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Application Potentials of Plant Growth Promoting Rhizobacteria and Fungi as an Alternative to Conventional Weed Control Methods

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Abstract

Weeds are the plants usually grown on unwanted places and are notorious for causing interruptions in agricultural settings. Remarkable yield losses have been reported in fields infested with weeds worldwide. So far, these weeds cause about 34% of losses to yields of major agricultural crops and pose threats to economic condition of the farmers. Conventionally, weed control was achieved by the use of chemical herbicides and traditional agronomic practices. But these methods are no more sustainable as the magnitude of threats imposed by these conventionally outdated methods such as chemical herbicides is greater than the benefits achieved and their continuous use has disturbed biodiversity and weed ecology along with herbicide resistance in some weeds. Herbicide residues are held responsible for human health hazards as well. Therefore the future of weed control is to rely on alternative approaches which may be biological agents such as bacteria and fungi. This chapter highlights the potentials of using bacterial and fungal biocontrol agents against weeds in farmer fields. Moreover, detailed review on merits and demerits of conventional weed control methods is discussed in this chapter.

Keywords: biological weed control, PGPR, fungi, environment, human health, economic losses

1. Introduction

Agriculture is an approach of deploying natural resources to grow the desired plants. Since the induction of green revolution in the 1950s, the food production has been substantially increased that helped to meet food demands for the ever-increasing world population [1]. Improved irrigation practices, tillage implements, fertilizers, and farm operations were some of the key outputs of green revolution. Nevertheless these practices have paved the way of agricultural sustainability yet

there are some concerns associated with these practices as, improved irrigation have given rise to salinity of soils, intensive tillage causes deterioration of soil structure, loss of soil organic carbon and destruction of natural habitats of different flora, higher yielding crop cultivars depleted soil nutrients. With all of the outputs of green revolution, introduction of pests is also acknowledged [2]. Disturbance in agricultural production due to invasion of other living organisms for their own existence is a natural phenomenon which cannot be stopped. These living organisms that survive on others are called as pests which include insects, plant pathogens, nematodes, rodents, and weeds.

Among the agricultural crop pests, weeds are the most potent crop pests reducing crop yields by almost 34% followed by animal pests (18%) and plant pathogens (16%) worldwide [3]. Weeds are unwelcomed plants that interfere with the management of agricultural production systems, compete with the main crops for available nutrient resources and space and reduce growth, yield, and quality of agricultural produce up to a certain extent [4]. Generally, they produce a larger number of seeds, which may remain dormant in the soil seedbank for several decades, having greater plasticity and equipped with specialized seed dispersal mechanisms. Further, they exhibit the ability to invade newly disturbed areas and compete with crops for scarcely available moisture, nutrients, and light [5]. Apart from yield and production losses, they may also provide niches and harbor insects, plant pathogens, and other pests, hence increasing their incidence of attack to the main crop [6]. Weeds are the firstborn problem in agriculture since about 10,000 BC [7] representing the main hindrance in profitable agricultural production under natural resource management. The presence of weeds in natural ecosystems causes various direct and indirect losses, including interference with successful crop production, damage to biodiversity, loss of possibly fruitful land, loss of grazing areas and livestock production, obstruction of navigational and irrigation channels, and reduction of available water in water bodies. Most of the weeds belong to families Poaceae and Asteraceae. A majority of the weeds are terrestrial plants, a few are aquatic weeds and some are parasitic weeds [8]. Globally, reduction losses of wheat yield due to weed infestation are 23% [2]. The economic losses incurred due to this wheat yield reduction amount to Rs. 146 billion [9].

In the light of the abovementioned properties and harmful effects of weeds, it becomes important to control them. Appropriate weed control strategy in arable soils employs both the direct and indirect methods. Direct methods include those with the prime objective of weed control such as mechanical, manual, chemical and biological weed control and indirect being the cultural and preventive practices reducing germination, growth and vigor of weeds [10]. Many practices are available to control and manage weeds in agricultural crops. In ancient times when synthetic herbicides were not introduced, people tried polyculture, crop rotation, and other management practices that have shown sustainability with low inputs [11]. Until recently, weeds were being controlled by manual, mechanical, and chemical methods [12]. However there were drawbacks associated with each of these methods that severely limited their practical use, for example, herbicides cast detrimental effects on environment, humans, and animals [13]. They also cause contamination of water bodies and pollute natural resources like air, soil, and plants, thus destroying nontarget entities such as wildlife [14]. Also due to repeated herbicide applications, there is an increasing trend in herbicide-resistant weed species [15]. Mechanical weeding on the other side requires several repetitions and is only feasible for crops sown in rows; therefore weeds grown near to crop plants and within rows are escaped of control [10]. Similarly, hand weeding needs a huge number of labor and hence cannot be applied on a large scale [10]. Therefore, repeated manual weeding and nonavailability of labor make this method unfeasible and uneconomic [16].

Hence, the prevailing situation demands some weed control measures other than chemicals, and in this context, biological control is gaining much importance around the world. Biological control is a general term used to define the introduction of organisms mostly bacteria and fungi in order to solve one or more problems in the farmer's field [17, 18]. Biological control using bacteria (bacterial herbicides), fungi (mycoherbicides), and viruses has recently gained much attention. Different kinds of fungi showing herbicidal activity are potential candidates of *Phoma* and *Sclerotina* genera. Among the bacteria some members of *Pseudomonas* and *Xanthomonas* depict these attributes.

Broadly speaking the control of weeds using microbes in green areas is a green approach that may reduce costs, decrease dependence on synthetic chemicals, and lower the negative impressions of chemicals on the environment. Microorganisms in the form of bioherbicides can be more selective than synthetic chemicals (herbicides) and target only the desired species [19]. Bioherbicides also lessen the chances of induction of resistance in the target weed species, due to the involvement of a number of mechanisms [20]. Therefore, keeping in view the abovementioned (even more) limitations of conventionally outdated methods necessitates the adoption of newer methods based on biological agents that are environmentally safer, friendly, economic, and feasible. We tried to highlight the need for adoption of innovative methods of weed control with higher efficacy. We then focused on harmful aspects of the judicious use of herbicides that in turn causes threats to environmental quality, food security, and human health followed by future research aims for improvement.

2. Weed control options

About one third of the total costs in field crop production is taken away by the weed management. There exist a variety of weed control strategies that can be applied depending upon various cropping systems [21]. Traditional farming practices generally rely on the application of herbicides and manual weeding. Generally, weed control measures include physical, chemical, and biological methods.

2.1 Physical weed control

Physical approaches of weed control include mechanical (tillage), manual methods, crop rotations, and crop fertilization and are separately discussed with possible limitations.

An increase in the density of weed species has been observed where monocropping was adopted. However due to the diverse nature of crop rotations, the density of such weeds can be tackled for profitable crop production [22]. Using a cover crop in rotation with the main crop is an attractive solution to cope with weed infestations [23, 24]. The integration of cover crops with no-till system has shown significant reduction (78%) in weed density in the USA [25]. The weeds with similar life cycles that match with the crop pose serious threats to crop production. These cover crops when used properly in rotation with the main crop compete with weeds for available nutrients, light, space, and water sources, hence reducing their emergence and numbers [26]. However the ability of cover crops to control weeds is largely governed by the growth habit and performance of the cover crop in a desired area [27]. That makes the use of this method to be only a small scale.

Increasing the competitive ability of crops against weeds is an important aspect to avoid field losses due to weeds and has been seen as a strategy for integrated weed management systems [28]. It can be achieved through manipulating fertilizer

timing, rate of fertilizer, and placement methods effectively [29]. Nitrogenous fertilizers have been known to involve in the activation of dormant weed seeds, thus directly affecting specific weed densities. The most agricultural weeds have shown growth rates equal to that of wheat in response to the added nitrogen [30]. However, it is not well known that phosphorus levels of soil affect weed growth and crop as well, but it is a fact that the crop-weed competition is considerably affected by phosphorus fertilizations, for instance, Bansal [31] reported that weed-crop (fenugreek) competition was increased with higher P levels. Similarly, Santos et al. [32] reported that lettuce (*Lactuca sativa* L.) showed a higher competitive ability than the common purslane (*Portulaca oleracea* L.) but not smooth pigweed (*Amaranthus hybridus* L.) with higher P levels than lower levels. Therefore, due to this uncertainty, this method is not widely adopted and acceptable.

