Scientific Research Publishing

Advances in Nanoparticles, 2025, 14(4), 101-120
https://www.scirp.org/journal/anp
ISSN Online: 2169-0529
ISSN Print: 2169-0510

Eco-Friendly Weed Management: Nanoformulated Bioherbicides for Improved Crop Productivity

Amra Bratovcic

Department of Physical Chemistry and Electrochemistry, Faculty of Technology, University of Tuzla, Tuzla, Bosnia and Herzegovina
Email: amra.bratovcic@untz.ba

How to cite this paper: Bratovcic, A. (2025) Eco-Friendly Weed Management: Nanoformulated Bioherbicides for Improved Crop Productivity. *Advances in Nanoparticles*, **14**, 101-120.
https://doi.org/10.4236/anp.2025.144007

Received: September 13, 2025
Accepted: October 24, 2025
Published: October 27, 2025

Abstract

Weed management is a major challenge in agriculture, causing global yield losses of approximately 32%, surpassing damage from pests and pathogens. Sustainable approaches, such as integrated weed management and bioherbicides derived from phytotoxic plants or microorganisms, are gaining attention, though their physiological effects on weeds are not fully understood. Bioherbicides disrupt cellular and biochemical processes, including root growth, nutrient uptake, hormone balance, and pigment synthesis, often inducing stress responses. Their efficacy depends on formulation, dosage, weed species, and application methods. Advances in nanotechnology, including nanoparticles, nanoemulsions, and nanocapsules, enable controlled release, precise dosing, and enhanced delivery of bioactive compounds, improving weed suppression and crop performance. Essential oils from plants such as artemisia, eucalyptus, thyme, satureja, fennel, peppermint, and citronella exhibit allelopathic and herbicidal effects by inhibiting seed germination, disrupting physiological processes, and inducing cellular damage. Nanoformulations of these oils enhance solubility, stability, and bioavailability, increasing efficacy while minimizing crop toxicity. Integrating plant-derived bioherbicides with nanotechnology-based delivery systems offers an environmentally friendly, efficient, and sustainable strategy for weed management, supporting enhanced crop productivity, resource efficiency, and global food security.

Keywords

Bioherbicides, Essential Oils, Nanoemulsions, Weed Management, Sustainable Agriculture

1. Introduction

In economic terms, weeds impose a substantial burden on agriculture worldwide. For instance, Australian grain producers face annual losses estimated at around AUD 3.3 billion due to weed infestations. In India, the impact is even greater, with weeds reducing agricultural output by more than USD 11 billion per year. Similarly, in the United States, crop production suffers losses valued at roughly USD 33 billion annually as a result of uncontrolled weed growth [1]. While herbicides have provided significant benefits to agriculture, their prolonged and intensive use has led to the repeated emergence of herbicide-resistant weed populations, changes in the composition of weed communities, and environmental contamination, particularly through water runoff. In addition to affecting crop yields and contributing to herbicide resistance, environmental issues are a major concern. Chemical residues from herbicides can alter soil microbial populations, pollute water bodies, and negatively impact soil quality and overall ecosystem health over time [2]. The extensive use of synthetic herbicides has led to significant environmental and health concerns. These chemicals persist in ecosystems, contaminating soil, water, and air, which adversely affect biodiversity and ecosystem services. Additionally, residues from herbicides have been detected in food and water supplies, posing potential risks to human health. For instance, glyphosate-based herbicides have been associated with various health issues, prompting calls for more sustainable agricultural practices. In response to these challenges, there is a growing shift towards eco-friendly alternatives. Bioherbicides, derived from natural organisms or substances, offer a promising solution. These include fungal bioherbicides, which have shown effectiveness in controlling weeds while being less harmful to the environment. Additionally, plant-based extracts such as those from neem, clove, and cinnamon have demonstrated potent herbicidal properties, providing safe and sustainable options for weed management [3]. Weed management remains one of the most challenging aspects of crop production. Weeds remain a major factor in reducing crop yields worldwide, causing losses of approximately 32%, which surpass the damage inflicted by pests (18%) and pathogens (15%) [4]. They can significantly disrupt ecological systems and agricultural landscapes by altering plant communities and ecosystem dynamics. Economic losses due to weeds vary across crops, in maize, in potatoes, and in wheat. In addition to yield reduction, weeds such as *Datura stramonium* can contaminate food and feed, posing serious health risks by affecting organs like the liver, heart, kidneys, and brain. Effective weed management is therefore essential to maintaining both global food security and safety [5]. Cultural practices enhance crop competitiveness against weeds, thereby reducing weed pressure. Strategies include optimizing planting densities, selecting competitive crop varieties, and maintaining proper row spacing. Mechanical methods involve physical interventions such as tillage, mowing, mulching, and flaming to control weeds. For instance, mulching with organic materials can suppress weed germination by blocking light, while mowing reduces seed production in annual weeds [6]. These non-chemical approaches are integral to integrated weed management systems, especially in organic farming.

Recent field trials show that alternative weed-management approaches are increasingly capable of matching or nearing the efficacy of conventional herbicides under practical conditions. For instance, a 2024 study on soybean demonstrated that terminating cover crops one week after planting combined with a pre-emergence herbicide achieved ~96% weed suppression, compared to significantly lower suppression (~71% - 76%) when cover crops were terminated earlier without pre-emergence herbicides [7]. In Germany, tests of seven robotic weeding systems in sugar beet and winter oilseed rape found that several robots reached weed control efficacies of 92% - 94%, exceeding or matching standard broadcast herbicide treatments (75% - 83%), while also reducing herbicide use by inter-row banding & hoeing [8]. A meta-analysis of U.S. fall and winter cover crops showed an average 62.6% reduction in weed biomass compared to untreated control plots, highlighting substantial suppression even without full herbicide integration [9]. In vegetable production in New York and New Jersey, laser weeding in 2024 trials achieved weed biomass reductions of at least 97 percent in beets, spinach, and peas, providing effectiveness that was superior to or comparable with herbicide treatments, while also increasing crop growth by more than 30 percent [10].

