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Use of natural products for weed management in high-value crops: An Overview

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ABSTRACT

Over the last five decades, weed management systems have relied primarily on synthetic herbicides. Due to the concerns over the potential impact of chemicals on human health and the environment, efforts are being made to reduce the heavy reliance on synthetic herbicides. To reduce synthetic herbicides, use of natural products such as essential oils, plant extracts, allelochemicals, agricultural by-products, and some microbes are gaining attention because they are safe due to their short environmental half-life and low toxicity. These natural product bioherbicides are a good alternative to synthetic herbicides especially in organic agriculture since they focus on environmental protection, practical viability, compatibility for integrated programs, and ecological stability. Most of the commercially available natural herbicides are non-selective and require careful application in order to preserve the crop of interest. Although many studies in this direction have been undertaken, the use of these natural products is still not common because of the difficulties in their synthesis due to their complex structure, cost effectiveness, poor results in field trials, and rapid degradation. No single above mentioned natural product has the potential to comprehensively replace chemical weed management; however, an integrated approach may provide better results. Thus, the role of bioherbicides in modern weed management is complementary rather than exclusive.

Keywords.

Allelopathy, bioherbicides, corn gluten meal, essential oils, mustard seed meal, pathogens, plant extracts

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Introduction

Weeds are arguably one of the most troublesome pests to control in crop production. Weeds compete with crop plants for nutrients, water and light and can have negative impact on crop yield and quality if remained uncontrolled. On an average, weeds can lower crop productivity by 34% (Oerke, 2006). Weed management is mostly achieved through cultural, mechanical, chemical and biological methods. From the last half century, the use of chemicals is one of the most dominant methods for weed control. Although the use of synthetic herbicides is apparently an easy and cost effective method for controlling weeds but their widespread use has resulted in soil and groundwater pollution, enhanced the toxic residue accumulation in agricultural products, increased herbicide resistance in weeds, and caused potential damage to human and animal health (Jabran et al., 2015). Several studies have shown that synthetic herbicides could cause health problems such as cancer, birth defects and nerve damage (Naik and Prasad, 2006). Moreover, synthetic herbicides residue persists in the soil and injure non-target plants and crops grown in rotation.

Concerns of ecological, environmental, and health problems associated with intensive use of chemicals have encouraged many producers to investigate new alternative non-chemical weed control methods and adopt organic agriculture (Duke et al., 2002; Walz, 1999). The replacement of synthetic herbicides with the natural compounds that have herbicidal potential would be a sustainable approach in protection of our environment. Unlike the chemical herbicides, the use of natural products such as essential oils, agricultural by-products, plant extracts, and living organisms (bacteria, fungi and insects) is supposed to be more environmental friendly. These natural products are rapidly degraded in the environment, neither stay long in the soil nor penetrate in the underground water; hence, they never cause environmental poisoning (Rassaeifar et al., 2013). In addition, the use of plant species that are able to produce and release phytotoxic allelochemicals could be an effective tool for weed control. Several plant species such as sunflower (*Helianthus annuus* L.), cereal rye (*Secale cereale* L.), and mustards (*Brassicaceae*) have allelopathic effects on other plant species (Dhima et al., 2006; Dhima et al., 2009; Putnam, 1979; Rice, 1974). There are different ways of using allelopathy in weed control. First is to use allelopathic cover crops in rotations, or apply residues of allelopathic plants as mulches (Caamal-Maldonado et al., 2001; Dhima et al., 2006). Another promising way to use allelopathy in weed control is using water extracts of allelopathic plants as herbicides (Dhima et al., 2009; Singh et al., 2005; White et al., 1989). Several researchers have described the application of allelopathic plant water extracts for weed suppression (Dhima et al., 2009; Jamil et al., 2009). The use of allelopathic plants/crops with significant weed inhibition qualities, together with common weed control tactics could play an important role in the establishment of sustainable agriculture. In high value crops, such as vegetables there are very few registered herbicides for weed control and secondly, people are more interested in organic products, therefore, today's agriculture requires a modified weed management system to deal with the problems associated with the use of synthetic herbicides. Keeping these problems in view, here we provide a short review of the existing natural products in the market and their use as an alternative method for weed control.

