Medicinal and aromatic plants as an emerging source of bioherbicides

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Weeds cause higher reductions in crop yield than any other pest or disease; yet they remain underestimated in tropical agriculture. Controlling composite culture of weeds in the crop field is difficult. Continuous use of synthetic herbicides may have an adverse impact on human health and the agro-ecosystem. Natural products such as essential oils, plant extracts, allelochemicals, agricultural by-products and some microorganisms are being studied in this area since they are environmentally friendly and have low toxicity. Being ecologically stable, they may provide an alternative to synthetic herbicides. In this article, we document the research done across the world to establish medicinal and aromatic plants as source of bioherbicides for sustainable agricultural production.

Keywords: Allelochemicals, bioherbicides, medicinal and aromatic plants, sustainable agriculture, weeds.

WEED management is a major challenge for agro-ecosystems across the world. It is reported that weeds roughly account for 37% of the total annual loss of agricultural produce due to various pests in India[1]. For combating yield loss due to weed interference, synthetic herbicides are widely used. Although herbicides are one of the major components of weed management, their continuous success is threatened by the evolution of herbicide resistance in weed plants, being reported in 75 crops of 69 countries. Globally, overuse of synthetic herbicides has led to problems of herbicide resistance in weeds as well as the build-up of toxic residues in the environment. Over 95% of the applied herbicides reach non-target plants instead of the target plant. Subsequently, 0.1% or less of the applied herbicides reaches the target plant, while the remaining amount pollutes the ecosystem[2]. This adversely affects the soil microcosm consisting of soil microfauna in field communities and the soil environment. So, efforts must be made to find more eco-friendly and environmentally sustainable natural alternatives for synthetic herbicides, to break down the chain of herbicide resistance in various weeds.

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Current status of biopesticides

Biopesticides were initially introduced to the market in 1980, and subsequently other biopesticides have been introduced including bioinsecticides, biobactericides, biofungicides and bionematicides; but bioherbicides still account for less than 10% of all biopesticides[3]. Figure 1 depicts the share of biopesticides in Indian agriculture, which shows that still there is great scope as organic farming is gradually gaining popularity, and both farmers and consumers have a keen interest in produce free from harmful chemicals[4]. The approval and commercialization of bioherbicides as phytopharmaceutical products is inadequate. Many of the commercial products like Weed Zap™, Bioorganic™, Interceptor™, GreenMatch EX™, PORGANIC™, AllDown™ have been used as herbicides containing natural plant products[5,6]. Six commercial bioherbicides produced from essential oils and/or their components are approved and marketed in the United States (Table 1), primarily for use in organic agriculture[7,8]. In addition, the attraction of these 'greener' weed control technologies has also begun to affect conventional agricultural systems.

Lemongrass oil has been commercialized as an organic herbicide due to its main constituent citral (up to 80%) (Figure 2). The commercial product contains 50% lemongrass oil preparations. However, the oil has to be diluted to 7–15% prior to application due to its high toxicity. Peppermint (*Mentha piperita*) oil contains 2-phenethyl

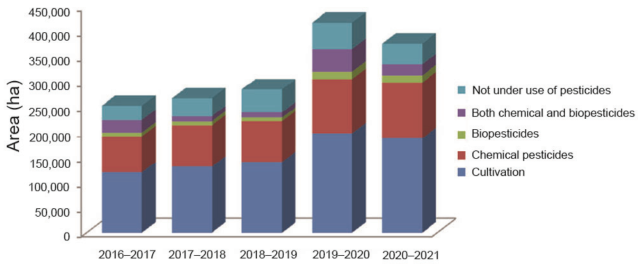

Figure 1. Current area under cultivation and use of chemical and biopesticides in India.