2. Biological Weed Control

Biological weed control involves the deliberate use of living organisms, or biotic agents, to reduce the vigor, reproductive capacity, density, or overall impact of weeds in agricultural and natural ecosystems. These biotic agents are primarily microorganisms that exhibit pathogenic or growth-inhibiting effects on weeds. When applied in concentrated formulations in a manner similar to chemical herbicides, they are referred to as bioherbicides.

2.1. Microorganisms and Plant-Derived Compounds as Bioherbicides

Bioherbicides, also known as allelopathic or allelochemical agents, are generally divided into two main types: 1) plant-derived bioherbicides, which are obtained from plants, plant extracts, or essential oils (EOs), and 2) microbial-based bioherbicides, which consist of naturally occurring microorganisms such as bacteria, fungi, or their metabolites [11]. These bioherbicides act through several mechanisms, including disruption of cell membranes, inhibition of photosynthesis and key enzymes, interference with cell division, reduction of nutrient uptake, alteration of plant hormone balance, and induction of reactive oxygen species (ROS) stress leading to hormonal imbalances and disrupted antioxidant activity [12]. Additionally, microorganisms can release enzymes and phytotoxins that suppress seed germination and impede weed growth. The specific mode of action often depends on the type of bioherbicide and the targeted weed species.

2.1.1. Microbial Bioherbicides

Microbial bioherbicides utilize pathogens like fungi and bacteria to target specific weed species. Allelopathic plants release chemicals that inhibit the germination and growth of neighboring weeds; for example, water extracts from sorghum and eucalyptus have demonstrated significant weed suppression. Additionally, certain plant species, such as *Parthenium hysterophorus*, exhibit allelopathic effects that can be harnessed for weed management [13]. The most effective applications of bioherbicides are those that consistently suppress economically important and difficult-to-control weeds. They are particularly valuable for managing herbicide-resistant weed populations, which can reduce the overall use of chemical herbicides and mitigate environmental impact. Despite their potential, commercial-scale bioherbicide development faces challenges due to the lack of standardized formulation protocols and components suitable for diverse biotic agents. Each host-agent system often has specific requirements, from culturing and screening to preparation for field application. This lack of integration in production technology has limited the availability of effective commercial bioherbicides.

2.1.2. Plant-Based Bioherbicides

Integrated weed management, which incorporates bioherbicides, is gaining attention as a sustainable strategy for controlling weeds. Bioherbicides are generally derived from either plants that produce phytotoxic allelochemicals or microorganisms capable of suppressing weed populations. Although bioherbicides have shown potential in inhibiting weed seed germination and growth, relatively few studies have explored the physiological responses of weeds to these products. This review highlights currently available bioherbicide products, examines their effects on weed physiology, and discusses factors that may influence their effectiveness. Phytotoxic compounds from plants or microbial metabolites disrupt key cellular and biochemical processes in weeds. These disruptions manifest as reduced root cell division, impaired nutrient uptake, altered hormone and pigment production, and the generation of (ROS) and other stress-related responses. Variability in bioherbicide effectiveness-affected by factors such as bioactive compound concentration, weed species, formulation, and application method-remains a major limitation to their widespread adoption [14]. Despite their potential, traditional bioherbicides face several challenges. Their efficacy can be inconsistent due to environmental factors like temperature and humidity, which affect microbial activity. Moreover, the stability and shelf-life of bioherbicides are often limited, complicating storage and application. Field persistence is another concern, as some bioherbicides degrade rapidly in the environment, reducing their effectiveness over time [15].

2.2. Formulations of Bioherbicides

Formulation components are essential for improving handling, storage stability, and consistency of weed control efficacy. Additionally, nanotechnology presents a promising approach to enhance the effectiveness, stability, and field applicability of bioherbicide formulations. Understanding the factors that influence bioherbicide formulation is critical for optimizing performance and advancing sustainable weed management strategies. Formulated bioherbicides generally consist of a living biotic agent as the active ingredient, along with a carrier and adjuvants. These adjuvants may provide nutrients to sustain the agent, protect it from adverse environmental conditions, assist in host infection, and enhance overall weed control effectiveness. Achieving uniform and precise application of microbial cells or their products directly on or near target weeds without harming the crop can significantly enhance bioherbicidal effectiveness. Utilizing technologies already common in general agricultural practice may improve farmer adoption of biocontrol agents, increase the use of biological control methods, and expand the market. However, the development of bioherbicides, particularly those containing living organisms, faces challenges such as the need for high humidity and warm temperatures to ensure optimal organism activity and efficacy. This necessitates specialized formulations to maintain viability and effectiveness once the agent is applied in the field [16].

