BioThink E – Magazine, Vol. -2, Issue -3, July 2025
ISSN No. – 3048- 7943
www.biothink.in

Essential Oils as Green Herbicides: A Sustainable Approach to Weed Control

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Introduction

Weeds are typically considered undesirable plants that thrive in areas where they are not wanted. They exhibit traits that allow them to quickly colonize a wide range of ecosystems (Qasem and Foy, 2001). They are known as botanical pests because they compete with commercial crops for light, water, and nutrients, leading to huge yield losses (Ramesh et al., 2017). Further, weeds reduce crop yield by hosting pests and diseases, and increase production costs by requiring additional control efforts. Several weeds exhibit allelopathy, releasing chemicals that hinder crop seedling growth and cause physiological and biochemical harm (Joshi and Joshi, 2016). Many weeds, particularly exotic species, are highly invasive and capable of spreading rapidly in new areas. In India, notable invasive weeds include *Ageratum conyzoides*, *Ageratina adenophora*, *Lantana camara*, *Parthenium hysterophorus*, *Mikania micrantha*, *Prosopis juliflora* and *Chromolaena odorata*, (Singh, 2005; Kohli et al., 2006).

Allelochemicals: a promising approach for sustainable weed management

Hans Molisch coined the term allelopathy in 1937 to describe the chemical influence that plants can have on one another, either positive or negative. Allelochemicals are diverse secondary metabolites that are produced by plants and are mainly classified as phenolics and terpenoids. These allelochemicals are stored in various plant parts like roots, stems, leaves, flowers and fruits and have the potential to be used in the development of environmentally friendly herbicides and long-term weed control techniques. They are released into the environment through leaching, volatilization, residue decomposition and root exudation. They are synthesized via pathways such as shikimic acid and mevalonic acid (Rice, 1984) and have ecological roles like defence against pest and diseases, controlling biotic and abiotic interactions, and affecting seed germination and overall plant growth (Kohli et al., 2006). Duke et al. (2000) recommended that selection of allelochemicals for weed control should be based on the anatomical, chemo-ecological, and ethnobotanical characteristics of potential source plants. Several weed management strategies are implemented, each with its own benefits and limitations. These include preventive methods like cleaning equipment and using certified weed-free seeds. Cultural control method involves controlling field conditions to suppress weeds including crop rotation, intercropping, clean cultivation, green manuring, cover cropping, and soil solarization. Mechanical methods like hand-pulling, hoeing, mowing, or plowing utilizes manual, animal, or fuel-powered tools to remove or destroy weeds from the field. In biological control specific living organisms such as insects, fungi, or competitive plant are used to suppress weeds without harming other crops. Chemical control uses synthetic herbicides which are effective and convenient but dangerous for the environment and human health. Overuse of synthetic herbicides has also led to herbicide-resistant weed biotypes i.e. 479 across 252 species worldwide (Heap, 2017). This emphasizes on the need of affordable and safer substitutes. Natural plant products have a promising and sustainable solution particularly allelopathic compounds that are known for their phytotoxicity.

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Plant extracts as bio-herbicides: a natural weed control solution

Allelopathic plants produce secondary metabolites that can inhibit weed growth. Most common examples of such plants are eucalyptus, cinnamon and sorghum that contains allelochemicals and extracts of such plants can be used as bio-herbicides. These bio-herbicides help lower herbicide resistance, are biodegradable and safe for the environment. By integrating allelopathic extracts into weed management, farmers can control weeds sustainably while protecting soil health and beneficial organisms.

A number of factors, including concentration, the type of weed, and environmental conditions, may impact the effectiveness of allelochemicals. To maximize the use of these natural compounds for effective weed control, more research is frequently required.

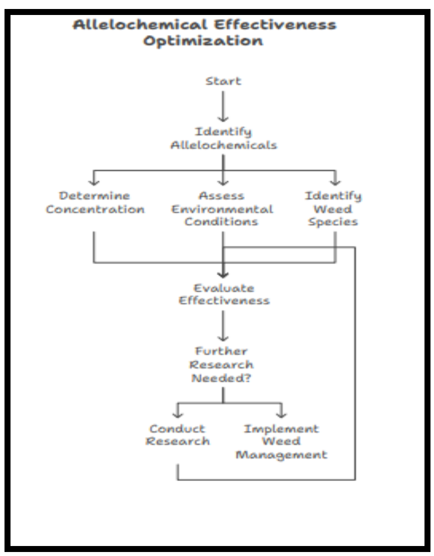

Figure 1. **Optimization Process for Enhancing Allelochemical Activity**

Mode of action of essential oil-based herbicides

The herbicidal action of essential oils is multifaceted including disruption of membrane, interference with energy production, oxidative damage and inhibition of plant growth hormones and photosynthesis. These broad-spectrum mechanisms reduce the chances of resistance development and highlights the use of essential oils as promising candidates for eco-friendly weed management strategies. Their diverse chemical composition and multiple target sites offer a promising alternative for weed control, especially against herbicide-resistant species (Azirak and Karaman, 2008; Dayan and Duke, 2014).