Weed control using agricultural by-products

Weed control using agricultural by-products provide an attractive and promising alternative solution to chemical herbicides. There are a number of natural products being used for weed management (Copping and Duke, 2007; Dayan et al., 2009; Dayan and Duke, 2010) such as corn gluten meal (CGM), Brassicaceae seed meals (BSMs), and soybean meal. CGM, the protein fraction of corn grain, is a by-product of the wet milling of corn kernels for use in corn syrup and corn starch (Liu and Christians, 1997). The remaining material has herbicidal properties that can suppress seedling root formation and plant survival of germinating plants but does not inhibit root growth of established plants (Liu et al., 1994). In the early 1990s, CGM was identified and patented as a natural pre-emergent herbicide for use in organic production systems (Bingaman and Christians, 1995). Bingaman and Christians (1995) showed that CGM when applied on the soil-surface at rates of 300-1000g m^{-2} caused reductions in plant survival, shoot length, and root development of common lambsquarters (*Chenopodium album* L.), curly dock (*Rumex crispus* L.), purslane (*Portulaca oleracea* L.), black nightshade (*Solanum nigrum* L.), creeping bentgrass (*Agrostis palustris* Huds.), and redroot pigweed (*Amaranthus retroflexus* L.). In a greenhouse and field study, Nonnecke and Christians (1992) reported that incorporated CGM significantly reduced weed density in strawberry plots and had no detrimental effect on the 'Honeoye' strawberry plants. Incorporating CGM in the soil before planting at a rate of 100-400 g m^{-2} reduced weed cover by 50- 84% as compared to unweeded control but showed toxicity on direct seeded vegetables [onion (*Allium cepa* L.), beet (*Beta vulgaris* L.), radish (*Raphanus raphanistrum* subsp. *sativus*), bean (*Phaseolus vulgaris* L.), carrot (*Daucus carota* subsp. *sativus*), pea (*Pisum sativum* L.), lettuce (*Lactuca sativa* L.), and sweet corn (*Zea mays* L. var. *rugosa*)] (McDade and Christians, 2000). Similarly, in a recent greenhouse study, Yu and Morishita (2014) found that application of CGM significantly decreased broadleaf and grass weeds, indicating CGM has a potential to be used as a weed suppressive soil amendment.

Dried distillers' grains with solubles (DDGS) is another natural by-product that is used for weed control. DDGS is a byproduct of ethanol production that is commonly used as cattle feed. DDGS typically contains 4.4% N, 0.16% P, 0.79% K, and 0.5% S (Boydston et al., 2008b). Due to its high nitrogen content it is used as a fertilizer supplement in horticultural crops. Other than fertilizer supplement it is also used for weed control in organic production systems. Boydston et al. (2008b) found that the application of DDGS on the soil surface at 800-1600 g m^{-2} significantly reduced annual bluegrass (*Poa annua* L.) number by 40-57% and common chickweed [*Stellaria media* (L.) Vill.] by 33 -58%, respectively in the container-grown ornaments, with no injury on ornamental plants.

BSMs are the by-products of edible and industrial-grade oil production after oil extraction from crops like mustard (*Brassica juncea* L. and *Sinapis alba* L.) and canola (*Brassica napus* L.). These seed meals possess herbicidal activity and are used as soil amendments to control weeds in vegetable cropping systems (Rice et al., 2007; Vaughn et al., 2006). *Brassicaceae* plants contain allelopathic compounds known as glucosinolates (GSL), which on hydrolysis by the enzyme myrosinase releases biologically active compounds such as isothiocyanates, thiocyanates, nitriles, epithionitriles, and oxazolidinethione, that are toxic to weeds (Matthiessen and Kirkegaard, 2006; Vaughn et al., 2006). In Brassica species, there are about twenty GSLs and their concentrations vary among species and plant tissues (Kirkegaard and Sarwar, 1998). For example, white mustard 'IdaGold' seed meal has 4-hydroxybenzyl glucosinolates (glucosinalbin), whereas Indian mustard 'Pacific Gold' seed meal 'contains 2-propenyl GSL (sinigrin) (Hansson et al., 2008). Furthermore, GSLs are found throughout *Brassicaceae* plant tissues but they are most concentrated in the seeds (Morra and Kirkegaard, 2002; Sang et al., 1984). Evidence from previous studies have confirmed that BSMs can be used as a potential bioherbicide (Boydston et al., 2018; Handiseni et al., 2011; Rothlisberger et al., 2012; Vaughn et al., 2006). Applying 3% Indian mustard seed meal in the soil reduced plant biomass of redroot pigweed by 74% as compared to unamended control (Rice et al., 2007). In another study, mustard seed meal application decreased the emergence of barnyardgrass (*Echinochloa* spp.), common lambsquarters, and kochia (*Bassia scoporia*) by 66%, 73% and 83%, respectively as compared to non-treated control (Yu and Morishita, 2014). Similarly, in strawberry production, application of BSMs lowered the emergence of Italian ryegrass (*Lolium multiflorum* L.), annual bluegrass, desert rock purslane (*Calandrinia ciliata*), and shepherd's purse (*Capsella bursa-pastoris*) and also increased strawberry fruit yield (Banuelos and Hanson, 2010). Mustard seed meal applied to the soil surface of container-grown ornamentals at 113, 225, and 450 g m^{-2} reduced the emergence of annual bluegrass, common chickweed, and creeping woodsorrel (*Oxalis corniculata* L.) upto 8-wk period (Boydston et al., 2008a). Also, in a carrot field study, the application of BSMs at 1 and 2 t ha^{-1} rates provided effective weed control and increased plant-available soil inorganic nitrogen as well as carrot yield (Snyder et al., 2009).