Manual weed control methods involve plucking, uprooting, and hoeing with and/or without hand-driven machines [33] and are in use since ancient times. Manual weed control is one of the most efficient methods and is applicable in areas where the labor is easily available. However, immediate availability of labor before the weeds have grown in crops [10], repeated hand weedings [16] and adoptation on only small scale farming are the major limitations of this method to be adopted. Mechanical methods use tillage implements such as cultivators, weeders, and different types of harrows which are being drawn by animals (in the past) or by engines (until recently) around world [34]. Tillage practices in the field affect weed management, weed seed bank in the soil, and soil disturbance patterns. Deep cultivation can be used to burry weeds that germinate in the upper soil layers such as *Phalaris minor* in wheat. However, timely sown wheat in integration with zero tillage has shown significant results in the reduction of *Phalaris minor* infestations, obtaining higher grain yields of wheat [35, 36]. Tillage for weed control is not suitable for all crops and is only limited to crops sown on rows with suitable row-to-row spacing. Weeds that grow in close association with crop plants are not managed properly by this method, and those weeds which are grown within crop rows cause more losses than those sown in between crop rows [10, 37]. Moreover, some weeds may regenerate which are not completely uprooted, and root injury to main crop may occur [38]. However, the use of tillage implements for weed control are associated with adverse environmental impacts such as deterioration of soil structure, disturbed soil biological processes and soil erosion [39], leaching of nutrients which would otherwise be available to plants and eutrophication [40]. Therefore the efficiency of mechanical weed control measures is less than that of chemical weed control [22, 38]. Tillage practices done for weeding aggravate more soil compaction than other tillage operations due to a shorter cover of wheel tracks [38].

2.2 Chemical weed control

The application of synthetic chemicals for crop protection began after the second world war when most of the selective herbicides for broad-leaved weeds were commercialized in 1946 [41]. However, with the advancement in crop protection measures usually at the start of the twentieth century, copper and sulfuric acid containing herbicides were developed [42]. Herbicides are chemical compounds which kill or control weeds and are largely synthesized by crop protection industries nowadays available for almost all cultivated crops. They were rapidly adopted by farming communities as they do not require much labor and hence are not costly; no risks of soil erosion and energy efficiency are further advantages of herbicides [43]. The most widely used chemicals in wheat to control grassy and non-grassy weeds are clodinafop, tralkoxydim, Atlantis (meso-/iodosulfuron), sulfosulfuron,

and pinoxaden. However, for the control of broad-leaved weeds, major chemical herbicides are carfentrazone, 2,4-D, and metsulfuron [44]. Herbicides account for 44% of all pesticides worldwide [45]. Nevertheless, chemical methods have controlled the weeds resultantly improving the yields of diverse crops from 10 to 50% [4]. However, the continuous application of such herbicides had led to intraspecific selection of weeds and caused the development of herbicide-resistant biotypes of weeds [46, 47]. Approximately, 300 herbicide-resistant weeds have been reported in 15 families of synthetic herbicides [45, 48, 49] (**Table 1**).

A major portion of applied herbicides falls on nontarget species and soil [50]. Some herbicides like triazines and sulphonylureas may persist in soil long enough to affect the growth of subsequent sensitive crops [38]. Herbicides have also caused toxicity and diseases to exposed animals [51]. Herbicides in soil however may not reduce the population of soil microflora and microfauna but may induce intraspecific and interspecific selections [38].

The magnitude of issues caused by herbicides is much bigger than the outcomes of herbicides (**Figure 1**). Therefore it is a dire need of the hour to move toward some newer methods other than chemicals that can ensure environmental safety and resource conservation and sustain crop production economically.

Herbicide-resistant weeds	Common names	Herbicide (s)
Eichhornia crassipes	Water hyacinth	2,4-D,Glyphosate
Chenopodium album	Common lambsquarters	Triazine
Salsola kali	Russian thistle	Sulfonylurea
Senecio vulgaris	Common groundsel	Triazine (atrazine)
Sesbania exaltata	Hemp sesbania	Glyphosate
Cyperus	Purple nutsedge	Sulfonylureas
Avena fatua	Wild oat	Glyphosate

Table 1.
Some worst weeds that evolved resistance against chemical herbicides.
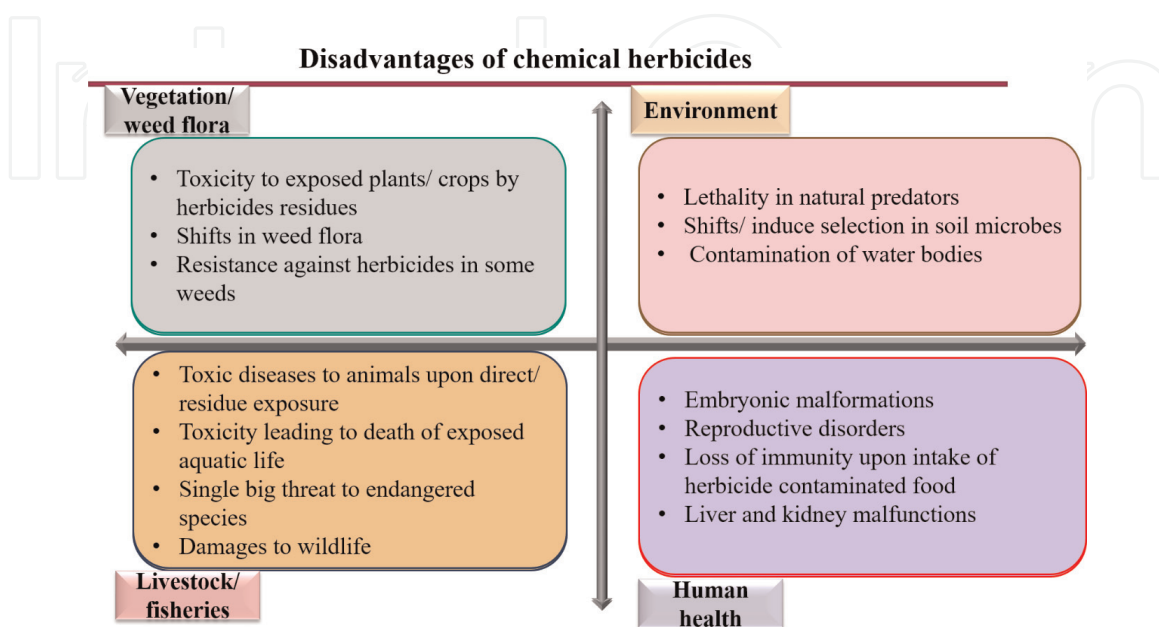

Figure 1.
Disadvantages of herbicides to all life forms. Modified and redrawn from [1].

2.3 Biological weed control

Biological control is the intentional use of biological agents (living organisms) to control plant pathogens or weeds in fields [52, 53]. The application of herbicides for sustaining agricultural production has created so many problems such as contamination of groundwater, destruction to the nontarget species, and induction of resistance against herbicides in a number of weed species [45], and other control methods become even more unsuitable where the land value is small and unaccessible with widespread weed infestations. This situation paved the way of researchers to move toward biological control as an alternative option in weed management. The chemical herbicides can persist in soil for longer periods of time, have limitations for crop rotation, and cause damage to the nontarget organisms [54]. Microbial herbicides on the other hand are more selective and affect only the target species [19]. The other advantage of using microbial agents is the reduced chance of induction of resistance in the target species [20].

Primarily there are two fields of application within the context of biological weed control, viz., the classical and augmentative or inundative. Classical biological control is the introduction and subsequent discharge of a natural enemy of a pest predator with the objective to reduce its virulence without becoming a pest itself [55]. This method is suitable for the control of perennial weeds that grow over a range of large areas such as in the forests, rangelands, along waterways, and roadsides and where reduction in weed competitiveness is required [56]. Several agents might be used in this strategy such as insects, fungi, mites, and different herbivores. The inundative biological control also called as bioherbicide approach is the

Trade name	Microbe(s) involved	Target weed(s)	Representative/initial report reference
BioMal	*Colletotrichum gloeosporioides* f. sp. *nalvae*	Round-leaved mallow	[60]
Casst	*Alternaria cassia*	Sicklepod, coffee senna	[61]
Biochon	*Chondrostereum purpureum*	Woody weeds	[62]
Collego	*Colletotrichum gloeosporioides* f. sp. *aeschynomene*	Northern joint vetch	[61]
Phoma	*Phoma macrostoma*	Broadleaf weeds	[18, 63]
Devine	*Phytophthora palmivora*	Strangle vine	[64]
Camperico	*Xanthomonas campestris* pv. *poae*	Annual bluegrass	[65]
Hakatak	*Colletotrichum acutatum*	*Hakea sericea*	[17]
Myco-tech	*Chondrostereum purpureum*	Deciduous tree species	[66]
Smolder	*Alternaria destruens*	Dodder	[67]
Dr. Biosedge	*Puccinia canaliculata*	Yellow nutsedge	[68]
Lubao	*Colletotrichum gloeosporioides* f. sp.	Dodder	[61]
Woad warrior	*Puccinia thlaspeos*	Dyer's woad	[69]
Chontrol	*Chondrostereum purpureum*	Alders and other hard woods	[66]
Sarritor	*Sclerotinia minor*	Dandelion	[70]

Table 2.
Successful microbial herbicides (registered) worldwide.

application of mass-produced fungal spores or bacterial cultures in higher concentrations with the objective to eradicate invasive weeds in a managed area [57]. The inundative biocontrol is more related to the agricultural needs and turf management because its implementation is similar to the conventional herbicides as liquid sprays and solid granules [58, 59]. A number of microbial herbicide formulations based on bacteria and fungi have been registered worldwide (**Table 2**).