Essential oils of clove, eucalyptus and lemongrass plants have shown strong herbicidal activity due to compounds like eugenol and cineole which are responsible for plant cell membranes disruption and growth inhibition. These oils are useful for spot treatments and non-crop areas because they work well against a variety of weeds like grasses, broadleaf species and mosses. Their efficacy varies with concentration and environmental conditions and they are usually applied as diluted foliar sprays or soil drenches. Although they provide a natural substitute for synthetic herbicides, they are typically non-selective and can cause skin irritation or damage to non-target plants, so they must be used carefully and sparingly.

These phytotoxic substances disrupt plant growth by interfering with key metabolic pathways. Physiologically, they can damage photosynthetic pigments, hinder nutrient and water uptake, and disturb hormonal balance. For essential oils to be developed and marketed as efficient bioherbicides, a deeper comprehension of these mechanisms and how formulations affect their activity is necessary.

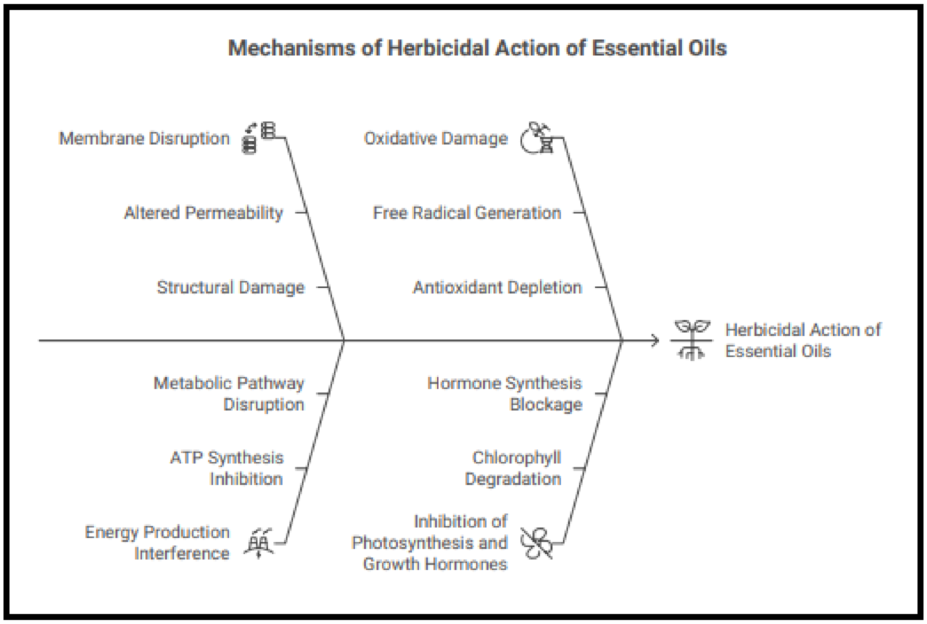

Figure 2: Mechanism of action of essential oils

Table 1: Herbicidal potential of some essential oils (arranged alphabetically)

Essential Oil	**Source**	**Major Compound**	**Target species**	**Reference**
Alpinia zerumbet (Per)	rhizome and leaf	camphor,1,8-cineole, β-linalool	*Parthenium hysterophorus*	Kumari et al., 2025
Betula nigra L.	Leaves	(2E)-hexenal, linalool and eugenol	*Lolium perenne* L. and *Lactuca sativa* L	Woods et al., 2013
Cupressus sempervirens L.	Needles	α-pinene, (Z) caryophyllene and α humulene	*Phalaris paradoxa* L., *Raphanus*	Amri et al., 2013

			raphanistrum L. and *Sinapis arvensis*	
Carum carvi L.	Seeds	Carvone and limonene	*Phalaris canariensis* L., *Linum usitatissimum* L., Zea mays L.	Marichali et al., 2014
Citrus aurantiifolia (Christm.) Swingle	Leaves	Limonene and citral	*Avena fatua* L., *Echinochloa crus-galli* (L.)	Fagodia et al., 2017
Callistemon viminalis (Gaertn.) G. Don	Leaves	1,8-cineole and α pinene	*Bidens pilosa* L., *Cassia occidentalis* L.,	Bali et al., 2017
Eucalyptus citriodora Hook	green and old fallen leaves	Citronellal and citronellol	*Amaranthus viridis* L.	Batish et al., 2006
Eupatorium adenophorum Spreng.	Inflores cence and roots	E,E-cosmene, γ muurolene, isothymol, α himachalene, limonene, Bornyl acetate	*Phalaris minor* Retz.	Ahluwalia et al., 2014
Foeniculum vulgare Mill	Aerial parts of plant	linalool and linalyl acetate; carvacrol	Lolium rigidum L., *Phalaris brachystachys* L.	Gitsopoulos et al., 2013