Similarly, Intanon et al. (2015) found that the single application of activated meadowfoam (*Limnanthes alba*) seed meal suppressed weeds in transplanted lettuce and also increased the nitrogen content, and lettuce yield. The application of soybean and mustard seed meal at a rate of 4.48 t ha^{-1} lowered the weed densities from 52 to 95% and 41 to 45% at 3 and 6 weeks after planting, respectively, in organically-grown broccoli and spinach (Shrestha et al., 2015). In a greenhouse study, mustard seed meal derived from "IdaGold" significantly reduced the emergence of redroot pigweed but negatively affected onion yield when applied from planting to the one-leaf stage of onions (Boydston et al., 2011). This suggests that mustard seed meal has a potential to be used as a weed-suppressive amendment in organic production systems, however, rates and timing of application of mustard seed meal should be considered to minimize the phytotoxicity on the crop.

Weed control using plant extracts

The extracts from different plant parts such as leaves, stems, roots, and seeds also have a potential to be used as natural herbicides. Some plants have the capacity to inhibit the germination and growth of other plants by exuding phytotoxic allelochemicals. These allelochemicals are released through volatilization, leaching or decomposition (Cheema and Khaliq, 2000; Putnam and Duke, 1974). Allelochemicals can inhibit the growth of weeds through inhibition of photosynthesis, decline in chlorophyll content, disruption of the cell membrane, and inhibition of enzymatic activity (Ghanizadeh et al., 2014). Numerous plants possess allelopathic potential and they have been used for weed control both in lab and field studies. It is estimated that there are about 400,000 compounds in plants with allelopathic activities, of which only 3% have been identified for herbicidal activity (Einhellig and Leather, 1988). The remaining compounds are unknown and might contain very promising growth inhibitors.

The aqueous extracts from the leaves of lettuce (*Lactuca sativa*), cocklebur (*Xanthium occidentale*) and Japanese thistle (*Cirsium japonicum*) inhibited the root growth of alfalfa [*Medicago sativa* L.] (Chon et al., 2003). Likewise, in another study, water extracts from the fresh leaves of Tree of Heaven (*Ailanthus altissima* L.) also showed inhibitory effect on seed germination and plant growth of alfalfa (Tsao et al., 2002). In greenhouse studies, Khanh et al. (2005) showed that Chinese taro (*Alocasia cucullata* L.), nerium (*Nerium oleander* L.), purple passionflower (*Passiflora incarnate* L.) and Japanese pagoda tree (*Sophora japonica* L.) powders at 1.5 t ha^{-1} significantly reduced paddy weeds growth and dry weight by 60–100% and 70–100%, respectively, whereas, in paddy fields weed dry weight was reduced by more than 80% and also rice yield was increased by 20% as compared to control. Therefore, this suggests that these plants might be useful as natural herbicides and might contain various growth inhibitors that could be used for the development of bioherbicides. The aqueous extracts (10 g L^{-1}) and powders (1, 2 and 4 t ha^{-1}) of castor (*Ricinus communis*), tobacco (*Nicotiana tabacum* L.), pricklyburr (*Datura inoxia* Mill.), and sorghum (*Sorghum vulgar* L.) significantly inhibited seed germination and growth of field bindweed [*Convolvulus arvensis*] (Nekonam et al., 2013). Similarly, in another greenhouse study, germination and growth of redroot pigweed was significantly inhibited by water extracts and powders of castor, tobacco, and pricklyburr (Nekonam et al., 2014), indicating these plant species could be used as post-emergence bioherbicides against field bindweed and redroot pigweed. Furthermore, extracts of sorghum aerial parts reduced density and dry weight of field bindweed and eucalyptus leaves extract inhibited germination of field bindweed (Cheema et al., 2001; Khan et al., 2008). Black walnut (*Juglans nigra*) has an allelopathic effect on other plants and its extract is commercially formulated as bioherbicide (NatureCur®, Redox Chemicals, LLC, Burley, ID, USA). This commercial product when applied as a soil-drench at a concentration of 42.9% completely inhibited the growth of horseweed and hairy fleabane [*Conyza bonariensis*] (Shrestha, 2009). Rice hull extracts could also be a good source of natural herbicide and have been shown to inhibit the seed germination and growth of barnyardgrass (Ahn and Chung, 2000).