3. PGPR and stimulation of plant growth

Rhizosphere is the region of the soil surrounded by plant roots and often extended from the surface of roots [94]. This constituency of the soil is much wealthier in bacteria than the contiguous bulk soil [95]. The plant growth-promoting rhizobacteria are the soil bacteria that reside in the rhizosphere and are involved in the stimulation of plant growth through direct and indirect methods [96]. Agricultural production currently relies on the judicious use of synthetic fertilizers [97, 98] that have shown negative environmental impacts due to overuse of these chemical fertilizers [99]. Therefore, the use of PGPR inoculants can be considered as an environmentally sound alternative approach for the sustainable management, decreasing the use of synthetic fertilizers [100–102]. Within the context of PGPR research and their modes of actions, there has been an increasing trend in literature to search for the best PGPR candidate in order to commercialize as bio-fertilizer. Plant growth-promoting rhizobacteria are equipped with a plenty of mechanisms that can result in the promotion of plant growth. For instance, Parmar and Dadarwal [103] suggested the involvement of *fluorescent pseudomonads* to promote nodulation process and increased nitrogen fixation in chickpea [104], in another study, confirmed the ability of *Azospirillum* sp. inoculation on some significant agricultural crops in terms of increased dry weights of the root and shoot. Similarly, [105], who suggested that the foliar application of rhizobacteria in apricot and mulberry causes an increase in total surface area and chlorophyll contents as compared to uninoculated control [106], documented the growth response in wheat after the inoculation with rhizobacteria and revealed that the growth and development of wheat largely depends on the nature of PGPR and environmental factors.

Spaepen et al. [107] reported that various genera of rhizobacteria use tryptophan as a precursor to produce IAA by different pathways. However, the plant pathogenic bacteria only use the indole acetamide pathway to synthesize IAA that causes tumor formation in plants. Swain et al. [108] suggested that cultures of *Bacillus subtilis* when applied on *Dioscorea rotundata* increased the root/stem ratio and number of sprouts as compared to the uninoculated control.

A recent study by Minorsky [109] reported the excellent colonization ability of a PGPR isolate *Pseudomonas fluorescens* (B16) in tomato roots. The positive effects were increased plant height, enhanced flowering, and increased fruit weight. Castro et al. [110] proposed that PGPR stimulates growth and development of crops both by direct and indirect methods. The direct methods of growth promotion may include biological nitrogen fixation, solubilization of mineral phosphorus and iron, production of phytohormones, and synthesis of enzymes and siderophores. Indirect growth promotion occurs through the production of antibiotics and fungal-degrading enzymes and competition for niche exclusion in the rhizosphere [111, 112].

As for the higher uptake of nutrients that is concerned through application of bacterial inoculants, Qin et al. [113] reported the ability of rhizobacteria to dissolve fixed phosphate is related to the rhizosphere acidification. The rhizobium inoculation in soybean plants causes increased availability of phosphorus as compared to

non-inoculated plants, hence positively influencing plant growth. Ambrosini et al. [114] suggested that sunflower-associated *Burkholderia* strains were found to be solubilizing $Ca_3(PO4)_2$, hence availing phosphorus for plant use. The management of soil, plant, and environmental interactions evidenced by boosted crop yields is gaining much attention globally. Moreover, agricultural inoculants (cultures) contain plant beneficial bacteria that help plants to meet the demands for nutrients.

4. Bacteria in biological weed control

A number of bacterial species have been studied due to their potential against weed management (**Table 3**). Two major classes of rhizobacteria that show herbicidal activity are *Pseudomonas* and *Xanthomonas* sp. Different rhizobacterial species have been investigated as weed control agents on different crops based on their secondary metabolites [115, 116]. As stated earlier *Pseudomonas* have gained much importance as an agent in biological weed management; there are many strains of this genera, some are plant beneficial [117] and others can have inhibitory effects on plants [118] and so can be applied in biological weed control. Production of extracellular metabolites from these strains is a key mechanism in inhibition of plant growth or germination inhibition [118–120]. However several other mechanisms showing herbicidal activity of bacteria are shown in **Figure 2**.

A strain of *Pseudomonas fluorescens* (D7) isolated from wheat and downy brome rhizosphere has shown inhibitory effects on a number of grassy weeds especially downy brome by virtue of production of a phytotoxin [116, 119, 121]. Kremer et al. [122] tested the phytopathogenic ability of different *fluorescent* and non*fluorescent pseudomonads* which were isolated from the rhizosphere of seven important weeds. About 18% of the strains show phytopathogenecity. However, the ratio of isolates that inhibited seedlings was ranged between 35 and 65%. The mechanism behind is the production of antibiotics, and about 75% of the isolates were active in siderophore production.

Kennedy et al. [121] reported the differential weed inhibition ability of *Pseudomonads* for downy brome and winter wheat. When the culture filtrates were tested on agar, about 8% of the isolates reduced the root growth of downy brome but have no effects on the root growth of wheat. However, under soil application only less than 1% inhibited the growth of downy brome. In the field study, only 0.2% of the total 1000 isolates inhibited the growth of downy brome but increased the growth of winter wheat by 18–35%. Kremer [123] worked with different cover crops associated with deleterious rhizobacteria. Seed bacterization with DRB reduces growth and biomass in weeds associated with cover crops. Adam and Zdor [124] described that rhizobacteria isolated from the rhizosphere of *Abutilon theophrasti* Medik caused growth inhibition of different weeds.

Weissmann and Gerhardson [125] suggested that the application of strain (A153) on *Chenopodium album* suppressed the growth of plants for 10–14 days; however in field conditions, this effect lasts for 2 months. Similarly Weissmann et al. [126] demonstrated excellent growth inhibition ability of a strain (A153) belonging to soil bacteria *Serratia plymuthica* when sprayed on a number of broad-leaved weeds. However, in field experiment this strain showed differential effects on *C. album*, *Stellaria media*, *Polygonum convolvulus*, and *Galeopsis speciosa*. Li and Kremer [127] suggested that the inoculation of *Pseudomonas fluorescens* strain (G2–11) inhibited the growth of *Ipomoea* sp. and *Convolvulus arvensis* weeds and increased the growth of wheat and soybean crops. Zermane et al. [128] in a study stated that *P. fluorescens* has the possible potential to control *Orobanche crenata* and *O. foetida* (Broomrape).

Microbe(s) involved	Target weed(s)	Growth condition (s)	Mechanism(s)	Observed effects/comments	References
Pseudomonas fluorescens	Sour cherry	Pot	IAA production	Significant loss in root weight	[71]
Streptomyces chromofuscus cluster	Barnyard grass	Axenic	Antibiosis and H_2S production	ND	[72]
Streptomyces sp. 0H-5093	Reddish	Axenic	Antifungal activity and production of 4-chlorothreonine	Significant growth inhibition	[73]
Streptomyces sp.	Reddish	Axenic	Cellulose inhibition and phthoxazolin A production	Significant growth inhibition due to cellulose inhibition	[74]
Thermoactinomyces sp. A-6019	*Lemna minor*	Axenic	Herbicidal activity and 5′-deoxyguanosine production	ND	[72]
Streptomyces hygroscopicus	*Barnyard grass*	Pot	Antimicrobial and herbicidal activity due to hydantocidine production	Germination inhibition, significant reduction in stem, and leaf structure of weed	[75]
Fusarium and *Rhizoctonia* sp.	Leafy spurge	Greenhouse	Exopolysaccharide and HCN production	Biocontrol activity on leafy spurge leading to significant growth suppression	[76]
Flavobacterium sp.	Sugar beet	Axenic	IAA production	Decreased root elongation and increased shoot to root ratio	[67]
Enterobacter taylorae	Bindweed	Axenic	IAA production	90.5% reduction in root growth, phytotoxic activity	[77]
Pseudomonas fluorescens	Leafy spurge	Field	Auxin production to phytotoxic levels	Reduced cell membrane integrity, inhibited root growth	[60]
Streptomyces saganonensis	Barnyard grass, goose grass, and tufted manna grass	ND	Herbicidine (vi)	Biocontrol activity	[78]
Pseudomonas syringae strain 3366	Corn spurry and fireweed	Pot	Phytotoxin production	Germination inhibition, reduced root, and shoot growth	[79]
Pseudomonas syringae pv. *tagetis*	Annual bluegrass	Field	ND	Greater than 70% weed control	[57]

