeleton* L. biotype (*Chondrilla juncea*)	(Adams and Line, 1984)
Puccinia carduorum	Musk thistle (*Carduus nutans* L.)	(Bruckart et al., 1996)
Puccinia jaceae var. *solstitialis*	Yellow star thistle (*Centaurea solstitialis*) (*Centaurea solstitial* L.)	(Fisher et al., 2011, Bruckart III, 2006)
Puccinia canaliculata	Yellow nutsedge *(Cyperus esculentus* L.)	(Greaves and MacQueen, 1992)
C. *gloeosporioides*	Dodder (*Cuscuta sppL.*)	(Mortensen, 1998)
Colletotrichum coccodes	Velvetleaf (*Abutilon theophrasti*)	(Wymore and Watson, 1989)
Chondrostereum purpureum	Red alder (*Alnus rubra*), black cherry (*Prunus serotine*), white birch (*Betula* L.), and aspen (*Alnus rubra, Prunus serotina, Betula papyrifera, and* species (*Populus tremuloides* L.)	(De Jong et al., 1990, Strunz et al., 1997)
Alternaria cassiae	Sicklepod (*Senna obtusifolia*), coffee senna (*Senna occidentalis*), and showy crotalaria (*Senna obtusifolia, Senna occidentalis, and Crotalaria spectabilis)*	(Walker and Boyette, 1985)
M. amaranthi 280 and *P. amaranthicola*	Common water hemp (*Amaranthus tuberculatus)* and pigweed (*Amaranthus* L.) in pumpkin and soybean (*Amaranthus tuberculatus, and Amaranthus*)	(Ortiz-Ribbing et al., 2011)
conjuncta/infectoria and *Fusarium tricinctum*	Dodder (*Cuscuta* L.) species in cranberry (*Cuscuta gronovii*)	(Hopen et al., 1996)

water hemp either applied alone or in a mixture (Ortiz-Ribbing et al., 2011). In addition, *Alternaria conjuncta, A. infectoria,* and *Fusarium tricinctum were* isolated from dodder weed, a parasitic weed used to successfully control dodder weed in cranberry (Ozerskaya et al., 2013).

Regarding fungal bioherbicides, Fungal bioherbicides have emerged as an eco-friendly alternative to chemical herbicides, offering targeted weed suppression while minimizing environmental impact. These biocontrol agents, derived from naturally occurring pathogenic fungi, infect and weaken invasive weed species through mechanisms such as enzyme production, toxin secretion, and direct tissue colonization (Harding and Raizada, 2015) .Several fungal species, including *Colletotrichum, Myrothecium*, and *Plectosporium*, have been successfully developed into bioherbicides for controlling a wide range of weeds (Charudattan, 2001). Additionally, integrating fungal bioherbicides with reduced doses of synthetic herbicides can enhance their efficacy while reducing herbicide resistance in weed populations. This synergistic approach improves sustainability and promotes healthier agroecosystems by preserving beneficial soil microbes and reducing chemical residues in the environment (Bailey et al., 2010).An overview of the mode of action of fungal bioherbicides is shown in Fig. 1.

2.2. Bacteria as biological weed controlling agent

Different types of bacterial strains have been identified as effective biological control agents against weeds, among which *X. campestris* and *Pseudomonas fluorescens* got considerable attention (Table 2). An overview of the mode of action of bacterial biocides is illustrated in Fig. 2. Various strains of *P. fluorescens* species, act as plant growth regulators (Caldwell et al., 2012), but some inhibit plant growth and germination (Banowetz et al., 2008). During different investigations, the inhibitory effect of 3 strains of *P. fluorescens* has been studied, the research studies revealed that these bacterial strains inhibit plant growth and germination by excreting extracellular metabolites (Banowetz et al., 2008, Sindhu et al., 2018). A strain D7 of *Pseudomonas fluorescens*, extracted from the rhizosphere of cheatgrass (*Bromus tectorum*) and wheat, has been used as a potential inhibitor against grassy weeds, such as downy brome (Gealy et al., 1996). Similarly, the inhibitory effect of *P. fluorescens* strain WH6, has been tested on various monocot and dicot species of weeds, and the WH6 strain is the germination inhibitor which is considered as a base for the production of a compound known as germination arrest factor (GAF) (Banowetz et al., 2009), so this strain has been used to control *Erwinia amylovora,* which is responsible of fire blight (Halgren et al., 2011). In another study, strain WH6 and strain D7 have been parallel studied and the culture of strain D7 was prepared like WH6 but strain D7 did not perform germination inhibitory action. Thus, the authors stated that strain D7 did not contain GAF activity (Banowetz et al., 2009).

The strain BRG100 of *P. fluorescens* can produce extracellular metabolites and is found to be effective against the grassy weed. Extracellular metabolites of *P. fluorescens* BRG100 have been investigated and were found effective in controlling green foxtail and grassy weeds

Table 2
Summary of Bacterial agent-based bioherbicides for the control of weeds.