Hesperozygis ringens (Benth.) Epling	Leaves	Pulegone	*Bidens pilosa* L., *Lolium multiflorum* Lam.	Pinheiro et al., 2018
Mentha piperita L.	*Aerial parts*	*Menthol, mentone, menthofuran and 1,8- cineole*	*Convolvulus arvensis L., Echinochloa colonum L. and Portulaca oleracea L.*	Mahdavikia and Saharkhiz, 2015
Nepeta pannonica L.	Aerial parts	1,8-cineole and 4aa,7β,7aα nepetalactone	*Agrostis canina* L.	Scrivanti et al., 2003 Kobaisy et al., 2005
Origanum acutidens (Hand.-Mazz.) Ietsw.	Aerial parts	Carvacrol, thymol and p-cymene	*Amaranthus retroflexus* L., *Chenopodium album* L. and *Rumex crispus* L.	Kordali et al., 2008
Pinus nigra L.	Needles	Germacrene D, δ cadinene and (E) caryophyllene	*Phalaris canariensis* L., *Trifolium campestre* Schreb. and *Sinapis arvensis* L.	Amri et al., 2017
Rosmarinus officinalis L.	Aerial parts	α pinene, camphor, camp	Lactuca serriola L. and	Alipour and Saharkhiz, 2016

		hene and 1,8-cineole	*Rhaphanus sativus* L.	
Skimmia laureola Franch.	Leaves	Linalyl acetate, linalool, geranyl acetate and cis-p menth-2-en-1-ol	*Lemna minor* L.	Ibrar et al., 2015
Tagetes minuta L.	Aerial parts	cis-β-Ocimene, dihydrotagetone, limonene and tagetone	*Cassia occidentalis L.*	Arora et al., *2016*
Tunisian Cupressus sempervirens L.	Leaves, branches and female cones	α-pinene, α-cedrol, δ-3-carene and germacrene D	*Lolium rigidum Gaud* and *Phalaris canariensis L.*	Ismail et al., 2013
Zataria multiflora Boiss.	Aerial parts	Carvacrol and linalool	*Hordeum spontaneum Koch, Secale cereale* L., *Amaranthus retroflexus* L. *and Cynodon dactylon* L.	Saharkhiz et al., 2010

The key to effective weed control lies in understanding the difference between selective and non-selective herbicides and choosing the appropriate method. The purpose of selective herbicides is to target specific types of plants while leaving desirable vegetation unharmed. They typically work by interfering with specific metabolic pathways or enzymes that are present in the targeted weeds. On the other hand, non-selective herbicides kill or damage any plant they come in contact with. These herbicides are used when total vegetation control is desired.

Advantages of bioherbicides over synthetic herbicides

Compared to synthetic counterparts bioherbicides offer several compelling advantages. These advantages place bioherbicides as a more sustainable and environmentally conscious methods to weed management.

Biodegradability

The biodegradability of bioherbicides is one of their greatest benefits. Bioherbicides are obtained from natural sources and easily decompose into innocuous compounds.

Reduced Environmental Persistence

Synthetic herbicides often contain complex chemical structures that are resistant to natural degradation processes. Bioherbicides are typically composed of organic compounds that are easily metabolized by microorganisms in the environment and reduces the potential for long-term contamination.

Breakdown Products

The breakdown products of synthetic herbicides are harmful and pose similar risks. Bioherbicides break down into simpler, non-toxic substances that can be utilized by plants and microorganisms.

Soil Health

The persistence of synthetic herbicides can negatively impact soil health. Bioherbicides due to their biodegradability, have a minimal impact on soil health.

Reduced Toxicity

Synthetic herbicides exhibit broad-spectrum toxicity and cause harm non-target organisms, including beneficial insects, wildlife, and even humans. Bioherbicides tend to be more target-specific, affecting only the intended weed species.

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Human Health

Exposure to synthetic herbicides has been linked to various health problems, including cancer, reproductive disorders, and neurological damage. Bioherbicides, being derived from natural sources, are generally considered to be less toxic to humans.

Resistance Management

The overuse of synthetic herbicides has led to the development of herbicide-resistant weeds, Bioherbicides, with their diverse modes of action, can help to manage herbicide resistance by providing alternative weed control strategies (Raza et al., 20025).

Challenges in the bioherbicide adoption

Bioherbicides hold great potential as a sustainable alternate to synthetic herbicides. However, there are several challenges and limitations that need to be addressed. This requires a concerted effort from researchers, industry, regulatory agencies and growers to develop and implement innovative solutions that enhance the efficacy, consistency, cost-effectiveness and market acceptance of bioherbicides (Ravi Kamal 2025).

Conclusion

Environmentally conscious agricultural systems can be obtained by incorporating bioherbicides into weed control plans in addition to other sustainable techniques like crop rotation, cover crops, and mechanical weeding. The rising concerns over environmental degradation with synthetic herbicides have encouraged interest in natural alternatives like essential oil-based bioherbicides. Derived from allelopathic plants, essential oils offer eco-friendly approach to weed management through mechanisms such as membrane disruption, inhibition of germination, interference with metabolic pathways and many more. Essential oils like clove, eucalyptus, and lemongrass have confirmed significant herbicidal activity against weed species. Moving forward, interdisciplinary study, better formulations, awareness campaigns, and supportive policies are essential to reveal the full potential of essential oils

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