Dhima et al. (2009) indicated that aqueous extracts of different plant parts of aromatic plants, such as anise (*Pimpinella anisum*), dill (*Anethum graveolens* L.), oregano (*Origanum vulgare* L.) and lacy phacelia (*Phacelia tanacetifolia* Benth.) could be used for the control of barnyard grass and some broadleaf weeds. Batish et al. (2007) observed that leaf powder of Mexican marigold (*Tagetes minuta* L.) applied to rice field soil at a rate of 1 to 2 t ha^{-1} significantly reduced the emergence and growth of barnyardgrass and purple nutsedge (*Cyperus rotundus* L.), and the results were similar to herbicide treatments, indicating that dried powder of Mexican marigold could be used as a natural herbicide for managing rice weeds. In an earlier study, oregano biomass mixed with soil (50 g of fresh biomass or 10 g of freeze-dried biomass per kg of soil) completely inhibited the germination and plant growth of ryegrass (*Lolium perenne*) and redroot pigweed in tomato crop due to presence of high content of carvacrol, a component of essential oils produced by several aromatic plants (Da Mastro et al., 2006). Therefore, oregano biomass could be a promising tool for weed control and it can be used as an alternative weed control method to avoid herbicide resistance problem.

Different plant species have different allelopathic activity and this variation is due to the different nature of allelochemicals released by these species. For example pricklyburr extract have atropine, scopolamine, essential oils, saponins, flavonoids, phenols, and cardiac glycosides (Ayuba et al., 2011). Cultivated tobacco extract have alkaloids, flavonoids, phytosterols, triterpinoids, tannins, and carbohydrates (Sunil et al., 2011). Sorghum extract releases benzoic acid, p-hydroxybenozoic acid, vanillic acid, m-coumaric acid and p-coumaric acid (Czarnota et al., 2001). The aqueous extracts of decomposing rice residue release coumaric acids, ferulic acid, and p-hydroxybenzoic acid (Ahn and Chung, 2000; Ma et al., 2006). These compounds could be an alternative weed management tool for crop production and can offer environmental benefits. This would consequently minimize the herbicide usage and resistance issues.

Weed control using plant essential oils

Among natural products, plant essential oils have shown great phytotoxicity against a wide range of weeds and are the natural alternative to non-selective synthetic herbicides. Essential oils are volatile compounds that are usually assumed to be the result of distillation or a steam-stripping process. They contain natural flavors and fragrances that provide characteristic odors (Mukhopadhyay, 2000), and also contain allelochemicals that inhibit seed germination and plant growth and therefore, can be used as a tool in weed control (Batish et al., 2012; Hazrati et al., 2017; Mutlu et al., 2010). Additionally, they break down quickly in the environment and therefore, they are acceptable for weed control by organic growers. Terpenoids, particularly monoterpenes and sesquiterpenes, are the main components of essential oil and are often responsible for their plant inhibitory activity (Weston and Duke, 2003). The inhibitory activity against seeds or plants varied with the species from which the essential oil is extracted (Dudai et al., 1999). Several researchers have reported the allelopathic effects caused by essential oils in the laboratory as well as in field conditions (Farooq et al., 2011).