Bacterial bioherbicide agent	Target weed control	References
P. fluorescens strain BRG100	Green foxtail (*Setaria viridis* L.)	(Caldwell et al., 2012)
Strain *X. campestris* pv. *poae* (Camperico)	Annual bluegrass (*Pao annua* L.)	(Kennedy, 2016)
P. syringae pv. *Tagetis*	Annual bluegrass (*Pao annua* L.) and *Asteraceae* weeds	(Johnson, 1994)

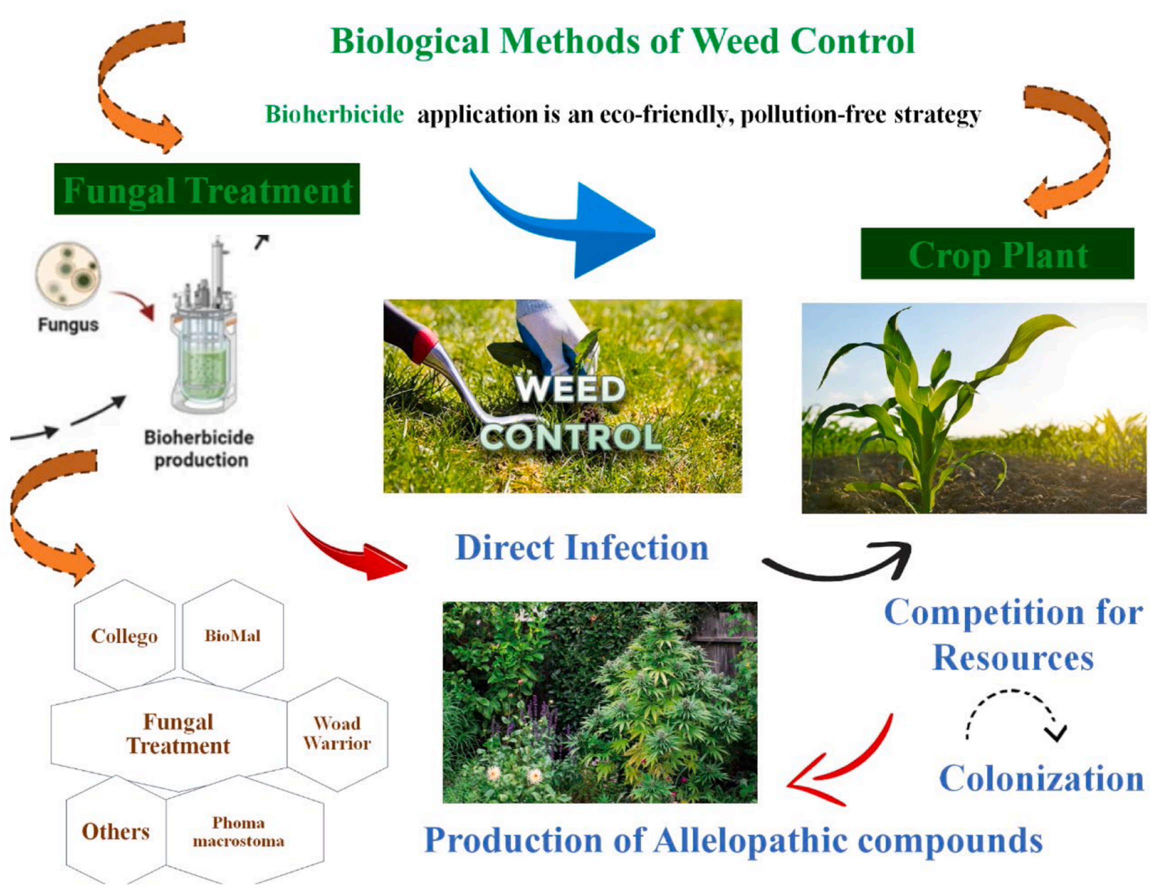

Fig. 1. Biological approaches for the management of weed using fungal bioherbicides as sustainable solutions.