Microbe(s) involved	Target weed(s)	Growth condition (s)	Mechanism(s)	Observed effects/comments	References
Pseudomonas syringae pv. *phaseolicola*	Kudzu	Greenhouse	ND	ND	[80]
Fusarium tricinctum	Dodder	Field	ND	Effectively controlled dodder at preemergence and postemergence application	[70]
Trichoderma virens	Several weeds	Field	Rhizosphere competence and production of herbicidal compound viridiol	Reduced emergence and seedling growth of different weeds up to a significant extent	[81]
Colletotrichum gloeosporioides f. sp. *malvae*	Round-leaved mallow	Greenhouse	ND	Significant biomass reduction, reduced fresh and dry weight, and inhibited root growth	[82]
Fusarium solani f. sp.	Texas gourd	Field	ND	Greater than 78% mortality, reduced vigor	[83]
Nectria ditissima	Red alder	Field	Infection	ND	[84]
Multiple isolates were screened belonging to *Pseudomonas* spp. and *Xanthomonas* spp.	Jointed goat grass	Axenic and field	ND	Inhibition of weeds by 71% in growth chamber and by 20–74% in different field conditions	[85]
Sclerotinia sclerotiorum	Dandelion	Field	Necrosis and discoloration	80.7% reduction in number of dandelion plants and overall weight reductions	[86]
Pseudomonas putida	Garden asparagus	Pot	Succinic acid and lactic acid production	ND	[87]
Pseudomonas fluorescens and *P. putida*	*Striga hermonthica* (Del.) Benth.	Pot	ND	Significant reduction of weeds and improved biomass of maize	[88]
Collection of multiple rhizobacteria	Leafy spurge	Axenic	Phytotoxin synthesis	30% reduction in leafy spurge growth	[89]
Pseudomonas syringae st. 1 and st. 2	*Polypogon monspeliensis*, *Convolvulus arvensis*, and *Phalaris paradoxa*	Laboratory and field	ND	Reduction in biomass up to 47.5%, 22.8%, and 51.3%. Inhibited 40%, 32.6%, and 46.4% of biomass over control in field conditions	[90]

Microbe(s) involved	Target weed(s)	Growth condition (s)	Mechanism(s)	Observed effects/comments	References
Pseudomonas aeruginosa, *Pseudomonas syringae*, and *Pseudomonas alcaligenes*	Broad-leaved dock, common lambs' quarter	Pot and field	HCN production, IAA production, antibiotic production	Grain yield losses of infested wheat were recovered up to 11.6 to 68% in pot trial, and 17.3 to 62.9% in field trial, respectively	[34]
T. harzianum, *T. pseudokoningii*, *T. reesei*, and *T. viride*	*Avena fatua* L.	Laboratory	ND	Culture filtrates of four *Trichoderma* spp. significantly reduced root, shoot growth, and biomass of *Avena fatua*	[91]
Trichoderma harzianum Rifai, *Trichoderma pseudokoningii* Rifai, *Trichoderma reesei* Simmons, and *Trichoderma viride* Pers	*Phalaris minor* L. and *Rumex dentatus* L.	Laboratory	Synthesis of butanol, n-hexane, chloroform, and ethyl acetate	Original concentration of filtrates reduced root and shoot length and biomass of *Rumex dentatus* significantly, but effect on shoot growth of *Phalaris minor* was not significant	[92]
Trichoderma virens combined with composted chicken manure and rye	Multiple broadleaf and grassweeds	Field	Viridiol (3H)-benzoxazolinone (BOA) and 2,4-dihydroxy-1,4-(2H)benzoxazine-3-one (DIBOA) production	Significant reductions in the emergence of broadleaf and grassweeds and higher reductions in weed biomass was resulted with all treatments as compared to control	[93]

ND = not described.

Table 3.
Features of opportunistic bacteria and fungi in weed control under varying growth conditions.
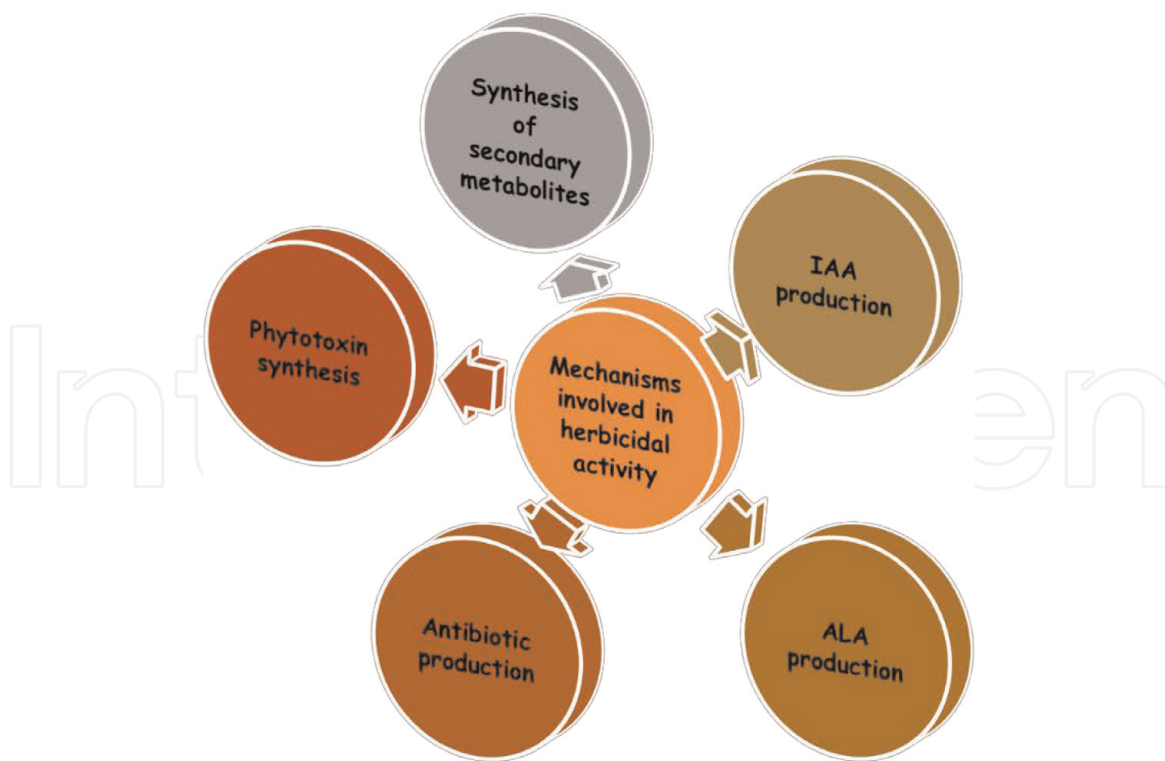
Figure 2.
Possible mechanisms of plant growth-promoting rhizobacteria and fungi involved in herbicidal activity. IAA refers to indole-3 acetic acid, and ALA refers to aminolevulinic acid.

Banowetz et al. [118] tested the germination inhibition activity in various monocot and dicot plants by the application of *P. fluorescens* (strain WH6). The germination inhibition activity was attributed due to the production of a compound called as Germination-Arrest Factor (GAF). Patil [129] screened 15 strains of deleterious rhizospheric bacteria isolated from rhizosphere of different weeds. Among these strains five isolates caused a significant reduction in root and shoot growth of weeds while showing no harmful effects on crop plants. Boyette and Hoagland [130] suggested that *X. campestris* (strain LVA-987) have shown strong growth suppressive effects against horseweed (*Conyza canadensis*). Some of the key herbicidal mechanisms shown by bacteria and fungi are shown in **Figure 2**.

5. Fungi (mycoherbicides) in biological weed control

A list of fungal biological weed control agents is given in **Table 3**. Within the scientific context, three genera of fungi have received worldwide attention to be used in biological weed control. In addition to the abovementioned BioMal and Collego, different other species of genus *Colletotrichum* have been researched extensively. Additionally, *C. truncatum* have been reported to control sesbania (*Sesbania exaltata*) [131] and *C. orbiculare* that has been found to control spiny cocklebur (*Xanthium spinosum*) [63, 132]. It is evident from the literature that these two *Colletotrichum* species produce indole acetic acid [133] which is a phytohormone and derivatives of which show herbicidal activity [134].