Aromatic plants are rich in essential oil content, and these essential oils have allelopathic effects, therefore, they could be used for weed control in agriculture (Ramezani et al., 2008). Palmer amaranth (*Amaranthus palmeri* L.) germination was inhibited by essential oils of certain aromatic plants, including oregano, sweet marjoram (*Origanum majorana* L.), and lemon basil (*Ocimum citriodorum* L.) (Dudai et al., 1999). The essential oils from Lawson cypress (*Chamaecyparis lawsoniana*), rosemary (*Rosmarinus officinalis* L.), white cedar (*Thuja occidentalis*), and eucalypt strongly inhibited the germination of amaranth, purslane and knapweed (*Acroptilon repens*), which indicates they can be used as a natural pre-emergent herbicide for weed control (Ramezani et al., 2008). Singh et al. (2005) reported the herbicidal activity of volatile oils from *Eucalyptus citriodora* against congress grass (*Parthenium hysterophorus*). Similarly, in the lab studies, Batish et al. (2005) reported the herbicidal activity of volatile oils from *E. citriodora* against some agricultural weeds such as canary grass (*Phalaris minor*), common lambsquarter, barnyardgrass, chickweed (*Ageratum conyzoides*), congress grass, and *Amaranthus* spp. The activity of these volatile oils was similar to that of glyphosate. The essential oils extracted from the leaves and flowers of five different plant species [common wormwood (*Artemisia vulgaris*), spearmint (*Mentha spicata* L. subsp. *Spicata*), basil (*Ocimum basilicum*), sage (*Salvia officinalis*), thyme (*Thymbra spicata* L. subsp. *spicata*)] showed inhibitory effect on seed germination and seedling growth of eight weed species from different families [corn cockle (*Agrostemma githago* L.), redroot pigweed, hoary cress (*Cardaria draba* - (L.) *Desv.*), common lambquarters, barnyard grass, wild mignonette (*Reseda lutea* L.), curly dock (*Rumex crispus* L.), red clover (*Trifolium pretense* L.)] (Onen et al., 2002). Similarly, the essential oils from red thyme, summer savory (*Satureja hortensis*), cinnamon (*Cinnamomum verum*), and clove (*Syzygium aromaticum L.*) showed strong phytotoxic effect on common lambsquarters, common ragweed (*Ambrosia artemisiifolia*), johnsongrass, and dandelion (*Taraxacum officinale* L.) due to rapid cellular electrolyte leakage (Tworkoski, 2002). Dhima et al. (2009) found that anise, sweet fennel (*Foeniculum vulgare*), lacy phacelia (*Phacelia tanacetifolia*), and coriander (*Coriandrum sativum*) aqueous extracts inhibited 100% germination, root length, and seedling fresh weight of barnyardgrass. The essential oils extracted from cinnamon, lavender (*Lavandula*) and peppermint (*Mentha x piperita*) showed inhibitory effect on seed germination of pigweed, wild mustard (*Sinapis arvensis*), and ryegrass (Campiglia et al., 2007), indicating that essential oils can act as a natural herbicides.

Manuka oil, obtained from the manuka tree (*Leptospermum scoparium*) with the main active ingredient, leptospermone inhibited the growth of large crab grass [*Digitaria* spp.] and this can be used as a tool for weed management in both organic and conventional farming systems (Dayan et al., 2011). Citrus oil, with the main active ingredient, D-limonene has been commercialized as an organic weed management product. D-limonene removes the waxy cuticular layer from the leaves of the treated plants causing dehydration and death of the green tissue (Erasto and Viljoen, 2008). Vetiver oil is an essential oil distilled from the roots of vetiver grass (*Vetiveria zizanioides* Lynn Nas) inhibit the seed germination of redroot pigweed, velvetleaf (*Abutilon theophrasti*), giant ragweed (*Ambroisia trifida*), pitted morninglory (*Ipomea lacunosa*) and common lambsquarters (Mao et al., 2004).

The use of essential oils seems promising for weed control and could be used as natural herbicides for the management of weeds in organic agriculture, but the efficacy of these natural herbicides is only for a limited time because they are very sensitive to photolysis and volatilize very quickly. Therefore, it is possible that essential oils could be integrated with other weed management tools to get broad-spectrum weed control.

Weed control using pathogens

There are a significant number of microbial agents that have a potential to be used as a bioherbicide for the control of weeds in several high value crops, such as obligate fungal parasites, soil-borne fungal pathogens, non-phytopathogenic fungi, pathogenic and non-pathogenic bacteria, and nematodes (Charudattan, 2005; Harding and Raizada, 2015). Such bioherbicides offer many advantages such as high degree of specificity of target weed, absence of weed resistance development, no effect on non-target or beneficial plants, and the absence of build-up of residue in the soil. In the last few decades, several pathogenic fungi and bacteria have gained much attention for the control of weeds (Kremer, 2005).