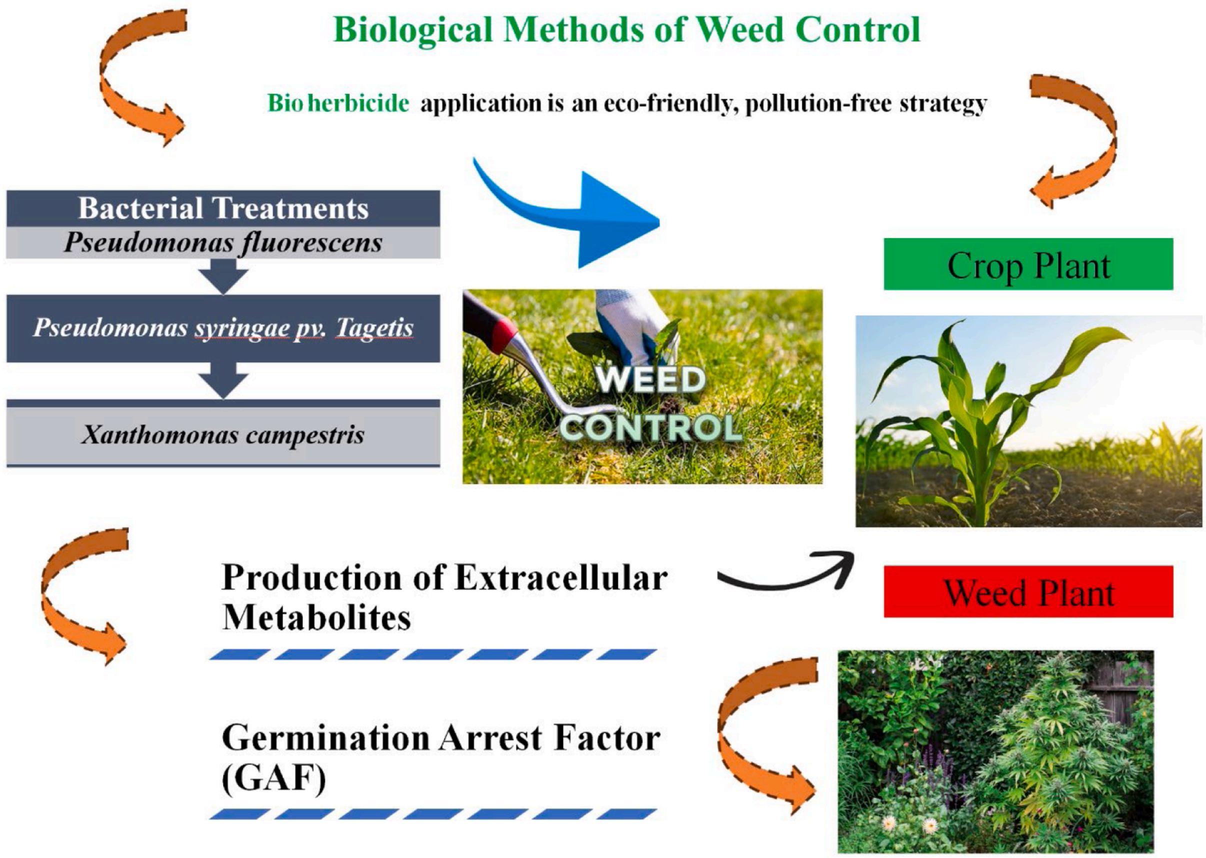

Fig. 2. Biological approaches for the management of weed using bacterial bioherbicides as sustainable alternatives for sustainable farming.

(Caldwell et al., 2012). Similarly, strains LS174 and LS102 of *P. fluorescens* were observed effective in controlling leafy spurge (Brinkman et al., 1999), and *P. syringae* pv. *Tagetis* has been found effective in controlling the germination of bluegrass, wild sunflower, aster weeds, cocklebur, creeping thistle, and ragweed (Johnson et al., 1996). Similarly, *X. campestris* also grabbed enough attention as a biological agent for weed management. In Japan, the JT-P482 strain of *X. campestris* pv. *poae* have been registered as biological agents against annual bluegrass with the product name Camperico (Kennedy, 2016). Similarly, strain LVA-987 of *X. campestris* gained attention as a biological control agent against horseweed (Harding and Raizada, 2015).

There are various advantages of bacteria over fungi to use as biological controlling agents, including faster growth (Deshwal et al., 2003), high genetic modification ability (Card et al., 2016), and better propagation ability.

2.3. Viruses as biological weed control agents

Under specific conditions, viruses have also been considered as biological weed control agents. Different researchers have studied the role of viruses in tackling different weed species (Hasiów-Jaroszewska et al., 2021, Wagemans et al., 2022). Whereas viruses have been used as bioherbicides against different weed species in a broad manner not specific to certain species (Table 3). Due to a lack of specificity with the host and variations in genetics, viruses are not considered appropriate agents for active biological control (Kazinczi et al., 2006). A virus with the name Tobacco Mild Green Mosaic was studied as a potential agent for *Solanum viarum* weed in Florida (Diaz et al., 2014). In New Zealand, Araujia Mosaic Virus was used to inhibit the growth of moth plants (Elliott et al., 2009), and in central and western Europe, a virus having a resemblance with Tobacco Rattle Virus was identified as a potential combating source against *Impatiens glandulifera* (Kollmann et al., 2007).

Table 3
Summary of Virus based bioherbicides for weed control.

Viral bioherbicide agent	Target weed control	References
Tobacco Mild Green Mosaic Tobamo virus	Soda apple (*Solanum elaeagnifoliumviarum*)	(Diaz et al., 2014)
Araujia Mosaic Virus	Moth plant (*AraujiaArujia sericifera)*	(Elliott et al., 2009)
Tobacco Rattle Virus	Himalayan Balsam *(Impatiens glandulifera)*	(Kollmann et al., 2007)
Óbuda Pepper Virus and Pepino Mosaic Virus	Black Nightshade *(Solanum nigrum*)	(Kazinczi et al., 2006)

Mostly baculovirus is used as an agent of biological control and belongs to Nucleopolyhedro virus (Ferrelli and Salvador, 2023). Therefore, they are also called nucleopolyhedro viruses (Ferrelli and Salvador, 2023). These are considered the best narrow spectrum, species to species specific, and apply as insecticidal. The viral-based bioherbicides have advantages that are nonharmful to mammals and humans. Therefore, these are safe to handle during the application. Repeated treatment in the case of viral-based bioherbicides is not important, because the virus is already present in the soil or on site sometimes and goes to hibernation. When the condition becomes suitable for them, they become active. In certain circumstances, the biological activities of viruses may offer more options for biological weed management since they differ greatly from pathogenesis brought on by bacteria or fungi (Giehl et al., 2023).