Table 1. Medicinal and aromatic products approved for use in the management of weeds in the production of certified organic foods in USA

Commercial products	Concentration of the major component	Dose
Greenmatch EX	Lemon grass oil 50%	47–70 l/ha
EcoExempt HC c	2-Phenethyl propionate/clove oil 24%/24%	There are no suggestions for volume per area on the label

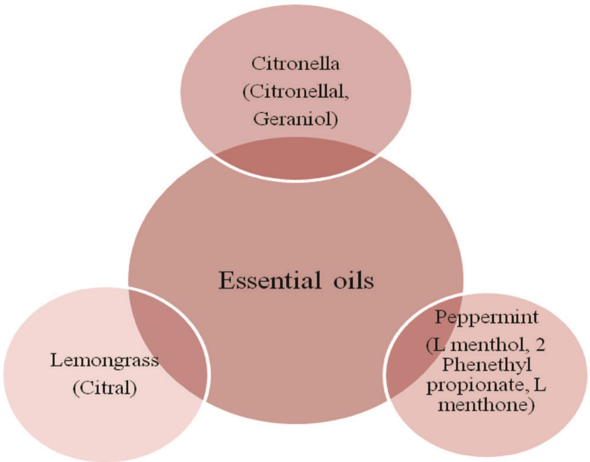

Figure 2. Common essential oils used to control weeds in organic food production, as well as their major components.

propionate as the main ingredient (Figure 2). It is now commercially patented as a bioherbicide and is included as chief constituent of several natural herbicides, commonly in composite with clove oil. It is safe to both human beings and the environment[7,8].

Scope of using medicinal and aromatic plant products as bioherbicides

Essential oils and their volatile compounds are in the spotlight due to their phytotoxicity and allelopathy combined with quick degradation in the environment. Allelopathy is the inhibitive/detrimental effect of one plant species on the germination, growth and metabolism of another plant species due to release of agrochemicals into the environment. Allelochemicals are mostly extracted from plant materials because their ability to synthesize aromatic secondary metabolites as phenolic acids, phenols, flavones, flavonoids, flavonols, saponins and coumarins, which accumulate in the cells of the epidermis of plant organs such as flowers, leaves, stems, roots, seeds and fruits in small quantities[9]. Various researchers have reported allelopathic effect of medicinal and aromatic plants (MAPs) on weed in previous studies. For example, allelopathy of vetiver on several types of weeds such as *Amaranthus retroflexus*, *Chenopodium album*, *Ambrosia trifida*, *Ipomoea lacunose* and *Mentha piperita* on *Amaranthus retroflexus*, *Portulaca oleracea*, *Sinapis arvensis*, *Convolvulus arvensis*, *Echinochloa colona*, *Avena fatua*, *Solanus nigrum*, *Chenopodium album* and *Echinochloa crus-galli* has been reported in previous studies[10,11]. Similarly, Kalmegh extract has been reported allelopathic and adversely affected the metabolism of *Parthenium hysterophorus* and *Tagetes minuta* on *Chenopodium muracle*, *Phalaris minor*, *Amaranthus viridis*, *Amaranthus tricolor*, *Echinochloa crus-galli*, *Cyperus rotundus*[12,13]. Rosemary essential oil inhibited germination percentage, root and seedling length in various weeds[14].

Allelopathic weed control using essential oils

Essential oils are the major constituents of a number of higher plants mainly containing terpenes. These oils are a mixture of different components in different amounts present in plants. Several reports have suggested that essential oils show allelopathic activity against many weeds. They are a complex mixture of natural volatile compounds and may contain approximately 20–60 different compounds at different concentrations. Essential oils have two or three major compounds, usually monoterpenes, and others in small quantities and molecular weight, usually aromatic or aliphatic[15]. The key components of essential oils are terpenoids, mainly monoterpenes and sesquiterpenes, which are responsible for their plant-inhibiting effect.