3. Nanotechnology in Bioherbicides

The application of nanoparticles and nanochips enables advanced material delivery systems in plants as well as the development of highly sensitive biosensors for precision farming. The use of nanoencapsulated fertilizers, pesticides, and herbicides allows for the controlled and sustained release of nutrients and agrochemicals, thereby ensuring accurate dosage and minimizing waste [17]. Furthermore, nanotechnology-based diagnostic kits for plant viral diseases are gaining prominence due to their ability to provide rapid and early detection. This article explores the potential applications and advantages of nanotechnology in advancing precision agriculture. According to the Directorate-General for Internal Policies of the European Union, precision agriculture refers to a comprehensive farm management strategy that involves assessing and addressing spatial and temporal variability within and between crop fields. This approach functions as a decision-support system aimed at optimizing farm operations and enhancing productivity through the efficient use of available resources. In contemporary agricultural practices, nanotechnology plays a pivotal role in advancing the implementation of precision agriculture, thereby contributing to its practical realization [18]. Nanobiotechnology introduces innovative tools for improving crop production through the application of nanoparticles, nanofibres, nanoemulsions (NE), and nanocapsules [19]. Nanoemulsions, which are colloidal dispersions of oil and water stabilized by surfactants, enhance the solubility and stability of hydrophobic bioactive agents, improving their application in herbicide formulations. These nanomaterials serve as effective platforms for delivering agrochemicals and essential macromolecules that promote plant growth and enhance resistance to biotic and abiotic stresses (**Figure 1**). The use of smart delivery systems ensures optimized water and nutrient utilization, thereby improving yield.

A key advantage of this technology lies in its ability to provide controlled release and site-specific delivery of agrochemicals. Moreover, further improvements in both crop quality and productivity can be achieved through nanoparticle-mediated gene transfer and the targeted delivery of macromolecules that regulate gene expression in plants. Experimental studies with different nanomaterials have yielded encouraging outcomes, highlighting their potential in advancing agricultural efficiency and sustainability [20].

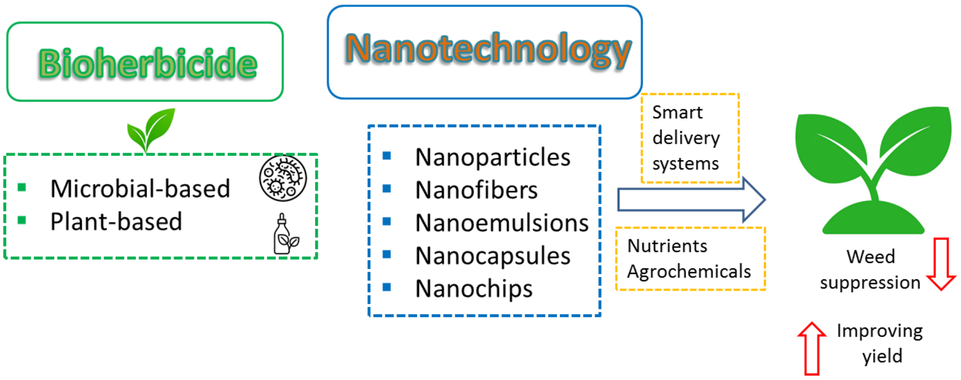

Figure 1. Sustainable weed management and enhanced crop productivity using nanotechnology-based bioherbicide delivery systems.

3.1. Nanoformulated Bioherbicides

Nanoformulated bioherbicides are innovative weed control agents that integrate natural herbicidal substances with nanotechnology to enhance their efficacy, stability, and environmental compatibility. These formulations aim to overcome the limitations of conventional herbicides and bioherbicides by providing controlled release, targeted delivery, and reduced toxicity to non-target organisms. The incorporation of nanotechnology allows for the encapsulation of active ingredients, protecting them from environmental degradation and facilitating their penetration into plant tissues. This approach aligns with sustainable agricultural practices by reducing chemical inputs and promoting eco-friendly weed management solutions.

3.2. Different Nano-Carriers

Various nano-carriers have been developed to deliver bioactive agents effectively in weed control. Polymeric nanoparticles, such as poly (lactic-co-glycolic acid) (PLGA) and chitosan-based nanoparticles, offer advantages like biodegradability, biocompatibility, and controlled release properties. These carriers can encapsulate herbicidal compounds, protecting them from environmental factors and ensuring sustained activity. Nanoemulsions, which are colloidal dispersions of oil and water stabilized by surfactants, enhance the solubility and stability of hydrophobic bioactive agents, improving their application in herbicide formulations. Liposomes, lipid bilayer vesicles, can encapsulate both hydrophilic and lipophilic substances, providing versatility in bioherbicide delivery. Chitosan nanoparticles, derived from chitin, possess antimicrobial properties and can be utilized as carriers for natural herbicides, offering an eco-friendly alternative to synthetic chemicals [21]. The modes of action of nanoformulated bioherbicides involve multiple mechanisms that disrupt weed growth and development. Upon application, these formulations can penetrate plant cell walls more effectively due to their nanoscale size, allowing for enhanced uptake of active ingredients. Once inside the plant, the encapsulated bioactive agents can interfere with various physiological processes, such as photosynthesis, enzyme activity, and cell division, leading to weed mortality. Additionally, the controlled release properties of nano-carriers ensure a sustained presence of the active ingredients in the target area, prolonging their herbicidal effects and reducing the frequency of application. This multifaceted approach not only improves the efficacy of bioherbicides but also minimizes the development of resistance in weed populations [22].

Potential Non-Target and Soil Micro-Biome Effects of Nano-Carriers

While nano-carriers offer promising advancements in agricultural pest management, their environmental impact, particularly on non-target organisms and soil microbiomes, warrants careful consideration. Recent studies have highlighted that certain nanoparticles can disrupt soil microbial communities, leading to altered microbial diversity and activity. For instance, exposure to silver nanoparticles has been shown to decrease the abundance of beneficial soil bacteria, potentially impairing essential soil functions such as nutrient cycling and organic matter decomposition [23]. Furthermore, a 2025 study found that a high-efficiency nanofungicide affected the community structure and diversity of non-target soil microorganisms, raising concerns about the long-term sustainability of such treatments [24]. These findings underscore the necessity for comprehensive risk assessments and the development of guidelines to mitigate potential adverse effects on soil ecosystems. Understanding the interactions between nano-carriers and soil microbiomes is crucial for ensuring the safe and sustainable application of nanotechnology in agriculture.