2.4. Agricultural byproducts for weed control

Agricultural by-products are promising alternatives to chemical herbicides and many natural products have been identified against weed control such as Brassicaceae seed meals (BSMs), corn gluten meal (CGM), and soybean meal (SBM) (Copping and Duke, 2007, Dayan et al., 2009; Table 4). In another research, it has been reported that CGM incorporation in soil significantly reduced weeds in strawberry fields (McDade and Christians, 2000), and it was found that the CGM application rate of 100–400 g m^{-1} in surface soil before planting reduced 50–84 % of weeds density as compared to the control treatment. However, the direct application showed toxicity in vegetables such as beet, onion, beans, carrot, pea, radish, lettuce, and sweet corn (McDade and Christians, 2000). It has also been reported, CGM applied at the rate of 300–1000 g m^{-2} to surface soil, significantly reduced the growth of creeping bentgrass (*Agrostis palustris* Huds.), redroot pigweed (*Amaranthus retroflexus* L.), black nightshade (*Solanum nigrum* L.), common purslane (*Portulaca oleracea* L), lambs quarters (*Chenopodium album* L.), and curly dock (*Rumex crispus* L.) (Bingaman and Christians, 1995). Similarly, Yu and Morishita (2014) declared CGM as a potential weed control source against narrow and broad-leaved weeds. Dried distiller grains with soluble (DDGS) are produced through the bio-ethanol fermentation process, and application of DDGS at 800–1600 g m^{-2} to soil reduced common chickweed and annual bluegrass 40–57 % and 33–58 %, respectively (Cai and Gu, 2016). Brassicaceae plants significantly consist of glucosinolates (GSL) which is an allelopathic compound, and an enzyme named myrosinase has the function of hydrolysis GSL and results to produce other biological compounds such nitriles, isothiocyanates, thiocyanates, oxazolidinethione and epithionitriles. These biological compounds caused toxicity to weed plants (Vaughn et al., 2006, Matthiessen and Kirkegaard, 2006). Almost twenty types of different GSLs with varying concentrations have been reported in *Brassica* species and their tissues (Kirkegaard and Sarwar, 1998). Seed meal of Indian mustard Pacific Gold and IdaGold contained 2-propenyl GSL and 4-hydroxybenzyl glucosinolates, respectively (Hansson et al., 2008), and the application of 3 % seed meal of Indian mustard to the surface soil decreased 74 % biomass of red-root pig-weed over control (Boydston et al., 2008).

Mustard seed meal (MSM) application to topsoil reduced the emergence and growth of common barnyard grass, lambs quarters, and kochia up to 66 %, 73 %, and 82 %, respectively as compared to their respective control treatments (Yu and Morishita, 2014). Furthermore, MSM application in strawberry fields significantly increased the strawberry yield and drastically reduced the weed growth of annual bluegrass, Italian ryegrass, and desert rock purslane (Banuelos and Hanson, 2010). Similarly, the BSMs application to the carrot field at the rate of 1 and 2 t ha^{-1} effectively controlled weeds enhanced the availability of mineral N, and significantly increased carrot yield (Snyder et al., 2009). Application of seed meal of mustard and soybean at the rate of 4.48 t ha^{-1} reduced the density of weeds by 4–45 % and 52–95 % after the 3rd and 6th week of the plantation, correspondingly (Shrestha et al., 2015). Boydston et al., (2011) recorded a significant decrease in the emergence of red-root pigweed with the application of mustard seed meal derived from "IdaGold".

Anaerobic soil disinfestation (ASD) is an emerging weed management method in which soil is modified by amendment before sowing by creating oxygen-free conditions in the soil (with organic residue plus water and covered with plastic). This condition not only suppresses the weeds but also promotes and encourages the germination of seeds (Khadka et al., 2021; Khadka et al., 2022). It also suppresses the pathogen especially soil born (Liu et al., 202). ASD was independently developed by The Netherlands (Blok et al., 2000) and by Japan (Momma et al., 2013). In The Netherlands, ASD is also recognized as a reductive soil disinfestation (RSD), and in Japan, it is also called a biological soil disinfestation (BSD), while in other regions of the world, it recognized as a bio-solarization (Momma et al., 2013). Studies show that ASD is a widely accepted method in those production systems where the chemical application is prohibited. ASD is also an environmentally and human-friendly strategy (MacLaren et al., 2020). In organic farming, weeds are the major barriers, and ASD is the most viable strategy to achieve the organic farming objective. The ASD is also an economical method of weed suppression in developing countries where chemical herbicides are not easily accessible for floriculture and vegetable production (Martins et al., 2019). ASD is also a very economical and eco-friendly method to control soil insects.

Table 4
Summary of Agricultural by-products' agent-based bioherbicides for the control of weeds.

Agricultural by-products bioherbicide agent	Target weed control	References
Corn gluten meal (CGM)	Seeded vegetables, beet, radish, bean, carrot, pea, lettuce, and sweet corn *(Beta vulgaris)*, radish (*Raphanus sativus, raphanistrum* L.), bean (*Phaseolus vulgaris*), carrot (*Daucus carota*), pea (*Pisum sativum,* L.), lettuce (*Lactuca sativa, serriola* L.), and sweet corn (*Zea mays*) L.)	(McDade and Christians, 2000)
Corn gluten meal	Common lamb's quarters (*Chenopodium album* L.), curly dock (*Rumex crispus* L.), purslane (*Portulaca oleracea* L.), black nightshade (*Solanum nigrum* L.), creeping bentgrass (*Agrostis stolonifera* L.), and redroot pigweed (*Chenopodium album, Rumex crispus, Solanum nigrum, Agrostis stolonifera*, and *Amaranthus retroflexus* L.)	(Bingaman and Christians, 1995)
Mustard seed meal (MSM)	Annual bluegrass (*Poa annua* L.), common chickweed (*Stellaria media* L.), redroot pigweed (*Poa annua, Stellaria media*, and *Amaranthus retroflexus* L.)	(Wymore and Watson, 1989)
Brassicaceae seed meals (BSMs)	Italian ryegrass (*Lolium multiforum*), annual bluegrass (*Poa annua* L.), desert rock purslane (*Calandrinia ciliate)*, and shepherd's purse (*Lolium multiflorum, Poa annua, Calandrinia ciliata*, and *Capsella bursa-pastoris* L.)	(Wymore and Watson, 1989)
Activated meadowfoam	Suppressed weeds in transplanted lettuce (*Lactuca sativa*)	(Intanon et al., 2015)