Artemisia species

Artemisia species contain aggravates that are phytotoxic to monocots, dicots, photosynthetic microscopic organisms, endomycorhizae, and regularly to the maker plants themselves. Particularly at low focus, a portion of these mixes causes hormesis, animating as opposed to curbing root advancement and plant development. Artemisinin is most likely the principal compound found in *Artemisia annua* to be assessed as a possible herbicide[16]. Allelopathic studies on artemisinin have been reported[17]. Test species included: carrot (*Daucus carota*), lettuce (*Lactuca sativa*), goliath foxtail (*Setaria faberi*), barnyardgrass (*Echinochloa crus-galli*) and enormous crabgrass (*Digitaria sanguinalis*) for seed germination; hedge bean (*Phaseolus vulgaris*) and mung bean (*Phaseolus aureus*) for root acceptance and duckweed (*Lemna minor* and *Lemna obscura*) for phytotoxic effect on hydrophilic plant[18]. Artemisia oil shows phytotoxicity against weeds (for obvious injury in showered plants) and hence could be useful as a bioherbicide. Among the showered test weeds, the phytotoxic impact of *Artemisia scorpia* oil was more on *Echiochloa crus-galli*, *Vicia villosa* and *Lathyrus annus*[19,20].

Tagetes minuta

Flowers and leaves of *T. minuta* contain flavonoids, polyphenols, polysaccharides, other phytochemicals and thiophenes present in the root. Major components of this plant are reported to be dihydrotagetone, E-ocimene, tagetone, cis-b-ocimene, zocimene, limonene and epoxyocimene[21]. It has been reported that extracts prepared from *T. minuta* had allelopathic impact on seed germination and root growth of *Lotus corniculatus* var. japonicas[22]. The oil showed herbicidal activity against the weeds *Chenopodium murale*, *Phalaris minor* and *Amaranthus viridis* and its seed germination response was dose-dependent[13]. *T. minuta* tissues might hinder with the germination of specialist species by delivering and discharging ocimenones. Mexican marigold was reported to be effective as a synthetic herbicide for controlling barnyardgrass and purple nutsedge in rice weeds[23].

Mentha species

Mentha spicata oil showed allelopathic effect on several weeds like *Amaranthus retroflexus*, *Centaurea salsotitialis*, *Raphanus raphanistrum*, *Rumex nepalensis*, *Sinapis arvensis*, *Sonchus oleraceus* and its extract on *Sorghum halepense*, *Cynodon dactylon* and *Rumex crispus*[11,24]. Phytotoxicity of *Mentha piperita* extract was reported on *Chenopodium album*, *Convolvulus arvensis* and *Echinochloa colona*, and its essential oil was found to inhibit seed germination (%), root/shoot length and dry weight of field bindweed (*Convolvulus arvensis* L.), purslane and jungle rice (*E. colonum* L.)[25,26].

Ocimum species

Allelopathic effect of *Ocimum basilicum* oil was reported on barnyardgrass and its extract showed activity against *Phalaris minor*, *Angalis arvensis* and *Amaranthus portulacea*[27–29]. *Ocimum tenuiflorum* adversely affected germination and seedling growth of cress (*Lepidium sativum*), lettuce (*Lactuca sativa*), alfalfa (*Medicago sativa*), Italian ryegrass (*Lolium multiflorum*), barnyard grass (*Echinochloa crus-galli*) and timothy (*Phleum pratense*) at concentrations greater than 30 mg dry wt equivalent extract ml^{-1}. At 10 mg dry wt equivalent extract ml^{-1}, the extracts severely reduced shoot and root development of all test species[30].

Other aromatic plants

The essential oils of Lawson cypress (*Chamaecyparis lawsoniana*), rosemary (*Rosmarinus officinalis* L.), white cedar (*Thuja occidentalis*) and eucalyptus affected the germination of amaranth, purslane and knapweed (*Acroptilon repens*), proving that they can be used as natural pre-emergent herbicides to control weeds. Vetiver oil inhibited seed germination of redroot pigweed, velvetleaf (*Abutilon theophrasti*), giant ragweed (*Ambroisia trifida*), pitted morninglory (*Ipomea lacunosa*) and common lambsquarters[10].