3.3. Specific Nanoformulations

Several case studies have demonstrated the effectiveness of nanoformulated bioherbicides in various agricultural settings. For instance, a study on a nanoencapsulated essential oil formulation showed enhanced herbicidal activity and stability compared to the free essential oil, indicating the potential of nanoformulations in improving bioherbicide performance [25]. Another example is the development of a pre-emergent nanoherbicide based on biodegradable polymers, which demonstrated improved weed control and reduced environmental impact, highlighting the advantages of using biodegradable nano-carriers in herbicide formulations [26]. These examples underscore the promise of nanoformulated bioherbicides as viable alternatives to conventional chemical herbicides, offering sustainable solutions for weed management in agriculture. **Table 1** summarizes all essential oil-based bioherbicides studied in this review.

Table 1. Summary of essential oil-based bioherbicidal studies, including target weeds, formulations, doses, key effects, and limitations.

Essential oil (EO)	Target Weed	Formulation/Dose	Key Effects	Limitations	Ref.
Satureja hortensis	*Amaranthus retroflexus*	Nanoencapsulated, 0 - 15 mL/L, AG/PGG/PG	Strong inhibition; complete control 48 h; mild crop effect	Crop selectivity; polymer required	[25]
Artemisia scoparia oil	*Achyranthes aspera*, *Cassia occidentalis*, *Parthenium hysterophorus*, *Echinochloa crus-galli*, *Ageratum conyzoides*	Seedling assay: 10, 25, 50 µg/g (sand); Post-emergence: 2%, 4%, 6% (v/v)	-Strong inhibition of seedling emergence and growth (root > shoot) -Visible post-emergence injury (chlorosis → necrosis → wilting) -Reduced chlorophyll, impaired photosynthesis & respiration -Electrolyte leakage and membrane disruption	Species-dependent; dosage optimization needed; root more affected than shoot	[27]
Natural compounds (12 monoterpenes, phenylpropenes, sesquiterpenes)	*Echinochloa crus-galli* (barnyard grass)	Seed/root/shoot: 0.5 - 8 mM; Post-emergence foliar: 0.5% - 2%	Trans-cinnamaldehyde, eugenol, thymol most effective; complete control at 1% - 2%; decreased fresh & dry weight	Only *E. crus-galli* tested; requires formulation for field use	[28]
Eucalyptus citriodora	*S. arvensis*, *S. oleraceus*, *X. strumarium*, *A. fatua*	EO 0.01% - 0.03% (lab), 1% - 3% (greenhouse)	Germination inhibition; leaf damage; chlorophyll reduction	Concentration-dependent; field-scale untested	[29]
Thyme EO	*Amaranthus retroflexus*	SiNPs 250 - 500 µL/mL	Up to 96% biomass reduction; ROS, membrane damage	Loading efficiency varies; field untested	[30]
Rosmarinus officinalis chemotypes	*A. retroflexus*, *L. perenne*	EO 400 - 2400 µL/L, chemotypes C1 - C4	Dose-, chemotype-dependent inhibition	Chemotype selection critical; field untested	[31]
F. vulgare, *S. hortensis*, *T. minuta*, *T. parthenium*	H. spontaneum, *A. retroflexus*	EO 0 - 800 µL/L	Strong germination & growth inhibition	Species-specific; formulation needed	[32]
F. vulgare EO nanoemulsion	*P. minor*, *A. ludoviciana*, *R. dentatus*, *M. denticulata*	NE 0.05 wt% - 0.4 wt%, <130 nm	Complete germination inhibition; ROS-mediated membrane damage	Only Petri dish tested	[33]
Peppermint EO nanoemulsion	Barnyard grass, maize	NE 1% - 10% EO, Eco-Polysorbate 80	Selective control; reduced chlorophyll & water content	Surfactant needed; field validation pending	[34]
Citronella EO (*C. nardus*) nanoemulsion	*E. crus-galli*, A. tricolor	NE 100 - 800 µL/L, HLB 14	Strong germination & seedling inhibition; REL & MDA ↑	HLB optimization critical; field data limited	[35]

A study [27] evaluated the bioherbicidal potential of volatile oil extracted from Artemisia scoparia against five weed species: *Achyranthes aspera*, *Cassia occidentalis*, *Parthenium hysterophorus*, *Echinochloa crus-galli*, and *Ageratum conyzoides*.

In a dose-response bioassay using sand treated with 10, 25, and 50 μg of Artemisia oil per gram, seedling emergence and growth were significantly reduced. Root growth was more strongly inhibited than shoot growth, with the greatest effect observed in *P. hysterophorus*, followed by *A. conyzoides*, and the least in *C. occidentalis*. Post-emergence application of Artemisia oil at 2%, 4%, and 6% (v/v) on six-week-old weed plants caused visible injury within 1 to 7 days, ranging from chlorosis to necrosis and complete wilting. The most pronounced effects were seen in *E. crus-galli* and *P. hysterophorus*. Treatment with the oil reduced chlorophyll content and impaired cellular respiration, indicating interference with photosynthetic and respiratory metabolism. Additionally, severe electrolyte leakage in *E. crus-galli* and *C. occidentalis* suggested membrane disruption and loss of cellular integrity. Overall, Artemisia oil exhibited strong bioherbicidal properties by causing phytotoxicity and disrupting growth and physiological functions in the tested weed species.