2.5. Weed control using plant extracts

Plant extracts derived from stems, leaves, roots, and seeds of different plants, and have been used as bioherbicides. Some plants could reduce the germination and growth of other plants due to the exuding phytotoxic allelochemicals. The extracts from the leaves of Japanese thistle (*Cirsium japonicum*), cocklebur (*Xanthium occidentale*), and lettuce (*Lactuca sativa*), can inhibit germination of alfalfa (*Medicago sativa* L.) (Chon et al., 2003). Similarly, water extracts of Heaven tree (*Ailanthus altissima* L.) leaves can inhibit the seed germination and growth of alfalfa (Tsao et al., 2002). A greenhouse study showed that purple passion-flower (*Passiflora incarnate* L.), Japanese pagoda tree (*Sophora japonica* L.), Nerium (*Nerium oleander* L.), and Chinese taro (*Alocasia cucullata* L.), powders at 1.5 t ha^{-1} effectively reduced growth of weeds in paddy fields. Resultantly, in paddy fields dry weight of weed was reduced by greater than 80 % and increased the rice yield by almost 20 % as compared to the control treatment (Khan et al., 2016). The water extracts (10 *g* per liter) and powders (1, 2, and 4 tons per hectare) of pricklyburr (*Datura inoxia* Mill.), castor (*Ricinus communis*), sorghum (*Sorghum vulgar* L.) and tobacco (*Nicotiana tabacum* L.) significantly reduced the seed germination and growth of bindweed (Nekonam et al., 2013). Likewise, the growth and germination of redroot pigweed were restricted by applying the extract of tobacco, castor, and pricklyburr (Nekonam et al., 2013).

Moreover, the germination of field bindweed was significantly inhibited by the eucalyptus leaf extract, and extracts of sorghum aerial parts effectively reduced the biomass of field bindweed (Cheema et al., 2001, Masoodi et al., 2008). Black walnut (*Juglans nigra*) also had a significant allelopathy effect on weed plants, and allelopathic extract of black walnut is commercially available under the name of NatureCur® as a bioherbicide formulated by Redox Chemicals, USA. It has been found that the rice husk extract can also be used as a promising bioherbicide against Barnyard grass (Ahn and Chung, 2000). (Dhima et al., 2009) declared that metabolites extracted from the different parts of aromatic plants like anise (*Pimpinella anisum*), dill (*Anethum graveolens* L.), lacy phacelia (*Phacelia tanacetifolia* Benth.), and oregano (*Origanum vulgare* L.) have allelopathy properties to kill different weeds. Application of Mexican marigold leaf (*Tagetes minuta* L.) in powdered form at the rate of 1–2 t ha^{-1} to rice fields significantly control the growth of purple nutsedge and barnyard grass (Wanzala et al., 2016).

2.6. Weeds control using plant allelopathic nature

Allelo chemicals are released in different ways i.e. leaching from plant leaves, root exudates, or volatilization from plant bodies (Vyvyan, 2002). Allelo chemicals are also known as bio-active metabolites (Vyvyan, 2002, Duke et al., 2002) and their suppressing potentials are highly reported and cited over time as shown in (Table 5).

Rice (*Oryza sativa* L.), Santa maria (*Parthenium hysterophorus* L.), common reed (*Phragmites australis* L.), and datura metel (*Datura alba* L.) are commonly reported plants species that release phytochemicals in their vicinity and have the inhibitory effect on the growth of other plants. Many scientists used this inhibitory mechanism of wild plants in bioherbicide development as an alternative to synthetic chemical-based herbicides for effective and sustainable weed control in crop fields (Khan and Khan, 2012, Dastagir and Hussain, 2013). Allelopathic water extract of rice (*Oryza sativa* L.) has the potential to inhibit the germination and growth of weeds (Chung et al., 2002), and rice exhibited allelopathic effects on *Heteranthera limosa* (duck salad) and many other broadleaf weeds. Glucosinolates is a hydrolysis enzyme that is present in *Brassica* species and has the capacity to suppress the germination of many weed seeds because glucosinolates mixed with water release organic cyanide which also inhibits the growth of weeds (Macnaughton et al., 1978). Plant-based natural products are volatile compounds (Singh et al., 2002), as aqueous extract of lichen (*Cladonia verticillaris*) contains phenolic compounds and these phenolics are mixed with solvents to develop bioherbicide and it have inhibitory action for weeds by changing their ultra-structural like its impact on *Lactuca sativa* plant seedlings (Tigre et al., 2015). Sorghum's allelochemical effects are selective and their effectiveness is dependent on allelochemical concentration (Sowiński et al., 2020). It was reported that the combined application of plant-based allelo chemicals with herbicides reduces their application dose for weed suppression and significantly increases the yield of the main crop (Scavo and Mauromicale, 2021). So, plant extract-based bioherbicides are the best alternate supplementation for sustainable and integrated weed management, these are also viable for environmental safety in the changing climate (Lázaro-dos-Santos et al., 2024).

Table 5
Summary of plant extract-based bioherbicides for weed control.