Allelopathic weed control using plant extracts

Plant extracts are being used as post-emergence natural herbicides in some countries. Medicinal plants contain various secondary metabolites in different parts having allelopathic nature. A study of 387 Japanese medicinal plants reported that many of them had growth-inhibitory properties[31]. The allelopathic potential of 83 Iranian medicinal herbs was assessed, and *Peganum harmala*, *Berberis vulgaris*, *Artemisia aucheri* and *Ferulago angulata* were shown to decrease lettuce root development by more than 80% (ref. 32). *Crocus sativus* stigma and style, *Artemisia kopetdaghensis* leaves, *M. piperita*, *Zhumeria majdae*, *Frulago subvelutina*, *Eugenia caryophyllata* blossoms bud, *Perovskia abrotanoides* flower, *Melia azedarach* fruits and *Ruta graveolen* fruits were found to have the strongest inhibitory effects on lettuce seedling growth[33]. It was also reported that hydroalcohalic extract of ashwagandha reduced seed germination and radical growth of *Cicer arietinum* and *Triticum aestivum*[34]. Water extract of *Cannabis sativa* showed phytotoxicity against *Parthenium hysterophorus* and oil showed activity against *Chenopodium album*[35,36]. Table 2 summarizes some of the important finding[37–63].

Mechanisms underlying allelopathy

Allelochemicals affect plant physiological and biochemical processes in many ways. Some plants can exude phytotoxic allelochemicals through volatilization, leaching or decomposition and thus inhibit plant activity. Allelochemicals can restrict weed potential through supression of germination and hindrance in physiological activities. Monoterpenes form the primary components of essential oils. Vapours released from monoterpenes have been shown to cause morphological and physiological alterations in plant seedlings, as well as accretion of lipoid globules in the cytoplasm and a decline in organelles such as mitochondria and nuclei. Understanding the mechanism and course of action of allelochemicals calls for an exploration of their heribicidal activities[64]. Natural products acknowledged as having allelopathic potential have been classified into the following groups: (1) cytotoxic gases, (2) organic acids, (3) aromatic acids, (4) simple unsaturated lactones, (5) coumarins, (6) quinones, (7) flavonoids, (8) tannins, (9) alkaloids, (10) terpenoids and (11) steroids. Allelochemicals cause a number of physiological and biochemical changes in plants (Figure 3).

Table 2. Summary of medicinal and aromatic plants showing allelopathic activity against weeds

Family	Plant species	Extract/oil	Test weed	Reference
Acanthaceae	*Andrographis paniculata*	Powder	*Parthenium hysterophorus*	12
Amaranthaceae	*Traganum nudatum*	Extract	*Avena fatua*	37
Anacardiaceae	*Retamaretum/Rhus tripartitum*	Extract	*Avena fatua*	37
	Rhus coriaria	Extract	*Chenopodium muracle* *Amaranthus retroflexus*	38
Apiaceae	*Carum carvi*	Oil	*Amaranthus retroflexus* *Centaurea salsotitialis* *Raphanus raphanistrum* *Rumex nepalensis* *Sinapis arvensis* *Sonchus oleraceus*	24
Apiaceae	*Pituranthos chloranthus*	Extract	*Avena fatua*	37
	Coriandrum sativum	Oil	*Vicia villosa* *Lathyrus annus*	20
		Extract	*Chenopodium album*	25
	Foeniculum vulgare	Oil	*Vicia villosa* *Lathyrus annus*	20
	Cuminum cyminum	Oil	*Vicia villosa* *Lathyrus annus*	20
	Foeniculum vulgare	Oil	*Echinochloa crus-galli*	27
Asteraceae	*Artemisia scorpia*	Oil	*Echinochloa crus-galli*	19
		Oil	*Vicia villosa* *Lathyrus annus*	20
	Artemisia herba-alba	Extract	*Avena fatua*	37
		Oil	*Mantisalea salmentica* *Sinapis arvensis* *Hordeum murimum*	39
	Artemisia annua	Extract	*Chenopodium album* *Amaranthus retroflexus*	40
	Artemisia dubia	Extract	*Ageratum conyzoides* *Galinsoga parviflora* *Cyperus rotundus*	41
	Matricarria chamomilla	Extract/compound	*Avena fatua* *Lolium multiflorum*	42
	Tagetes minuta	Oil	*Chenopodium miracle* *Phalaris minor*	13
		Dried powder	*Echinochloa crus-galli* *Cyperus rotundus*	23
		Oil	*Amaranthus tricolor* *Chenopodium muracle* *Bidens pilosa* *Amaranthus viridis*	43
	Tagetes erecta	Oil	*Echinochloa crus-galli*	44
	Sunflower	Extract	*Coronopus didhymus* *Chenopodium album* *Avena fatua* *Phalaris minor*	45
Boraginaceae	*Heliotropium indicum*	Methyl caffeate (compound)	*Vulpia myuros*	46
		Extract	*Lepidium sativum* *Phleum pratense* *Vulpia myuros*	46
Cannabaceae	*Cannabis sativa*	Extract	*Parthenium hysterophorus*	35
		Oil	*Chenopodium album*	36
Capparaceae	*Capparis spinosa*	Extract	*Chenopodium muracle* *Amaranthus retroflexus*	38
Cucurbitaceae	*Citrullus colocynthis*	Extract	*Chenopodium muracle* *Amaranthus retroflexus*	38
	Lavandula officinalis	Extract	*Chenopodium muracle* *Amaranthus retroflexus*	38
Euphorbiaceae	*Ricinus communis*	Extract	*Chenopodium muracle* *Amaranthus retroflexus*	38