Within the genus *Phoma*, three species have a potential against weed control. *P. herbarum* is a fungus that is isolated from lesions of dandelion leaf that have shown control effects of dandelion [135]. *P. macrostoma* has also been studied for weed control due to its inhibitory effects on the dicot plants [18, 136, 137]. *P. macrostoma* strain (94-44B) has been found to control turf associated with broad-leaved weeds in Canada. Mass spectrometric analysis of *P. macrostoma*

revealed the production of photobleaching of macrocidins [138] that do not have any inhibitory effects on monocot plants [18]. Despite this macrocidins an anthra-quinone pigment in *P. macrostoma* has shown prominent herbicidal effects on some weeds in Central India [139]. The third species under this genus is *Phoma chenopodicola* that is studied widely for its potential against common lamb's quarter [62]. The mechanism behind its virulence against lamb's quarter is the production of diterpene and chenopodolin, a phytotoxic compound isolated from this species [62].

Two species within the genus *Sclerotinia* have been investigated for their herbi-cidal activity. It is evidenced by the work of Abu-Dieyeh and Watson [140] that *Sclerotinia minor* effectively controlled dandelions in turf management systems. A closely related species of this genus *S. sclerotiorum* has also shown the potential against noxious weeds [141]. Production of oxalic acid has been found by these two species that cause virulence on the host plant [142].

Apart from these three genera, there are other fungal candidates that are regis-tered to control weeds in forest lands and ecosystem managements [143]. A worth mentioning bioherbicide is De Vine containing a fungus *Phytophthora palmivora* [144]. This formulation was registered in 1981 and again in 2006 with the EPA [144].

The mycoherbicide "EcoClear" contains *Chondrostereum purpureum*, a patho-genic fungus which should be applied after the injury to the weeds' branches to retard resprouting [145].

Soil-borne fungi also serve as an important tool in weed management. Their direct application in the soil causes decay of the seeds or emerging seedlings [146]. *Trichoderma virens* is one example that reduces weed populations in horticultural crops [81].

Khattak et al. [147] tested two fungi *Aspergillus* and *Penicillium* for their herbi-cidal activity against two separate weeds *Silybum marianum* L. and *Lemna minor*. Results showed excellent weed-suppressive characters in the extracts of these fungi.

6. Conclusion and future strategy

Biological control of weeds using bacteria and fungi should be the prime priority for mitigating the negative impressions posed by conventionally adopted weed control methods in order to ensure environmental safety and human health. These biological control agents should be adopted in areas with higher and multiple weed infestations; areas of low value land, where weeds have gotten resistance against herbicides; and areas with lack of labor and where the recommended cultural practices cannot be carried out, for example, restrictions posed by topography and narrow rowed crop cultivations. However, in special cases the combination of biological control agents with other methods could also be a promising approach as an alternative to conventional methods.

The future advancement in biological agents for weed control should be based on advancements in microbial genetics (metagenomics), microbe-plant interac-tions, and microbial community-level analyses. Further investigations need to be discovered in the future in order to make biological weed control more pragmatic and instrumental. In this context, additional microbe-host relationships containing a match of biological agent and its potential host at greater susceptibility of viru-lence should be further explored. Since the 1960s a number of formulations have been registered in the world. Formulations that can ensure greater shelf lives, efficacy, and survival of microbial agents should be investigated in the future. Investigations on microbial community structure and function can advance micro-bial weed control. Traditional methods of microbial community structure solely rely on phenotypic characters; molecular-level characterization should be explored in

the future. In a nutshell, fatty acid profiling should be the initial step in targeted weed control. Nucleic acid tools, array pyrosequencing, metagenomics, construction of molecular probes, selection of hyper virulence, genomic studies, and host-microbe interactions should be investigated for the development of innovative weed control methods, reducing reliance on herbicide usage.

Acknowledgements

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References

[1] Abbas T, Zahir ZA, Naveed M, Kremer RJ. Limitations of existing weed control practices necessitate development of alternative techniques based on biological approaches. Advances in Agronomy. 2018;**147**: 239-280

[2] Oerke EC. Crop losses to pests. The Journal of Agricultural Science;**144**: 31-43

[3] Jabran K, Mahajan G, Sardana V, Chauhan BS. Allelopathy for weed control in agricultural systems. Crop Protection. 2015;**72**:57-65

[4] Ashiq M, Aslam Z. Chemical control of weeds. In: Weeds and Weedicides. Faisalabad. Pakistan: Department of Agronomy, Ayub Agricultural Research Institute, Faisalabad and University of Agriculture; 2014. pp. 235-256

[5] Rajcan I, Swanton CJ. Understanding maize-weed competition: Resource competition, light quality and the whole plant. Field Crops Research. 2001;**71**: 139-150

[6] Booth BD, Murphy SD, Swanton CJ. Weed Ecology in Natural and Agricultural Systems. Cambridge, UK: CABI Publishing; 2003

[7] Avery AA. Nature's Toxic Tools: The Organic Myth of Pesticide-Free Farming. Center for Global Food Issues; 2006. Available from: www.cgfi.org

[8] Kostov T, Pacanoski Z. Weeds with major economic impact on agriculture in Republic of Macedonia. Pakistan Journal of Weed Science Research. 2007;**13**: 227-239

[9] Razzaq A, Cheema ZA, Jabran K, Hussain M, Farooq M, Zafar M. Reduced herbicide doses used together with allelopathic sorghum and sunflower water extracts for weed

control in wheat. Journal of Plant Protection Research. 2012;**52**:281-285

[10] Alam SM. Weeds and Their Ill Effects on Main Crops. Karachi, Pakistan: DAWN media group; 2003. Dawn the internet edition: http://DAWN.com

[11] Singh HP, Daizy Batish R, Kohli RK. Allelopathic interactions and allelochemicals: New possibilities for sustainable weed management. Critical Reviews in Plant Sciences. 2003;**22** (3–4):239-311

[12] Chauvel B, Guillemin JP, Gasquez J, Gauvrit C. History of chemical weeding from 1944 to 2011 in France: Changes and evolution of herbicide molecules. Crop Protection. 2012;**42**:320-326

[13] Annett R, Habibi HR, Hontela A. Impact of glyphosate and glyphosate based herbicides on the fresh water environment. Journal of Applied Toxicology. 2014;**34**:458-479

[14] Geiger F, Bengtsson J, Berendse F, Weisser WW, Emmerson M, Morales MB, et al. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic and Applied Ecology. 2010;**11**: 97-105

[15] Heap I. The International Survey of Herbicide Resistant Weeds. 2015. Available from: www.weedscience.org [Accessed: June 16, 2015]

[16] Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM. Weed management in direct-seeded rice. Advances in Agronomy. 2007;**93**: 153-255

[17] Charudattan R. Biological control of weeds by means of plant pathogens: Significance for integrated weed management in modern agroecology. BioControl. 2001;**46**:229-260

[18] Bailey KL, Pitt WM, Falk S, Derby J. The effects of *Phoma macrostoma* on non-target plant and target weed species. Biological Control. 2011;**58**: 379-386

[19] Bolton H, Elliott LF. Toxin production by a rhizobacterial *Pseudomonas* spp. that inhibits wheat growth. Plant and Soil. 1989;**114**:269278

[20] Crump NS, Ash GJ, Fagan RJ. The development of an Australian Bioherbicide. In: Bishop AC, Boersma M, Bames CD, editors. 12th Australian Week Conference; 1999. p. 235237

[21] Anderson WP. Methods of weed control. In: Weed Science: Principles. 2nd ed. Saint Paul: West; 1983. pp. 65-122

[22] Liebman M, Mohler CL, Staver CP. Ecological Management of Agricultural Weeds. Cambridge: Cambridge University Press; 2001. p. 532

[23] Chauhan BS, Singh RG, Mahajan G. Ecology and management of weeds under conservation agriculture: A review. Crop Protection. 2012;**38**:57-65

[24] Mhlanga B, Cheesman S, Maasdorp B, Muoni T, Mabasa S, Mangosho E, et al. Weed community responses to rotations with cover crops in maize-based conservation agriculture systems of Zimbabwe. Crop Protection. 2015;**69**: 1-8. DOI: 10.1016/j.cropro.2014.11.010

[25] Fisk JW, Hesterman OB, Shrestha A, Kells JJ, Harwood RR, Squire JM, et al. Weed suppression by annual legume cover crops in no tillage corn. Agronomy Journal. 2001;**93**:319-325

[26] Teasdale JR. Cover crops, smother plants, and weed management. In: Hatfield JL, Buhler DD, Stewart, editors. Integrated Weed and Soil Management. Chelsea, MI: Ann Arbor Press; 1998. pp. 247-270

[27] Mhlanga B, Cheesman S, Maasdorp B, Mupangwa W, Thierfelder C. Contribution of cover crops to the productivity of maize-based conservation agriculture systems in Zimbabwe. Crop Science. 2015;**55**: 1791-1805. DOI: 10.2135/ cropsci2014.11.0796