Plant extracts based Bioherbicides	Target weed control	References
Leaves of lettuce (*Lactuca sativa*), cocklebur (Xanthium strumarium), and Japanese thistle (*Cirsium japonicum*)	Root growth of alfalfa (*Medicago sativa*) L.)	(Chon et al., 2003)
Water extracted from the fresh leaves of the Tree of Heaven. (*Ailanthus altissima* L.)	Alfalfa (*Medicago sativa*) L.) seed germination and growth	(Tsao et al., 2002)
Chinese taro (*Alocasia cucullata* L.), purple passionflower (*Passiflora incarnata* L.), Nerium (*Nerium oleander* L.), and powders from Japanese pagoda tree (*Styphnolobium japonicum*)	Growth of paddy rice (*Oryza sativa)* weeds (*Echinochloa crus-galli* and *Scirpus* spp.,)	(Khan et al., 2016)
Tobacco (*Nicotiana tabacum* L.), castor (*Ricinus communis*), prickly burr (Datura inoxia Mill.), and sorghum (*Sorghum vulgar L.*) aqueous extracts (10 g per liter) and powders (1, 2 and 4 tons per hectare)	Bindweed (*Convolvulus arvensis* L.) in the field	(Nekonam et al., 2013)
Extract from Black Walnut (Juglans nigra)	hairy fleabane (*ConyzaErigeron bonariensis* L.) and horseweed (*Conyza Canadensis*), *Erigeron canadensis* L.)	(Shrestha et al., 2015)
Extracts from eucalyptus leaves (*Eucalyptus* spp.) and sorghum (*Sorghum bicolor*) aerial parts	Field bindweed (*Convolvulus arvensis* L.)	(Cheema et al., 2001)
Powders and water extracts made from tobacco (*Nicotiana tabacum*), castor (*Ricinus communis*), and pricklyburr (*Xanthium spinosum*)	Redroot pigweed (*Amaranthus retroflexus* L.)	(Nekonam et al., 2013)
Aqueous extracts of many aromatic plant components, including lacy phacelia, anise (*Pimpinella anisum*), dill, and oregano	Barnyard grass (*Echinochloa crus-galli* L.) and some broadleaf weeds (*Chenopodium album*)	(Intanon et al., 2015)
Mexican marigold (*Tagetes minuta* L.) leaf powder	Barnyard grass (*Echinochloa crus-galli* L.)and purple nutsedge (*Cyperus rotundus* L.)	(Intanon et al., 2015)
Soil and oregano (Origanum vulgare) biomass combined	Ryegrass (Lolium sppperenne L.) and redroot pigweed (*Amaranthus retroflexus* L.)	(Da Mastro et al., 2006)

2.7. Weed management with plant essential oils

Essential oils could reduce the weeds' herbicidal activity, and their application act in various ways to minimize weed infestation (Table 6), as they cause potential damage to the DNA, biochemical activities, mitosis, and meristematic cells in germinating weed seeds (Zanellato et al., 2009). For example, pelargonic acid (an essential oil) causes damage to cell membranes and has a wide spectrum of bioherbicide activities which in turn can impair cell functioning (Sokuti and Ghasemi, 2018; Sturchio et al., 2014). The size and type of seed coat affect how well plant extracts contribute to controlling weeds (El Mahdi et al., 2020) and weed seed germination decreases due to the phenolic compounds in plant extract which suppress the amylase activity (Zrig et al., 2022).

Natural essential oils of plants have demonstrated strong phytotoxicity against a range of undesirable species, as oils contain fragrances and natural flavors which produce characteristic odors (Mukherjee et al., 2000) and also hold allelochemicals that inhibit plant growth and seed germination, hence, it can be taken as a promising biological weed control tool (Chum et al., 2012, Hazrati et al., 2017). Terpenoids, particularly monoterpenes, and sesquiterpenes are vital components of essential oils and frequently have inhibitory effects against weed species (Weston and Duke, 2003). Palmer amaranth weed (*Amaranthus palmeri*) was inhibited from germination by the essential oils of some fragrant herbs, such as sweet marjoram (*Origanum majorana*), lemon basil (*Ocimum americanum*), and oregano (*Origanum vulgare*; Dudai et al., 1999). The germination of purslane (portulaca oleracea), amaranth (*Amaranthus* spp.), and knap weeds (*Centaurea* spp.) was significantly suppressed by the application of essential oils from rosemary (*Salvia rosmarinus*), *Lawson cypress*, eucalyptus (*Eucalyptus* spp.), and white cedar (*Melia azedarach*), which indicated their potential application as a pre-emergent natural herbicide for weed control (Ramezani et al., 2008). (*Parthenium hysterophorus*). Similarly, a study conducted in a lab found that *E. citriodora*'s volatile oils have herbicidal effects on a number of undesirable agricultural plants, including barnyard grass (*Echinochloa crus-galli*), canary grass (Phalaris canariensis), chickweed (Stellaria

Table 6
Summary of essential oils-based bioherbicides for weed control.