(*Contd*)

Table 2. (*Contd*)

Family	Plant species	Extract/oil	Test weed	Reference
Fabaceae	*Tephrosia purpurea*	Extract	*Acalypha indica*	47
			Amaranthus spinosus	
	Rhynchosia minima	Oil	*Dactyloctenium aegyptium*	48
			Rumex dentatus	
	Alhagi maurorum	Extract	*Chenopodium miracle*	38
			Amaranthus retroflexus	
Geraniaceae	*Geranium koreanum*	Oil	*Amaranthus viridis*	49
			Portulaca oleracea	
Hypericaceae	*Hyperium perforatum*	Extract	*Amaranthus retroflexus*	50
Lamiaceae	*Origanum onites*	Oil	*Amaranthus retroflexus*	24
			Centaurea salsotitialis	
			Raphanus raphanistrum	
			Rumex nepalensis	
			Sinapis arvensis	
			Sonchus oleraceus	
	Thymbra spicata	Oil	*Amaranthus retroflexus*	24
			Centaurea salsotitialis	
			Raphanus raphanistrum	
			Rumex nepalensis	
			Sinapis arvensis	
			Sonchus oleraceus	
	Mentha arvensis	Oil	*Angallis arvensis*	51
			Cynodon dactyalon	
			Cyperus rotundus	
	Mentha spicata	Oil	*Amaranthus retroflexus*	24
			Centaurea salsotitialis	
			Raphanus raphanistrum	
			Rumex nepalensis	
			Sinapis arvensis	
			Sonchus oleraceus	
		Extract	*Sorghum halepense*	11
			Cynodon dactylon	
			Rumex crispus	
	Mentha longifolia	Oil	*Vicia villosa*	20
			Lathyrus annus	
	Mentha pipperita	Extract	*Chenopodium album*	25
		Extract	*Sorghum halepense*	11
		Extract	*Convolvulus arvensis*	26
			Echinochloa colona	
		Oil	*Echinochloa colona*	26
		Oil	*Amaranthus retroflexus*	52
			Portulaca oleracea	
			Vicia sativa	
		Microencapsulated oil	*Chenopodium album*	53
			Echinochloa crus-galli	
	Salvia officinalis	Extract	*Amaranthus retroflexus*	50
		Extract	*Chenopodium album*	25
	Rosmarinus officianalis	Extract	*Chenopodium muracle*	38
			Amaranthus retroflexus	
		Extract	*Chenopodium album*	25
	Teucrium polium	Extract	*Chenopodium muracle*	38
			Amaranthus retroflexus	
	Thymus vulgaris	Extract	*Chenopodium album*	25
	Thymus capitatus	Extract	*Medicago polymorpha*	54
	Origanum syriacum	Extract	*Chenopodium muracle*	38
			Amaranthus retroflexus	
	Ocimum basilicum	Oil	*Echinochloa crus-galli*	27
		Extract	*Phalaris minor*	28
			Angalis arvensis	
		Extract	*Amaranthus portulacea*	29
	Ocimum sanctum	Extract	*Amaranthus spinosus*	47
		Extract	*Cassia uniflora*	55