The first registered bioherbicide in the USA was DeVine® (Encore Technologies, Plymouth, MN, USA), a liquid formulation comprised of chlamydospores of the soilborne fungus *Phytophthora palmivora* for the control of stranglervine (*Morrenia odorata*) in citrus (Charudattan, 2005). Collego®, a wetabble powder formulation of endemic anthrocnose fungus *Collectotrichum gleosporiodes* f. sp. a*eschynemone* (cga) was the first commercially available bioherbicide for the control of weeds in annual crops (Ahluwalia, 2007). After the successful development of Collego®, another *Collectotrichum*-based mycoherbicide Biomal® (*C. gleosporiodes* (Penz.) Sacc. f. sp. *malavae*) was developed to control round-leaved mallow (*Malva pusilla*) in USA and Canada (Charudattan, 1990). Thereafter, several other pathogens have been developed and registered for use as bioherbicides (Cai and Gu, 2016; Harding and Raizada, 2015). Most mycoherbicides consist of fungal pathogens such as the *Colletotrichum* species that could be mass cultured in artificial media to produce large quantities of inoculum and applied to the weed host in a similar manner to conventional herbicides (Caldwell et al., 2012). These fungal plant pathogens infect the aerial portions of host plant (weeds), resulting in visible disease symptoms and ultimately cause plant mortality. However, some fungal pathogens are obligate parasites that can only proliferate on host plants. Such pathogens are cultured in mass on the host plant (weeds) in greenhouses or in small areas from which uredospores are vacuum-harvested and later mycoherbicides are prepared. The harvested uredospores can be applied in the field through different irrigation systems (Kremer, 2005; Phatak et al., 1983).

Puccinia canalicuta, a rust fungus, commercialized under the name of Dr. Biosedge is a foliar pathogen used for the control of yellow nutsedge (*Cyperus esculantus* L.). It is endemic rust that completely parasitizes yellow nutsedge (Phatak et al., 1983). However, this fungus was effective only on certain biotypes of yellow nutsedge and completely ineffective on purple nutsedge. Later, Kadir and Charudattan (2000) and Shabana et al. (2010) reported significant reduction in shoot numbers, shoot dry weight, and tuber dry weight of greenhouse-grown purple nutsedge with foliar *Dactylaria higginsii* fungus, and no harmful effect was observed on most vegetable crops. Yandoc et al. (2005) tested two fungal pathogens, *Drechslera gigantea* and *Bipolaris sacchari* and concluded that these fungi, alone or in combination, can effectively suppress cogongrass (*Imperata cylindrica*). Another fungus, *Phoma chenopodicola* has been investigated as a potential control agent for common lambsquarter, creeping thistle (*Cirsium arvense*), green foxtail (*Setaria virdis*) and annual mercury (*Mercurialis annua*) (Cimmino et al., 2013). Bailey and Derby (2010) reported that the naturally occurring fungus *Phoma macrostoma* or extracts obtained therefrom, control several broadleaf weeds, including Canada thistle (*Cirsium arvense*), perennial sowthistle (*Sonchus arvensis*), dandelion (*Taraxacum officinale*), scentless chamomile (*Matricaria perforata*), false cleavers (*Galium spurium*), chickweed (*Stellaria media*), wild buckwheat (*Fallopia convolvulus*), and field bindweed, and its effect is equivalent to the synthetic herbicide pendimethalin. In a study by Weidemann et al. (1992), the fungal pathogen *Microsphaeropsis amaranthi*, *Phoma proboscis* and *Colletotrichum capsici* controlled certain pigweed species, field bindweed and morning glory (*Ipomoea* spp.), respectively. In another study, the spore suspensions of *M. amaranthi* and *P. amaranthicola* alone or in mixture significantly reduced the biomass of common waterhemp (*Amaranthus rudis*) and pigweed in pumpkin and soybean (Ortiz-Ribbing et al., 2011).