Essential oils-based Bioherbicide	Target weed control	References
Lawson cypress (Chamaecyparis lawsoniana), rosemary (Rosmarinus officinalis), white cedar (Thuja occidentalis), and eucalypt	Inhibits the germination of (Amaranthus spp.), *Amaranthus* L., purslane (Portulaca oleracea L.), and knapweed (Centaurea L.)	(Ramezani et al., 2008)
(Eucalyptus citriodora)	Congress grass (*Parthenium hysterophorus) hysterophporus* L.)	(Singh et al., 2005)
Aromatic plants, including oregano (Origanum vulgar), sweet marjoram (Origanum majorana), and lemon basil (Ocimum × citriodorum)	inhibits the germination of Palmer amaranth (*Amaranthus palmeri)*	(Dudai et al., 1999)
Common wormwood (Artemisia absinthium), spearmint (Mentha spicata), basil (Ocimum basilicum), sage (Salvia officinalis), thyme (Thymus vulgaris)	Corn cockle (*Agrostemma githago*), L.), redroot pigweed (*Amaranthus retroflexus*), L.), hoary cress (*Lepidium draba* L.), common lamb's quarters (*Chenopodium album*), L.), barnyard grass (*Echinochloa crus-galli*), L.), wild mignonette (*Reseda lutea*), L.), curly dock (*Rumex crispus*), L.), red clover (*Trifolium* pretense)	(Onen et al., 2002)
Red thyme (Thymus vulgaris), summer savory (Satureja hortensis), cinnamon (Cinnamomum verum), and clove (Syzygium aromaticum)	Common lamb's quarters (*Chenopodium album*), L.), common ragweed (Ambrosia artemisiifolia), johnsongrass (Sorghum halepense), and dandelion (Taraxacum officinale L.)	(Tworkoski, 2002)
Aqueous extracts of coriander (Coriandrum sativum), sweet fennel (Foeniculum vulgare), lacy phacelia (Phacelia tanacetifolia), and anise (Pimpinella anisum)	Barnyard grass (*Echinochloa crus-galli* L.)	(Dhima et al., 2009)
Cinnamon (Cinnamomum verum), lavender (Lavandula angustifolia), and peppermint (Mentha)	Pigweed (*Amaranthus sppretroflexus* L.), wild mustard (Sinapis arvensis), and ryegrass (*Lolium* spp.) *perenne* L.)	(Campiglia et al., 2007)
E. citriodora (Corymbia citriodora)	Canary grass (Phalaris canariensis), common lamb's quarter (*Chenopodium album*), L.), barnyard grass (*Echinochloa crus-galli*), L.), chickweed (*Stellaria media*), L.), and congress grass (*Parthenium* hysterophorus) *hysterophporus* L.)	(Saini and Singh, 2018)
Vetiver oil (Chrysopogon zizanioide)	Common lamb's quarters (*Chenopodium album*), L.), pitted morning glory (Ipomoea lacunose spp.), velvetleaf (*Abutilon theophrasti*), giant ragweed (*Ambrosia trifida*), and redroot pigweed (*Amaranthus retroflexus* L.)	(Mao et al., 2004)

media), common lamb's quarter (*Chenopodium album*), and congress grass (*Parthenium hysterophorus*; Saini and Singh, 2018).

Likewise, common ragweed (*Ambrosia artemisiifolia*), common lambs-quarters, dandelion (*Taraxacum officinale* L.), and johnsongrass (Tworkoski, 2002) were strongly affected by the essential oils from summer savory (*Satureja hortensis*), red thyme, clove (*Syzygium aromaticum* L.), and cinnamon (*Cinnamomum verum*). According to Dhima et al., (2009), it was discovered that the aqueous extracts of sweet fennel (*Foeniculum vulgare*), anise, coriander (*Coriandrum sativum*), and lacy phacelia (*Phacelia tanacetifolia*) completely decreased seed germination, root length, and seedling fresh weight of barnyard grass. The germination of wild mustard (*Sinapis arvensis*), pigweed, and ryegrass seeds was inhibited by the essential oils derived from lavender (*Lavandula*), peppermint (Mentha × Piperita), and cinnamon (Campiglia et al., 2007), thus from this, we suggest that essential oils have considerable potential to function as natural sustainable herbicides.

Manuka oil can be used as a natural weed control agent in both conventional and organic farming systems. It has been extracted from the manuka tree (*Leptospermum scoparium*). Leptospermum inhibited the growth of large crabgrass (*Digitaria* spp.) (Dayan and Duke, 2014). Commercially acknowledged biological weed control agent, citrus oil was utilized in conjunction with D-limonene, the primary active component, and the plant treated with D-limonene removed weeds waxy cuticle layer, which resulted in dryness and the death of the green tissue (Erasto et al., 2004). Essential oil known as vetiver oil, extracted from the roots of vetiver grass (*Vetiveria zizanioides Lynn Nas*) has a significant seed germination inhibitory effect on Petunia trifida, giant ragweed (*Ambrosia trifida*), velvetleaf (*Abutilon theophrasti*), and common lambs quarters (*Chenopodium album*; Mao et al., 2004)

3. Constraints in using bioherbicides

3.1. Difficulties in statutory and regulatory requirements

Formulating rules and prescriptions is a way to ensure safety regarding the use of any bioherbicide. Failure to get approval to test or import any bioherbicide from the concerned organization may risk research projects concerning that particular bioherbicide (Barratt et al., 2018). Such legislation and rigorous risk assessment of novel formulations might create additional expenses, and delay in releasing. Some countries need to pay attention to bioherbicide registration in line with pesticide legislation (Malamud-Roam, 2007), and the lack of bioherbicide markets to cover registration expenses within an acceptable time frame may limit this development.

3.2. Technological constraints

Different technological constraints have been recognized that are limiting bioherbicide utilization worldwide. The pathogenic strains, preparation method, and the interconnection of these two parameters highly affect the shelf life and the preparations of bioherbicides at room temperature (Evans, 2002). To improve the activity of biological herbicides, high concentration, and comprehensive fermentation to produce fungal biomass as easily available carrier material are required. The compatibility testing of ingredient formulation from registered agricultural products to new substances, such as humectants, starches, and sunscreens consumes a lot of resources and time (Mortensen, 1998, Gerhardson, 2002).