(*Contd*)

Table 2. (*Contd*)

Family	Plant species	Extract/oil	Test weed	Reference
	Plectranthus amboinicus	Extract	*Phlalaris minor* *Angalis arvensis*	28
Lauraceae	*Cinamomum camphora*	Oil	*Parthenium hysterophorus*	56
	Cinnamomum zeylanicum	Oil	*Amaranthus retroflexus*	52
Liliaceae	*Aloe vera*	Extract	*Amaranthus retroflexus* *Taraxicum officinalis*	57
Meliaceae	*Swietenia mahagoni*	Extract	*Echinochloa crus-galli* *Lepidium sativum*	58
Myrtaceae	*Eucalyptus*	Oil	*Parthenium hysterophorus*	56
		Oil	*Amaranthus retroflexus* *Portulaca oleraceae*	50
		Citronellol (compound)	*Ageratum conyzoides* *Parthenium hysterophorus* *Chenopodium album* *Phalaris minor*	59
		Cineole (compound)	*Ageratum conzyzoides*	60
	Eucalyptus lehmanii	Oil	*Sonchus arvensis* *Diplotaxis harra*	61
	Eucalyptus tereticornis	Oil	*Echinochloa crus-galli*	62
	Eucalyptus citriodora	Citronellol (compound)	*Amaranthus viridis*	63
Poaceae	*Cymbopogon citratus*	Oil	*Parthenium hysterophorus*	56
	Chrysopogon zizanioides	Oil	*Amaranthus retroflexus*	10
	Achillea santolina	Extract	*Medicago polymorpha*	54
	Artemisia monosperma	Extract	*Medicago polymorpha*	54

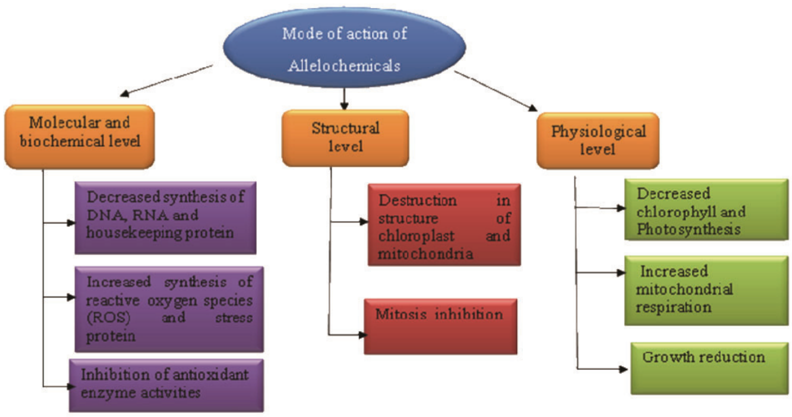

Figure 3. Mode of action of allelochemicals in weeds.

Since the last few decades, essential oils have been reported for their allelopathic potential. Citral is the key component of the essential oil extracted from lemongrass (*Cymbopogon citrates*) and other aromatic crops. Citral compound showed strongest allelopathic potential and interfered with the major constituent of the cytoskeleton, i.e. microtubules in wheat and *Arabidopsis thaliana*[65]. It also affected the seedlings of *A. thaliana* through interfering with the cell ultra structure, resulting in a lack of communication between cells[66].

Previous studies reported that higher concentration of aqueous leaf extract of *Datura stramonium* L. treatment in soybean hindered the primary and lateral root development and also interfered with the chromosome number and structure[67]. Ethyl acetate fraction of *Aglaia odorata* leaves inhibited cell division in *Allium cepa* roots by destroying the organization of chromatin and microtubules[68]. Allelochemicals affected the growth and development of plants by influencing the production of phytohormones in seed germination and seedling growth.