[28] Mohler CL. Weed life history: Identifying vulnerabilities. In: Liebman M, Mohler CL, Staver CP, editors. Ecological Management of Agricultural Weeds. Cambridge, UK: Cambridge University Press; 2001. pp. 40-98

[29] O'Donovan JT, Sharma MP, Harker KN, Maurice D, Baig MN, Blackshaw RE. Wild oat (*Avena fatua*) populations resistant to triallate are also resistant to difenzoquat. Weed Science. 1994;**42**: 195-199

[30] Blackshaw RE, Brandt RN, Janzen HH, Entz T. Weed species response to phosphorus fertilization. Weed Science. 2004;**52**:406-412

[31] Bansal C. Efficiency of various weed control methods on growth and yield of fenugreek (*Trigonella foenum-graecum* L.) [Doctoral dissertation]. Gwalior, MP: Rvskvv; 2012

[32] Santos BM, Dusky JA, Stall WM, Shilling DG, Bewick TA. Phosphorus effects on competitive interactions of smooth pigweed (*Amaranthus hybridus*) and common purslane (*Portulaca oleracea*) with lettuce (*Lactuca sativa*). Weed Science. 1998:307-312

[33] Young SL, Pierce FJ, Nowak P. Introduction: Scope of the problem-rising costs and demand for environmental safety for weed control. In: Automation: The Future of Weed Control in Cropping Systems. Dordrecht, The Netherlands: Springer; 2014. pp. 1-8

[34] Abbas T, Zahir ZA, Naveed M, Aslam Z. Biological control of broad-

leaved dock infestation in wheat using plant antagonistic bacteria under field conditions. Environmental Science and Pollution Research. 2017;**24**(17): 14934-11494

[35] Chhokar RS, Sharma RK, Jat GR, Pundir AK, Gathala MK. Effect of tillage and herbicides on weeds and productivity of wheat under rice-wheat growing system. Crop Protection. 2007; **26**:1689-1696

[36] Franke AC, Singh S, McRoberts N, Nehra AS, Godara S, Malik RK, et al. Phalaris minor seed bank studies: Longevity, seedling emergence and seed production as affected by tillage regime. Weed Research. 2007;**47**:73-83

[37] Melander B, Holst N, Rasmussen IA, Hansen PK. Direct control of perennial weeds between crops—Implications for organic farming. Crop Protection. 2012; **40**:36-42

[38] Hakansson S. Soil tillage effects on weeds. In: Weeds and Weed Management on Arable Land: An Ecological Approach. Cambridge: CABI Publishing; 2003

[39] Ahlgren S. Environmental Impact of Chemical and Mechanical Weed Control in Agriculture: A Comparing Study Using Life Cycle Assessment (LCA) Methodology. Sweden: The Swedish Institute for Food and Biotechnology, Gothenburg; 2004. SIK Rapport No. 719-2004

[40] Birkas M, Jolankai M, Gyuricza C, Percze A. Tillage effects on compaction, earthworms and other soil quality indicators in Hungary. Soil and Tillage Research. 2004;**78**:185-196

[41] Cobb AH, Kirkwood RC. Herbicides and Their Mechanisms of Action. Boca Raton, FL: CRC Press; 2000

[42] Hamill AS, Holt JS, Mallory-Smith CA. Contributions of weed science to

weed control and management. Weed Technology. 2004;**18**:1563-1565

[43] Ghorbani R, Leifert C, Seel W. Biological control of weeds with antagonistic plant pathogens. Advances in Agronomy. 2005;**86**:191-225

[44] Chhokar RS, Sharma RK, Gill SC. Compatibility of herbicides against grassy weeds in wheat. Indian Journal of Weed Science. 2013;**45**:239-242

[45] Quimby PC, King LR, Grey WE. Biological control as a means of enhancing the sustainability of crop/ land management systems. Agriculture, Ecosystems and Environment. 2002;**88**: 147-152

[46] Bradley KW, Hagood ES Jr. Identification of a Johnsongrass (*Sorghum halepense*) biotype resistant to aryloxyphenoxypropionate and cyclohexanedione herbicides in Virginia. Weed Technology. 2001;**15**:623-627

[47] De Prado R, Osuna MD, Fischer AJ. Resistance to ACCase inhibitor herbicides in a green foxtail (*Setaria viridis*) biotype in Europe. Weed Science. 2004;**52**:506-512

[48] Chhokar RS, Sharma RK, Chauhan DS, Mongia AD. Evaluation of herbicides against (*Phalaris minor*) in wheat in north-western Indian plains. Weed Research. 2006;**46**:40-49

[49] Heap IM. International Survey of Herbicide Resistant Weeds. 2014. Available from: http://www.weedscience.org [Accessed: July, 2014]

[50] Crone EE, Marler M, Pearson DE. Non-target effects of broadleaf herbicide on a native perennial forb: A demographic framework for assessing and minimizing impacts. Journal of Applied Ecology. 2009;**46**:673-682

[51] Pimentel D. Environmental and economic costs of the application of

pesticides primarily in the United States. Environment, Development and Sustainability. 2005;**7**:229-252

[52] Hallet SG. Where are the bioherbicides? Weed Science. 2005;**53**: 404-415

[53] Chutia M, Mahanta JJ, Saikia R, AKS B, Sarma TC. Effect of leaf blight disease on yield of oil and its constituents of *Java citronella* and in vitro control of the pathogen using essential oils. World Journal of Agricultural Sciences. 2006;**2**: 319-321

[54] Guske S, Schulzand B, Boyle C. Biocontrol options for *Cirsium arvense* with indigenous fungal pathogens. Weed Research. 2004;**44**:107-116

[55] Shaw RH, Bryner S, Tanner R. The life history and host range of the Japanese knot weed psyllid, *Aphalara itadori* Shinji: Potentially the first classical biological weed control agent for the European Union. Biological Control. 2009;**49**:105-113

[56] Templeton GE, TeBeest DO, Smith RJJ. Biological weed control with mycoherbicides. Annual Review of Phytopathology. 1979;**17**:301-310

[57] Johnson DR, Wyse DL, Jones KJ. Controlling weeds with phytopathogenic bacteria. Weed Technology. 1996;**10**:621-624

[58] Auld BA, Hetherington SD, Smith HE. Advances in bioherbicide formulation. Weed Biology and Management. 2003;**3**:61-67

[59] Caldwell CJ, Hynes RK, Boyetchko SM, Korber DR. Colonization and bioherbicidal activity on green foxtail by *Pseudomonas fluorescens* BRG100 in a pesta formulation. Canadian Journal of Microbiology. 2012;**58**:1-9

[60] Brinkman MA, Clay SA, Kremer RJ. Influence of deleterious rhizobacteria on

leafy spurge (*Euphorbia esula*) roots. Weed Technology. 1999;**13**:835-839

[61] Julien MH, Griffiths MW. Biological control of weeds. In: A World Catalogue of Agents and Their Target Weeds. Wallingford, UK: CAB International; 1998

[62] Cimmino A, Andolfi A, Zonno MC, Avolio F, Santini A, Tuzi A. Chenopodolin: A phytotoxic unrearranged ent-pimaradiene diterpene produced by *Phoma chenopodicola*, a fungal pathogen for *Chenopodium album* biocontrol. Journal of Natural Products. 2013;**76**:1291-1297

[63] Auld BA, Say MM, Ridings HI, Andrews J. Field applications of *Colletotrichum orbiculare* to control *Xanthium spinosum*. Agriculture, Ecosystems and Environment. 1990;**32**: 315-323. DOI: 10.1016/0167-8809(90) 90168-d

[64] Burnett HC, Tucker DPH, Patterson ME, Ridings WH. Biological control of milk weed vine with a race of *Phytophthora citrophthora*. Proceedings of the Florida State Horticultural Society. 1973;**86**:111-115

[65] Imaizumi S, Nishino T, Miyabi K, Fujimori T, Yamada M. Biological control of annual bluegrass (*Poa annua* L.) with a Japanese isolate of *Xanthomonas campestris* pv. poae (JT-P482). Biological Control. 1997;**8**:7-14

[66] Setliff EC. The wound pathogen *Chondrostereum purpureum*, its history and incidence on trees in North America. Australian Journal of Botany. 2002;**50**:645-651. DOI: 10.1071/bt01058

[67] Loper JE, Schroth MN. Influence of bacterial source of indole-3-acetic acid on root elongation of sugar beet. Phytopathology. 1986;**76**:386-389

[68] Phatak SC, Summer DR, Wells HD, Bell DK, Glaze NC. Biological control of

yellow nutsedge with the indigenous rust fungus *Puccinia canaliculata*. Science. 1983;**219**:1446-1447

[69] Lovic BR, Dewey SA, Thomson SV, Evans JO. *Puccinia thlaspeos* a possible biocontrol agent for Dyers woad. Proceedings - Western Society of Weed Science. 1988;**41**:55-57