A study assessed the herbicidal potential of twelve natural compounds, including monoterpenes, phenylpropenes, and sesquiterpenes, against *Echinochloa crus-galli* in both laboratory and greenhouse settings [28]. The effects of various concentrations (0.5, 1, 2, 4, and 8 mM) on seed germination and root and shoot development were investigated. Among the compounds tested, trans-cinnamaldehyde, eugenol, and thymol exhibited the strongest inhibitory effects on seed germination and shoot growth. The compounds p-cymene (EC50 = 0.22 mM) and trans-cinnamaldehyde (EC50 = 0.34 mM) were particularly effective at reducing root growth. In post-emergence trials, thymol, trans-cinnamaldehyde, eugenol, farnesol, and nerolidol significantly decreased shoot growth, fresh weight, and dry weight of two-leaf stage barnyard grass within two days of foliar application at concentrations of 0.5%, 1.0%, and 2.0%. Severe injury symptoms were observed, and trans-cinnamaldehyde, eugenol, farnesol, and nerolidol achieved complete weed control at 1.0% and 2.0% concentrations. Formulated as emulsifiable concentrates, these compounds demonstrated enhanced herbicidal efficacy, indicating their potential for development as novel bioherbicides against *E. crus-galli*.

3.3.1. Nano-Encapsulated Bioherbicides

The excessive application of chemical pesticides has led to numerous environmental and ecological concerns, prompting increased interest in the use of plant-derived natural products as alternatives. The multiple advantages of natural herbicides have increasingly attracted the attention of researchers, leading to growing interest in the development of bioherbicides formulated with natural ingredients. Weed management is a major concern in agriculture, highlighting the need for herbicides that are both effective and environmentally friendly. Encapsulating plant essential oils (EOs) in nanoscale carriers offers advantages such as increased loading efficiency and controlled delivery. Essential oils (EOs), particularly those rich in terpenes, have been shown to exhibit potent herbicidal, fungicidal, and insecticidal properties, making them promising candidates for pest management strategies. Furthermore, due to their complex composition, EOs can help mitigate the emergence of resistant biotypes, as their diverse constituents often act through synergistic or antagonistic interactions and nonspecific mechanisms of action. Despite these benefits, the practical application of EOs is constrained by their poor water solubility, high volatility, and rapid degradation, particularly in aqueous environments. Encapsulation using surfactants and polymers has been demonstrated to improve the solubility, stability, bioactivity, and shelf life of EOs, thereby enhancing their potential for use in sustainable pest management systems. Taban *et al.* [25] studied nano-encapsulated bioherbicides. The various concentrations of savory (*Satureja hortensis* L.) essential oil (0, 5, 10, and 15 mL/L) were nanoencapsulated using Arabic gum (AG), Persian gum/gelatin (PGG), and Persian gum (PG) as wall materials. The herbicidal activity of the resulting nanocapsules was assessed against tomato (*Lycopersicon esculentum* Mill.) and amaranth (*Amaranthus retroflexus* L.) by evaluating 18 physiological and biochemical parameters. The nanocapsules exhibited an average size ranging from 81 to 208 nm, with polydispersity indices between 0.210 and 0.536. Encapsulation efficiency varied between 72.1% and 92.8%. The stability of the nano-encapsulated herbicides (NCHs) was monitored for 42 days, with oil release following a mathematical model. Results demonstrated significant herbicidal effects of NCHs against *A. retroflexus*, while only mild effects were observed on tomato plants. Additionally, encapsulated essential oils displayed higher herbicidal efficiency compared to non-nano essential oil emulsions (without polymer). The most pronounced and rapid effect on *A. retroflexus* was observed with cross-linked Persian gum at 15 mL/L, achieving complete weed control within 48 hours. These findings highlight the potential of biopolymer-based encapsulation with cross-linkers as a promising strategy for developing natural and eco-friendly herbicides.

The present study [29] investigated the allelopathic effects of *Eucalyptus citriodora* essential oil on several problematic weeds in Algeria, including *Sinapis arvensis*, *Sonchus oleraceus*, *Xanthium strumarium*, and *Avena fatua*. Volatile oils released by aromatic shrubs such as *Salvia leucophylla* and *Artemisia scoparia* can inhibit the growth of neighboring plants, resulting in distinctive vegetation patterns. The strong growth-suppressive properties of these essential oils have generated considerable interest in their potential application for weed management [36].

The chemical composition of the oil was determined using gas chromatography-flame ionization detector (GC–FID) and gas chromatography-mass spectrometry (GC–MS), revealing citronellal (64.7%) and citronellol (10.9%) as the predominant compounds. Laboratory experiments were conducted using oil concentrations of 0.01%, 0.02%, and 0.03%, while greenhouse studies employed 1%, 2%, and 3%. The results indicated that seed germination and seedling growth were significantly inhibited by the essential oil, with complete suppression of *S. arvensis* germination at 0.03%. Additionally, strong allelopathic effects were observed in 3 - 4 leaf stage plants 1 and 6 days post-treatment. At a 3% concentration, complete mortality occurred in *S. arvensis*, *S. oleraceus*, and *A. fatua*, with severe damage observed in *X. strumarium*. Treatment also caused a significant reduction in chlorophyll content and compromised cell membrane integrity, indicating substantial physiological stress. These findings suggest that *E. citriodora* essential oil has potential as a bioherbicide and could serve as an alternative approach for sustainable weed management [29].