Allelochemicals affected photosynthesis by influencing the function of PS II (refs 69, 70). It inhibited the synthesis of ATP by reducing enzyme activity and also affected stomatal conductance and transpiration rate[71]. Lemongrass leaves oil at higher concentration hindered the photosynthetic metabolism[72].

Plants on coming in contact with allelochemicals quickly produce reactive oxygen species and change the activity of antioxidant enzymes such as superoxide dismutase, peroxidase and ascorbic acid peroxidase and increase the free radical levels, which creates an imbalance in the antioxidant system[73–75]. It has been reported that essential oil of lemongrass affect the membrane system of barnyardgrass, damages the cell and increases cell membrane permeability.

Different stages of respiration such as electron transfer in the mitochondria, oxidative phosphorylation, CO_2 generation and ATP enzyme activity are adversely affected by allelochemicals. It has been reported that limonene inhibits coupled respiration and ATP synthetase, and the activities of adenine nucleotide translocase complexes at concentrations of 1.0 and 5.0 mM (ref. 76).

Opportunities, limitations and challenges of using MAPS as bioherbicides

Opportunities

Bioherbicides derived from natural sources have showed significant promise in organic farming. As there is a growing demand for greener technologies for producing organic farm products, these are gaining widespread attention. These allelochemicals are easy to apply without the need of surfactants. They also do not stay in the environment for a long time, are less prone to pollute soil and water, and have no negative impacts on non-target organisms. Thus they are usually negligibly harmful to human health. This is because the biochemical structure of allelochemicals is more eco-friendly than those of synthetic herbicides. Their biodegradability is fast because of the diverse course of action, which reduces the risk of herbicide refusal.

Limitations of using plant products as bioherbicides

There are few restrictions that make bioherbicide application less suitable than the currently used herbicides, especially at field-scale. Plants from the same location or taxonomic group often do not produce the same amount or quality of secondary metabolites. Thus, they do not exude the same amount or quality of allelochemicals, making commercial availability of bioherbicides more difficult. Because they are short-lived in the environment, they are less effective than synthetic herbicides that last long enough to have the intended effect on weed species. Bioherbicides efficacy is limited as they dissipate quickly and are photosensitive. Furthermore, because of their structural intricacy, many allelochemicals are prohibitively expensive; for example, the cyclic tetrapeptide toxin is a good herbicide, but it is expensive. Application of many essential oils having potential as bioherbicide faces challenges of a suitable surfactant which is essential for effectiveness and good dispersion. Besides, aqueous plant extracts as bioherbicides are not widely studied and the extraction methodology is also diverse, despite their good potential in pre- and post-emergency bioassays. Formulations need to be improved and the technology of application needs to be widely researched, specially in field conditions.

Challenges ahead

Development of bioherbicides still faces various challenges. Very few studies have been conducted on field scale, as most of the allelopathic studies are based on laboratory experiments conducted in controlled environment condition. Very less information is available on molecular mechanism of bioherbicides on plant growth inhibition of target weeds, mode of action of specific compounds and synergies, identifying the mechanisms at the origin of phytotoxicity to reinforce it and understand selectivity and identifying the most sensitive weed growth stages to increase efficiency. Field use of biopesticide products can be enhanced using nanotechnology and microencapsulation to improve their stability, residual effects and effectiveness. Alternative formulations such as microencapsulation and the addition of natural photoprotectants should be developed to reduce the amount applied and to increase the duration of their effectiveness by reducing their volatilization and photolysis, and simplifying handling of the material.

Conclusion

In summary, the usage of MAPs may be a viable alternative for weed management and as a major component of integrated weed management. The bioactive compounds found in many MAPs make them useful, and therefore may have potential as bioherbicides. Further research is needed on the mechanism of action, understanding selectivity, analysing the side effects on beneficial plants and exploring novel formulations for successful application. Research should also focus on exploiting these potential crops for the development of ecologically stable bioherbicides showing efficient performance under field conditions, and controlling a wide range of target weeds. There is also a need to promote bioherbicides for research, production and sensitizing farmers about their ecological benefits.

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