3.3. Environmental constraints

Environmental factors are affecting the performance of biological herbicide formulations and application as the production of inoculum depends on the sporulation although this process is fast, and it may last several weeks after application. However, it has very low efficacy (Ghosheh, 2005). When applying biological herbicides, the environmental conditions of plant parts such as leaf margin or stem margin are usually not conducive to biological controlling agents (Hollingsworth and Bailey, 2000). They target plant's physiology, consequently, how they interact with biological herbicides that are distributed by air will depend on the soil's environment, moisture content, and soil nutrient content (Patel and Patel, 2015). Climate change, including increased climatic variability and global warming, may affect biological weed control. The possible impact of these changes on the effectiveness of weed management further needs to be evaluated across different climatic conditions.

3.4. Biological limitations

From a biological point of view, decent biological herbicides act relatively quickly and are acceptable for the effective control of weeds. Unfortunately, Charudattan (2005) revealed that even under ideal conditions, many of the weed pathogens found may control only one weed species (Abbas et al., 2018), and the particularity of this host is related to the basic biological physiology of the pathogen and the variability of the host (Harris, 1993) and resistance (Auld et al., 2003). Additionally, there is usually a series of genetically diverse biotypes in weeds (Pacanoski, 2011) that may include some resistant biotypes, similar to micro-organisms (Boyetchko and Peng, 2004). For instance within fungal species, with partially several host ranges (TeBeest, 2012), so, it is possible to mix and change the biological species used as biological herbicides (Hoagland, 1990).

Protection of non-target plants in connection with the possible application of Chondrostereum purpureum (Pers ex Fr.) Pouzar, black cherry in coniferous forests can be managed by simulating the transmission of spores; hence, hazards to susceptible fruit trees can be statistically assessed from outside the forest (Pacanoski, 2011). Several researchers (Auld and Morin, 1995; Chacko et al., 1994) have expressed concerns over the likelihood of asexual or sexual gene exchange between biological pesticide strains and strains that attack distant crops.

Few commercial restrictions involve patent protection, market capacity, adjustment, and confidence (Mathur and Gehlot, 2018, Scheepens et al., 2001). Biological herbicide failures have typically resulted of tactical blunders or human errors. The employees who lack knowledge and experience in using biological pesticides have led to a rise in local failures. Regarding the application, inadequate training, and information dissemination to the farmers have resulted in significant limitations for biological weed control.

Several challenges are faced in the development of bioherbicides for example due to the complexity of weed diversity across the world, very difficult to find the biological agent against each weed. Furthermore, the research and development of bioherbicides take a long-time long time. Also, the bioherbicidal legislation and regulation approval take a long time and cost for approval. Additionally, very difficult to present bioherbicides in the farming market as traditional chemical herbicides are difficult to replace due to the farmer mentality. Moreover, the choice and variety of bioherbicides limited the availability of bioherbicides.

International organizations play a very important role in the development of bioherbicides as well as their regulation. For example, FAO can leverage big agricultural networking to coordinate bioherbicide testing in the field and then establish efficacy standards. Similarly, WHO can leverage the toxicology testing aspect of bioherbicides to evaluate their impact in the area of health including human and animal exposure. The International Plant Protection Conventions (IPPC), Organization for Economic Cooperation and Development (OECD), and United Nations Environment Programme (UNEP) can help to evaluate the ecological impacts, promote environmental sustainability, develop regional-level regulations, collaborate with each other to harmonize regulatory frame work for easy and smooth approval of the processes around the world. Collectively, all the organizations together can be bridged between research and development, and market to accelerate the effectiveness and environment-friendly alternative of chemically developed herbicides.

4. Conclusion

In general, allelochemicals are naturally occurring bioactive compounds present in the rhizosphere of most of the field crops either in low or high concentrations. These bioactive chemicals are entering into the soil through many mechanisms e.g., crop residues decomposition, root exudation, and volatilization. The agriculture industry's reliance on chemical pesticides, herbicides, and insecticides for weed control can be reduced by exploiting the appropriate use of crops with allelopathic traits. Microorganisms used in the formulation of bioherbicides mostly have no negative impact on their vicinity, soil, or environment and provide support during plant lifetimes. Numerous bacterial species possess the capacity to inhibit seed germination and seedling growth; however, their effectiveness is severely restricted because of various factors such as poor environmental circumstances and insufficient availability of nutrients. Nutrients are an important key factor that plays a critical role in the potential of the bacteria to suppress the growth of weed plants. Plant extracts used in allelopathy are a great source of nutrients. Considering this attribute of allelochemicals, the use of bacteria in conjunction with allelochemicals may demonstrate and enhance the capacity of bacteria to impede weed seed germination and growth. The combined effects of bacteria and allelopathic extract decrease weed development by twice as compared to the sole application of plant extract for weed management. Bacterial consortiums can boost soil fertility and encourage crop growth and development. Combined application of allelopathy water extract with a consortium of bacteria exhibited more weed control efficacy and increased crop yield, especially in wheat, maize, and cotton. Therefore, it offers a novel idea to discover natural product-based herbicides and pesticides.

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Taqi Raza: Conceptualization, Writing – original draft. **Muhammad Farhan Qadir:** Data curation, Visualization. **Shakeel Imran:** Writing – review & editing. **Zobia Khatoon:** Visualization, Software. **Muhammad Yahya Khan:** Writing – review & editing. **Mouna Mechri:** Writing – review & editing. **Waleed Asghar:** Conceptualization. **Muhmmad Ishaq Asif Rehmani:** Writing – review & editing. **Sergio de los Santos Villalobos:** Writing – review & editing, Funding acquisition. **Tooba Mumtaz:** Data curation. **Rashid Iqbal:** Writing – review & editing.

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