This study examined thyme EO encapsulated in silica nanoparticles (SiNPs) for controlling redroot pigweed (*Amaranthus retroflexus*), a weed known for resistance to multiple herbicides [30]. Three EO volumes 500, 750, and 1000 μL were loaded into SiNPs to achieve concentrations of 250 μL/mL ("500"), 375 μL/mL ("750"), and 500 μL/mL ("1000"), resulting in loading efficiencies of 26%, 42%, and 64%, respectively. Transmission electron microscopy revealed spherical nanoparticles measuring 220 - 300 nm, and FT-IR spectroscopy confirmed EO incorporation through characteristic isoprenoid signals. In post-emergence trials, untreated thyme EO reduced shoot biomass in a concentration-dependent manner, achieving 85% reduction at the highest dose. Encapsulation in SiNPs further enhanced the herbicidal effect, with up to 96% biomass reduction. Additionally, EO-SiNP treatments triggered reactive oxygen species (ROS) accumulation, leading to membrane damage and disruption of the antioxidant system, reflected by increases in malondialdehyde (40%) and activities of ascorbate peroxidase (65%), catalase (52%), and superoxide dismutase (36%). These findings suggest that thyme EO delivered via SiNPs could serve as an effective nanobioherbicide.

In recent years, the development of bio-based products for biocontrol has gained increasing attention due to their potential to reduce reliance on synthetic herbicides in agriculture. Conventional herbicides, which are chemically synthesized, can have harmful effects on human health, including cancer, neurodegenerative disorders, and reproductive issues. They also pose environmental risks through air drift, water contamination, and persistence across ecosystems. Natural compounds offer a promising alternative, enabling productive agriculture while minimizing these negative impacts. In this context, essential oils and their constituent compounds are being extensively explored for use in various biopesticides, owing to their well-documented biocidal properties. Nonetheless, it is important to recognize that these natural molecules may also present certain risks to humans and the environment if not properly managed [35]. Weeds represent one of the costliest pests across all agricultural systems, contributing to approximately 30% of potential crop losses. This issue is particularly pronounced in organic farming, where the use of synthetic herbicides is restricted, making weed management a major challenge. Consequently, research has increasingly focused on the allelopathic properties of plants as a sustainable approach to weed control. Certain plant species produce allelopathic compounds with strong phytotoxic effects, which can be harnessed to manage weeds. Among these, species from the Lamiaceae family have received considerable attention, as their essential oils (EOs) show promise as bioherbicides. Despite this potential, significant obstacles remain in developing these products for practical use [36].

Given their unique chemical composition and volatility, essential-oil-based formulations are discussed separately to highlight their distinct mechanisms of action and formulation challenges compared with other nano-carrier systems.

3.3.2. Essential Oil-Based Formulations

Essential oils (EOs), naturally synthesized by aromatic plants, consist of a complex mixture of volatile compounds, mainly secondary metabolites, which display a wide range of biological activities. These oils are recognized for their antioxidant, antimicrobial, and anti-inflammatory properties, which have long been utilized in traditional medicine, cosmetics, and the food industry. Despite evidence of their efficacy against various phytopathogenic fungi, oomycetes, bacteria, and weeds, the use of EOs in agriculture remains limited. Their potential as sustainable alternatives to synthetic pesticides offers promising opportunities for controlling weeds and plant diseases without negatively affecting crop yields. The biological activity of essential oils largely depends on their main chemical components, which can be grouped into two categories. The first includes terpene hydrocarbons, such as monoterpenes and sesquiterpenes, with monoterpenes sometimes making up as much as 80% of the oil. The second consists of oxygen-containing compounds, mainly alcohols, phenols, aldehydes, and esters [37].

Although oxygenated compounds are usually present in smaller amounts than terpenes, they are frequently found and contribute significantly to the oil's bioactivity. The chemical profile of an EO can vary depending on the plant species and the specific organ from which the oil is extracted. Plant essential oils (EOs) have gained considerable attention as a natural and sustainable approach to addressing post-harvest challenges. They not only serve as a rich source of antioxidants but also provide effective control of fungal pathogens and stored-product pests, which is critical for maintaining food safety and quality.

The present study [38] focused on two main objectives: first, to identify the predominant chemical constituents of *Satureja sahendica* EOs, and second, to evaluate their antioxidant and biological activities, including fungicidal, allelopathic, and insecticidal properties. Analysis of the EOs revealed a total of 19 compounds, with thymol (33.53%), γ-terpinene (28.2%), and m-cymene (21.9%) as the most abundant. Notably, m-cymene was reported for the first time in *S. sahendica*. The antioxidant activity of the EOs increased with concentration, reaching a maximum of 88.48% at 7 µL/L over 30 minutes. In terms of antifungal activity, the EOs achieved complete inhibition of *Botrytis cinerea*, *Aspergillus niger*, and *Penicillium expansum* at concentrations of 500, 750, and 750 µL/L, respectively. Similarly, full inhibition was observed against common weeds, including *Panicum miliaceum*, *Lactuca sativa*, and *Amaranthus retroflexus*, at comparable concentrations. Furthermore, *S. sahendica* EOs exhibited strong insecticidal activity, with *Callosobruchus maculatus* showing higher susceptibility compared to *Sitophilus oryzae*. These results highlight the potential of *S. sahendica* EOs as effective biopesticides and suggest their utility in eco-friendly and efficient strategies for post-harvest pest management.

The increasing interest in natural, plant-derived products, particularly essential oils (EOs), as environmentally friendly agrochemicals has fueled consumer demand for clean-label and sustainable solutions. Owing to their potent antimicrobial and pesticidal activities, EOs hold considerable promise for applications in both food preservation and agriculture. Nevertheless, their practical use is constrained by poor water solubility and high volatility. To overcome these limitations, nanoemulsions (NEs) have emerged as effective delivery systems for EOs, providing advantages such as reduced particle size, enhanced solubilization, high encapsulation efficiency, and controlled release of active compounds [39].