It has been known that approximately eight *Myrothecium* species, including *M. gramineum, M. roridum*, and *M. verrucarium*, have been reported worldwide. The fungus could effectively control several common weeds under field conditions (Anderson and Hallett, 2004; Boyette et al., 2007; Lee et al., 2008). In tomato crop, the conidial spray of *M. verrucaria* controlled 90-95% of purslane species and 85-95% of spurge species without harmful effect on transplanted tomato plants (Boyette et al., 2007). Furthermore, soilborne fungi have become important candidate for bioherbicides since these fungi's can be directly applied to the soil to control weeds by decaying seeds prior to emergence or by killing the seedlings shortly after emergence (Jones and Hancock, 1990). *Trichoderma virens* (*Gliocladium virens*), a soilborne fungus, significantly reduced the emergence and growth of redroot pigweed and broadleaf weeds in high value crops when inoculated in composted chicken manure (Héraux et al., 2005). Two fungi's, *Alternaria conjuncta/infectoria* and *Fusarium tricinctum* isolated from parasitic weed dodder (*Cuscuta* spp.) used alone or in combination have significantly controlled dodder in cranberry beds (Hopen et al., 1996).

A number of bacteria have also been studied to control several weeds (Harding and Raizada, 2015). Out of these *Pseudomonas fluorescens* and *Xanthomonas campestris* have gained most attention. In greenhouse and field tests, *Pseudomonas* spp. have shown herbicidal activity against several weeds, for instance*, P. syringae* pv. *tagetis* against annual bluegrass and Asteraceae weeds including common cocklebur (*Xanthium strumarium*), wild sunflower (*Helianthus spp*.), common ragweed (*Ambrosia artimisifolia*), and Canada thistle (*Cirsium arvense*) (Johnson et al., 1996), *P. fluorescens* LS102 and LS174 against leafy spurge (*Euphorbia esula*) (Brinkman et al., 1999), and *P. fluorescens* D7 against downy brome (*Bromus tectorum*) (Kremer, 2005). The phytotoxin produced from a crude extract of *P. syringae* (strain 3366) controlled germination of annual weeds in newly established `Stevens' cranberry bogs (Norman et al., 1994). Banowetz et al. (2008) have reported that *P. fluorescens* produce and secrete herbicidal compounds, termed germination-arrest factor that target the seeds of certain grassy weeds. This natural occurring herbicide irreversibly blocks the germination process immediately after the emergence of the plumule and coleorhiza.

The other bacterial species that have received attention for weed control is *Xanthomonas campestris*. A host-specific pathogen, *X. campestris* pv. *poae* (JT-P482) have been used for the control of annual bluegrass (Imaizumi et al., 1997). Recently, in greenhouse studies, Boyette and Hoagland (2015) have also reported the bioherbicidal activity of *X. campestris* (isolate LVA-987) against horseweed (*Conyza canadensis* L. Cronq.).

Besides many advantages of pathogens to be use as bioherbicides, certain factors have been reported to limit its use and adoption. These include biological constraints (narrow host range and resistance), environment constraints (specific environmental conditions for culturing and formulation to assure biotic agent efficacy), commercial limitations (intense evaluation, patent protection, stringent regulations, and high cost), and the potential human health threats (Kremer, 2005). Therefore, bioherbicides should not be viewed as a total replacement of current or future synthetic herbicides, but they could be integrated into production systems with other weed management technologies to get broad-spectrum weed control, avoid the buildup of herbicide-resistance and invasive weeds, and increase crop production.

Natural products as a tool for integrated weed management

Integrated weed management includes different weed control methods to provide the crop with an advantage over weeds (Swanton and Weise, 1991). Interest in non-chemical weed control has been increasing due to the demand for organically grown produce, environmental concerns over herbicide use, and spread of herbicide-resistant biotypes. Therefore, an alternative weed management tools are needed under current situations. Although none of the above described natural products have potential to comprehensively replace chemical weed management; but, an integrated approach may lead to success. These natural products can be integrated with other weed control methods to get broad-spectrum weed control, avoid herbicide resistance, reduce production costs, and increase crop yield. The use of natural products along with other weed management tools will be an important step towards sustainability in agriculture. Thus, more field research on non-synthetic herbicides is required that would support sustainable agricultural production.

Conclusions

From the above discussion, it is clear that many natural products have a great potential for controlling weeds. We expect that these natural products bioherbicides would first be used in organic production systems but due to increased demand for new herbicidal products for resistance management, they could also serve as a template for the synthesis of new herbicides based on their chemistry. These natural product bioherbicides could be used as a component in integrated weed management system to reduce the risk of herbicide resistance, increase crop production, and reduce production rates. To date, there are few bioherbicides that are commercially available, therefore, future research should focus on the development of new bioherbicides, so that they can become mainstream products in the future.

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