[70] Hopen HJ, Carusoand FL, Bewick TA. Control of dodder in cranberry vaccinium macrocarpon with a pathogen-based bioherbicide. Acta Horticulturae. 1997;**446**:427-428

[71] Dubeikovsky AN, Mordukhova EA, Kochetkov VV, Polikarpova FY, Boronin AM. Growth promotion of blackcurrant softwood cuttings by recombinant strain *Pseudomonas fluorescens* BSP53a synthesizing an increased amount of indole-3-acetic acid. Soil Biology and Biochemistry. 1993;**25**:1277-1281

[72] Isaac BG, Ayer SW, Letendre LJ, Stonard RJ. Herbicidal nucleosides from microbial sources. The Journal of Antibiotics. 1991;**44**:729-732

[73] Yoshida H, Arai N, Sugoh M, Iwabuchi J, Shiomi K, Shinose M, et al. 4-chlorothreonine, a herbicidal antimetabolite produced by *Streptomyces* sp. OH-5093. The Journal of Antibiotics. 1994;**47**:1165-1166

[74] Tanaka Y, Kanaya I, Takahashi Y, Shinose M, Tanaka H, Omura S. Phthoxazolin A, a specific inhibitor of cellulose biosynthesis from microbial origin. The Journal of Antibiotics. 1993;**46**:1209-1213

[75] Nakajima M, Itoi K, Takamatsu Y, Kinoshita T, Okazaki T, Kawakubo K, et al. Hydantocidin: A new compound with herbicidal activity from *Streptomyces hygroscopicus*. The Journal of Antibiotics. 1991;**44**:293-300

[76] Kremer RJ, Caesar AJ, Souissi T. Soilborne microorganisms of Euphorbia

are potential biological control agents of the invasive weed leafy spurge. Applied Soil Ecology. 2006;**32**:27-37

[77] Sarwar M, Kremer RJ. Enhanced suppression of plant growth through production of L-tryptophan-de rived compounds by deleterious rhizobacteria. Plant and Soil. 1995;**172**: 261-269

[78] Cutler HG. Perspectives on discovery of microbial phytotoxins with herbicidal activity. Weed Technology. 1988;**2**:525-532

[79] Norman MA, Patten KD, Gurusiddaiah S. Evaluation of a phytotoxin(s) from *Pseudomonas syringae* for weed control in cranberries. Horticultural Science. 1994;**29**: 1475-1477

[80] Zidack NK, Backman PA. Biological control of kudzu (*Pueraria lobata*) with the plant pathogen *Pseudomonas syringae* pv. phaseolicola. Weed Science. 1996; **44**:645-649

[81] Héraux FMG, Hallett SG, Ragothama KG, Weller SC. Composted chicken manure as a medium for the production and delivery of *Trichoderma virens* for weed control. Horticultural Science. 2005;**40**:1394-1397

[82] Grant NT, Prusinkiewicz E, Mortensen K, Makowski RMD. Herbicide interactions with *Colletotrichum gloeosporiodes* f. sp. malvae, a bioherbicide for round leaved mallow (*Malva pusilla*) control. Weed Technology. 1990;**4**:716-723

[83] Weidemann GJ, Templeton GE. Control of Texas gourd, *Cucurbita texana*, with *Fusarium solani* f. sp. cucurbitae. Weed Technology. 1988;**2**: 271-274

[84] Dorworth CE. Biological control of red alder (*Alnus rubra*) with the fungus

Nectria ditissima. Weed Technology. 1995;**9**:243-248

[85] Kennedy AC, Stubbs TL. Management effects on the incidence of jointed goatgrass inhibitory rhizobacteria. Biological Control. 2007; **40**:213-221

[86] Riddle GE, Burpee LL, Boland GJ. Virulence of *Sclerotinia sclerotiorum* and *S. minor* on dandelion (*Taraxacum officinale*). Weed Science. 1991;**39**: 109-118

[87] Yoshikawa M, Hirai N, Wakabayashi K, Sugizaki H, Iwamura H. Succinic and lactic acids as plant growth promoting compounds produced by rhizospheric *Pseudomonas putida*. Canadian Journal of Microbiology. 1993;**39**:1150-1154

[88] Ahonsi MO, Berner DK, Emechebe AM, Lagoke ST. Selection of rhizobacterial strains for suppression of germination of *Striga hermonthica* (Del.) Benth. seeds. Biological Control. 2002; **24**:143-152

[89] Souissi T, Kremer RJ. A rapid microplate callus bioassay for assessment of rhizobacteria for biocontrol of leafy spurge (*Euphorbia esula* L.). Biocontrol Science and Technology. 1998;**8**(1):83-92

[90] Omer AM, Balah MA. Using of rhizo-microbes as bioherbicides for weeds. Global Journal of Biotechnology and Biochemistry. 2011;**6**(3):102-111

[91] Javaid A, Ali S. Alternative management of a problematic weed of wheat *Avena fatua* L. by metabolites of trichoderma. Chilean Journal of Agricultural Research. 2011;**71**(2):205-211

[92] Javaid A, Ali S. Herbicidal activity of culture filtrates of *Trichoderma* spp. against two problematic weeds of wheat. Natural Product Research. 2011; **25**(7):730-740

[93] Héraux FM, Hallett SG, Weller SC. Combining *Trichoderma virens*-inoculated compost and a rye cover crop for weed control in transplanted vegetables. Biological Control. 2005; **34**(1):21-26

[94] Bringhurst RM, Cardon ZG, Gage DJ. Galactosides in the rhizosphere: Utilization by *Sinorhizobium meliloti* and development of a biosensor. Proceedings of the National Academy of Sciences of the United States of America. 2001;**98**:4540-4545

[95] Hiltner L. Uber neuere Erfahrungen und Probleme auf dem Gebiet der Bodenbakteriologie und unter besonderer Berucksichtigung der Grundungung und Brache. Arbeiten der Deutschen Landwirtschaftlichen Gesellschaft. 1904;**98**:59-78

[96] Ahemad M, Kibret M. Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. Journal of King Saud University - Science. 2014;**26**:1-20

[97] Wartiainen I, Eriksson T, Zheng W, Rasmussen U. Variation in the active diazotrophic community in rice paddy-nifH PCR-DGGE analysis of rhizosphere and bulk soil. Applied Soil Ecology. 2008;**39**:65-75

[98] Adesemoye AO, Torbert HA, Kloepper JW. Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial Ecology. 2009;**58**:921-929

[99] Shenoy VV, Kalagudi GM, Gurudatta BV. Towards nitrogen autotrophic rice. Current Science. 2001; **81**:451-457

[100] Alves BJR, Boddey RM, Urquiaga S. The success of BNF in soybean in Brazil. Plant and Soil. 2004;**252**:1-9

[101] Hungria M, Campo RJ, Souza EM, Pedrosa FO. Inoculation with selected

strains of *Azospirillum brasilense* and *A. lipoferum* improves yields of maize and wheat in Brazil. Plant and Soil. 2010;**331**: 413-425

[102] Hungria M, Nogueira MA, Araujo RS. Co-inoculation of soybeans and common beans with rhizobia and azospirilla: Strategies to improve sustainability. Biology and Fertility of Soils. 2013;**49**:791-801

[103] Parmar N, Dadarwal KR. Stimulation of nitrogen fixation and induction of flavonoid like compounds by rhizobacteria. Journal of Applied Microbiology. 1999;**86**:36-44

[104] Dobbelaere S, Croonenborghs A, Thys A, Ptacek D. Responses of agronomically important crops to inoculation with Azospirillum. Australian Journal of Plant Physiology. 2001;**28**:871-879

[105] Esitken A, Karlidag H, Ercisli S, Turan M, Sahin F. The effect of spraying a growth promoting bacterium on the yield, growth and nutrient element composition of leaves of apricot (*Prunus armeniaca* L. cv. Hacihaliloglu). Australian Journal of Agricultural Research. 2003;**54**:377-380

[106] Khalid A, Arshad M, Zahir ZA. Screening plant growth-promoting rhizobacteria for improving growth and yield of wheat. Journal of Applied Microbiology. 2004;**96**:473-480

[107] Spaepen S, Vanderleyden J, Remans R. Indole-3-acetic acid in microbial and microorganism-plant signaling. In: Unden F, editor. FEMS Microbiology Reviews. New York: Blackwell Publishing Ltd; 2007. pp. 1-24

[108] Swain MR, Naskar SK, Ray RC. Indole-3-acetic acid production and effect on sprouting of yam (*Dioscorea rotundata* L.) minisetts by *Bacillus subtilis* isolated from culturable

cowdung microflora. Polish Journal of Microbiology. 2007;**56**:1 03-1 1110

[109] Minorsky PV. On the inside. Plant Physiology. 2008;**146**:323-324

[110] Castro RO, Cornejo HAC, Rodriguez LM, Bucio JL. The role of microbial signals in plant growth and development. Plant Signaling & Behavior. 2009;**4**:701-712