The study investigated the allelopathic effects of *Rosmarinus officinalis* essential oils (EOs) to determine their potential against weed species by examining different chemotypes and their main constituents [31]. EOs from eight accessions were analyzed using gas chromatography, which led to the identification of four chemotypes: C1 (β-pinene), C2 (camphor), C3 (β-pinene/1,8-cineole), and C4 (β-pinene/1,8-cineole/camphor). Laboratory assays tested four concentrations of each EO (400, 800, 1200, and 2400 μL/L) and the main compounds of each chemotype against *Amaranthus retroflexus* and *Lolium perenne* in both pre- and post-germination stages. The results showed that the EOs significantly affected germination, early growth, and physiological and histological parameters in a dose-, chemotype-, and species-dependent manner. *A. retroflexus* was more sensitive at the germination stage, showing significant inhibition even at the lowest dose across all chemotypes. Among the chemotypes, C2 (camphor) and C3 (β-pinene/1,8-cineole) were the most potent and induced distinct types of damage. These findings highlight the importance of monoterpene composition in the bioherbicidal activity of EOs, providing insights for developing EO-based bioherbicides.

Given the adverse effects of synthetic herbicides on human health and the environment, natural products such as plant-derived compounds are receiving increasing attention. This study evaluated the herbicidal activity of essential oils (EOs) from *Foeniculum vulgare* var. azoricum, *Satureja hortensis* L., *Tagetes minuta* L., and *Tanacetum parthenium* L. against the weeds *Hordeum spontaneum* L. and *Amaranthus retroflexus* L. Seed germination and seedling growth were assessed at EO concentrations of 0, 100, 200, 400, 600, and 800 μL L^{-1} [32]. Gas chromatography–mass spectrometry analysis revealed that (E)-anethole (84.32%) and γ-terpinene (59.75%) were the primary constituents of *F. vulgare* var. azoricum and *S. hortensis*, respectively; dihydro-tagetone (62.57%) dominated *T. minuta*, and camphor (56.63%) was the main component of *T. parthenium*. All tested essential oils significantly inhibited weed germination and early growth, with *T. parthenium* and *T. minuta* showing the strongest suppression of *H. spontaneum* and *A. retroflexus*, respectively. These results indicate that the studied essential oils have potential as natural herbicidal agents.

Wahba *et al.* (2024) [40] conducted field trials in Egypt, comparing nanoemulsions of peppermint and eucalyptus essential oils with conventional imidacloprid treatments on potato crops. The study demonstrated that the nanoformulations effectively controlled the whitefly pest *Bemisia tabaci*, with performance comparable to standard chemical pesticides. This research underscores the potential of EO-based nanoformulations as viable alternatives in integrated pest management strategies.

Sharifiyan *et al.* (2024) [41] evaluated the toxicity and sublethal effects of nanoformulated *Mentha pulegium* essential oil against the greenhouse whitefly (*Trialeurodes vaporariorum*) in greenhouse conditions. The study found that the nanoformulation exhibited enhanced toxicity compared to the pure essential oil, affecting the biological and population growth parameters of the pest. These findings highlight the efficacy of EO nanoformulations in pest control and their potential integration into sustainable pest management practices.

3.3.3. Nanoemulsions

Bio-based nanoemulsions are increasingly used in sustainable agriculture as part of eco-friendly pest management strategies. Essential oil-based bioherbicides have emerged as a promising focus in modern agriculture due to the global demand for weed control solutions with minimal environmental impact. In this study [33], oil-in-water nanoemulsions of fennel (*Foeniculum vulgare* Mill.) essential oil were prepared using ultrasonic emulsification and assessed for their herbicidal efficacy against *Phalaris minor* Retz., *Avena ludoviciana* Durieu, *Rumex dentatus* L., and *Medicago denticulata* Willd through Petri dish bioassays. Complete inhibition of seed germination was achieved at concentrations of 0.4, 0.3, 0.3, and 0.05 wt% for *P. minor*, *A. ludoviciana*, *R. dentatus*, and *M. denticulata*, respectively. The principal constituents of *F. vulgare* oil-estragole, anethole, and their binary mixture - did not fully suppress germination of the tested weeds even at the highest concentrations, highlighting the superior efficacy of the nanoemulsion formulation. The prepared nanoemulsions, containing 0.05 and 0.01 wt% fennel oil, exhibited spherical morphology with an average particle size below 130 nm, along with strong stability against centrifugation and dilution. They remained clear and transparent after 30 days of storage at room temperature. Notably, the nanoemulsions were highly effective at low concentrations (0.05 wt%), completely inhibiting seed germination by disrupting physiological processes such as membrane integrity and inducing reactive oxygen species-mediated cellular damage. These findings demonstrate that fennel oil nanoemulsions possess significant bioherbicidal potential and can serve as an eco-friendly alternative for sustainable weed management.

Rys *et al.* (2022) evaluated the physicochemical characteristics and herbicidal effectiveness of peppermint essential oil nanoemulsions (PNs) at concentrations ranging from 1% to 10%, stabilized with Eco-Polysorbate 80, on germinating seeds and young plants of maize and barnyard grass [34]. Using a design of experiment (DOE) approach, final nanoemulsion formulations were prepared with 1%, 1.5%, 2%, and 5% essential oil concentrations. Biological assays were conducted to identify the most effective formulation for selectively controlling barnyard grass in maize. Seedlings exposed to PNs showed overall metabolic inhibition, as indicated by calorimetric analyses, likely due to significant changes in carbohydrate content and composition. Concentration-response analysis revealed that a leaf-sprayed PN concentration causing 10% damage to maize was 2.2%, while concentrations causing 50% and 90% damage to barnyard grass were 1.1% and 1.7%, respectively. Applications of PN at 5% or 10% significantly reduced leaf relative water content and chlorophyll a fluorescence 72 hours after spraying. Overall, peppermint nanoemulsion with 2% Eco-Polysorbate 80 shows promise for selective control of barnyard grass in maize, warranting further evaluation under controlled and field conditions.