[111] Zahir ZA, Muhammad A, Frankenberger WT. Plant growth promoting rhizobacteria: Applications and perspectives in agriculture. Advances in Agronomy. 2004;**81**:97-168

[112] Van Loon LC. Plant responses to plant growth-promoting rhizobacteria. European Journal of Plant Pathology. 2007;**119**:243-254

[113] Qin L, Jiang H, Tian J, Zhao J, Liao H. Rhizobia enhance acquisition of phosphorus from different sources by soybean plants. Plant and Soil. 2011;**349**: 25-36

[114] Ambrosini A, Beneduzi A, Stefanski T, Pinheiro FG, Vargas LK, Passaglia LMP. Screening of plant growth promoting rhizobacteria isolated from sunflower (*Helianthus annuus* L.). Plant and Soil. 2012;**356**:245-264

[115] Tranel PJ, Gealy DR, Kennedy AC. Inhibition of downy brome (*Bromus tectorum*) root growth by a phytotoxin from *Pseudomonas fluorescens* strain D7. Weed Technology. 1993;**7**:134139

[116] Gealy DR, Gurusiddah S, Ogg AG Jr, Kennedy AC. Metabolites from *Pseudomonas fluorescens* strain D7 inhibit downy brome (*Bromus tectorum*) seedling growth. Weed Technology. 1996;**10**:282-287

[117] Gamalero E, Lingua G, Tombolini R, Avidano L, Pivato B, Berta G. Colonization of tomato root seedling by *Pseudomonas fluorescens* 92rkG5:

spatio-temporal dynamics, localization, organization, viability, and culturability. Microbial Ecology. 2005;**50**:289-297

[118] Banowetz GM, Azevedo MD, Armstrong DJ, Halgrenand AB, Mills DI. Germination-arrest factor (GAF): Biological properties of a novel, naturally-occurring herbicide produced by selected isolates of rhizosphere bacteria. Biological Control. 2008;**46**: 380-390

[119] Kennedy AC, Elliott LF, Young FL, Douglas CL. Rhizobacteria suppressive to the weed downy brome (*Bromus tectorum* L.). Soil Science Society of America Journal. 1991;**55**:722-727

[120] Quail JW, Ismail N, Pedras MSC, Boyetchko SM. Pseudophomins A and B, a class of cyclic lipodepsipeptides isolated from a *Pseudomonas* species. Acta Crystallographica Section E: Crystallographic Communications. 2002;**58**:o268-o271

[121] Kennedy AC, Johnson BN, Stubbs TL. Host range of a deleterious rhizobacterium for biological control of downy brome. Weed Science. 2001;**49**: 792-797

[122] Kremer RJ, Begonia MFT, Stanley L, Lanham ET. Characterization of rhizobacteria associated with weed seedlings. Applied and Environmental Microbiology. 1990;**56**:1649-1655

[123] Kremer RJ. Growth suppression of annual weeds by deleterious rhizobacteria integrated with cover crops. In: Spencer NR, editor. Proceedings of the Xth International Symposium on Biological Control of Weeds; Bozeman, MT: USDA-ARS and Montana State University; 2000. pp. 931-940

[124] Adam O, Zdor R. Effect of cyanogenic rhizobacteria on the growth of velvetleaf (*Abutilon theophrasii*) and corn (*Zea mays*) in autoclaved soil and

the influence of supplemented glycine. Soil Biology and Biochemistry. 2001;**33**: 801-809

[125] Weissmann R, Gerhardson B. Selective plant growth suppression by shoot application of soil bacteria. Plant and Soil. 2001;**234**:159-170

[126] Weissmann R, Uggla C, Gerhardson B. Field performance of a weed-suppressing *Serratia plymuthica* strain applied with conventional spraying equipment. Biological Control. 2003;**48**:725-742

[127] Li J, Kremer RJ. Growth response of weed and crop seedlings to deleterious rhizobacteria. Biological Control. 2006; **39**:58-65

[128] Zermane N, Souissi T, Kroschel J, Sikora R. Biocontrol of broom rape (*Orobanche crenata* Forsk. and *Orobanche foetida* Poir.) by *Pseudomonas fluorescens* isolate Bf7-9 from the faba bean rhizosphere. Biocontrol Science and Technology. 2007;**17**:487-497

[129] Patil VS. Isolation, characterization and identification of rhizospheric bacteria with the potential for biological control of *Sida acuta*. Journal of Environmental Research and Development. 2014;**8**:411-417

[130] Boyette CD, Hoagland RE. Bioherbicidal potential of *Xanthomonas campestris* for controlling *Conyza canadensis*. Biocontrol Science and Technology. 2015;**25**:229-237

[131] Schisler DA, Howard KM, Bothast RJ. Enhancement of disease caused by *Colletotrichum truncatum* in *Sesbania exaltata* by co inoculating with epiphytic bacteria. Biological Control. 1991;**1**:261-268

[132] Auld BA, McRae CF, Say MM. Possible control of *Xanthium spinosum* by a fungus. Agriculture, Ecosystems and Environment. 1988, 1988;**21**:219-223

[133] Gan P, Ikeda K, Irieda H, Narusaka M, O'Connell RJ, Narusaka Y. Comparative genomic and transcriptomic analyses reveal the hemibiotrophic stages shift of *Colletotrichum* fungi. The New Phytologist. 2013;**197**:1236-1249

[134] Grossmann K. Auxin: Current status of mechanism and mode of action. Pest Management Science. 2010;**66**:113-120

[135] Stewart-Wade SM, Boland GJ. Oil emulsions increase efficacy of *Phoma herbarum* to control dandelion but are phytotoxic. Biocontrol Science and Technology. 2005;**15**:671-681

[136] Bailey KL, Falk S, Derby JA, Melzer M, Boland GJ. The effect of fertilizers on the efficacy of the bioherbicide, *Phoma macrostoma*, to control dandelions in turfgrass. Biological Control. 2013;**65**:147-151

[137] Smith J, Wherley B, Reynolds C, White R, Senseman S, Falk S. Weed control spectrum and turfgrass tolerance to bioherbicide *Phoma macrostoma*. International Journal of Pest Management. 2015;**61**:91-98

[138] Graupner PR, Carr A, Clancy E, Gilbert J, Bailey KL, Derby JA. The macrocidins: Novel cyclic tetramic acids with herbicidal activity produced by *Phoma macrostoma*. Journal of Natural Products. 2003;**66**:1558-1561

[139] Quereshi S, Khan NA, Pandey AK. Anthraquinone pigment with herbicidal potential from *Phoma herbarum* FGCC#54. Chemistry of Natural Compounds. 2011;**47**:521-523

[140] Abu-Dieyeh MH, Watson AK. Efficacy of *Sclerotinia minor* for dandelion control: Effect of dandelion accession, age and grass competition. Weed Research. 2007;**47**:63-72

[141] Skipp RA, Bourdot GW, Hurrell GA, Chen LY, Wilson DJ, Saville DJ. *Verticillium dahliae* and other pathogenic fungi in *Cirsium arvense* from New Zealand pastures: Occurrence, pathogenicity and biological control potential. New Zealand Journal of Agricultural Research. 2013;**56**:1-21

[142] Briere SC, Watson AK, Hallett SG. Oxalic acid production and mycelial biomass yield of *Sclerotinia minor* for the formulation enhancement of a granular turf bioherbicide. Biocontrol Science and Technology. 2000;**10**:281-289

[143] Bailey KL. The bioherbicide approach to weed control using plant pathogens. In: Abrol DP, editor. Integrated Pest Management: Current Concepts and Ecological Perspective. San Diego, CA: Elsevier; 2014. pp. 245-266

[144] Kenny DS. DeVine the way it was developed: An industrialist's view. Weed Science. 1986;**34**:15-16

[145] Prasad R. Development of bioherbicides for integrated weed management in forestry. In: Brown H et al., editors. Proceedings of the 2nd International Weed Control Congress; Slagelse, Denmark: Department of Weed Control and Pesticide Ecology; 1996. pp. 1197-1203

[146] Jones RW, Hancock GJ. Soilborne fungi for biological control of weeds. In: Hoagland RE, editor. Microbes and Microbial Products as Microbial Herbicides. Washington, DC: American Chemical Society; 1990. pp. 276-286

[147] Khattak SU, Iqbal Z, Lutfullah G, Bacha N, Khan AA, Saeed M, et al. Phytotoxic and herbicidal activities of *Aspergillus* and *Penicillium* species isolated from rhizosphere and soil. Pakistan Journal of Weed Science Research. 2014;**20**:293-303