Nanoemulsions containing citronella (*Cymbopogon nardus*) essential oil (CEO) were prepared using a high-pressure homogenization technique, with surfactant blends (Tween 60 and Span 60) having hydrophilic-lipophilic balance (HLB) values ranging from 9 to 14.9 [35]. Chemical analysis revealed that CEO was rich in monoterpenes, including geraniol (36.3%), trans-citral (17.9%), cis-citral (15.3%), citronellal (9.0%), and β-citronellol (5.0%). Among the formulations, the nanoemulsion with HLB 14 displayed the smallest particle size (79 nm, PI 0.286), as confirmed by transmission electron microscopy, and was thus selected as the optimal formulation. After 28 days of storage, particle sizes changed to 58 nm at 4˚C and 140 nm at 25˚C. Biological assays using *Echinochloa crus-galli* seeds demonstrated that all nanoemulsions, across HLB values of 9 - 14.9 and concentrations of 100 - 800 μL/L, significantly inhibited germination and seedling growth in a dose-dependent manner. The HLB 14 formulation had the strongest inhibitory effect, reducing both seed imbibition and α-amylase activity. These results indicate that CEO nanoemulsions possess potent phytotoxic activity, highlighting their potential as bioherbicidal agents for weed management.

A natural herbicidal nanoemulsion was prepared using citronella (*Cymbopogon nardus* L.) essential oil (CEO) combined with the nonionic surfactants Tween 60 and Span 60 at a hydrophilic-lipophilic balance (HLB) of 14 through a microluidization technique. Analysis of CEO revealed that its main components were citronellol (35.2%), geraniol (21.9%), and citronellal (13.6%) [42]. The droplet size and polydispersity index (PI) of the nanoemulsion were measured using dynamic light scattering (DLS), with the smallest droplets (33.2 nm, PI 0.135) achieved after seven cycles at 20,000 psi in a microluidizer. Transmission electron microscopy confirmed the DLS results, indicating successful formation of the CEO nanoemulsion. The herbicidal potential of the nanoemulsion was tested as a foliar spray against *Echinochloa cruss-galli* and Amaranthus tricolor, representative narrowleaf and broadleaf weeds, both of which showed visible toxicity symptoms. Further investigation into its mode of action revealed increased relative electrolyte leakage (REL) and malondialdehyde (MDA) levels, indicating cellular damage, along with a reduction in chlorophyll and carotenoid contents. These findings suggest that CEO nanoemulsions could serve as a natural herbicide, offering a promising alternative for sustainable agricultural practices.

4. Discussion

Weed management remains a critical challenge in agriculture, with global yield losses from weeds exceeding 30%, highlighting the urgency for sustainable alternatives to synthetic herbicides. Plant-derived bioherbicides, particularly essential oils (EOs), have emerged as promising eco-friendly solutions due to their multifaceted phytotoxic mechanisms. EOs disrupt membrane integrity, photosynthesis, nutrient uptake, and hormone balance, inducing oxidative stress and impairing root and shoot development, which makes them effective against both conventional and herbicide-resistant weed species. The biological activity of EOs is strongly influenced by their chemical composition. Terpenes and oxygenated compounds, such as thymol, γ-terpinene, citronellol, and geraniol, have been identified as major contributors to allelopathic and herbicidal effects. Studies on *Satureja sahendica*, fennel, peppermint, and citronella demonstrated that these compounds inhibit seed germination, reduce chlorophyll content, disrupt water relations, and induce cellular damage, confirming their broad-spectrum activity. However, the practical application of EOs is often limited by volatility, low water solubility, and rapid degradation in the field. Nanotechnology-based formulations, particularly nanoemulsions, have addressed these limitations by enhancing EO solubility, stability, and controlled release, enabling effective weed suppression at low concentrations. Nanoencapsulated EOs maintain bioactivity while improving selectivity, reducing crop damage, and enabling precise application. The combination of natural phytotoxic compounds with nanodelivery systems therefore represents a powerful strategy for sustainable weed management, aligning with integrated pest management and precision agriculture approaches. Future research should focus on optimizing nanoformulation parameters, assessing species-specific responses, and conducting large-scale field trials to validate laboratory findings. The integration of EO-based nanoherbicides holds significant potential for reducing reliance on synthetic chemicals, improving crop productivity, and promoting environmentally sustainable agricultural practices.

5. Conclusion

Weed management remains one of the most pressing challenges in modern agriculture, with conventional synthetic herbicides often associated with environmental risks, herbicide resistance, and non-target effects. Bioherbicides derived from plants or microorganisms offer an eco-friendly alternative, acting through mechanisms that disrupt cellular integrity, nutrient uptake, hormone regulation, photosynthesis, and induce stress responses in target weeds. Despite their promise, widespread commercial adoption is constrained by formulation stability, viability of biological agents, and effective field application. Nanotechnology presents a transformative solution, enabling precise delivery, controlled release, and enhanced stability of bioactive compounds. Nanoencapsulation of essential oils and other plant-derived compounds improves solubility, persistence, and herbicidal potency, while reducing off-target effects and environmental impact. Studies with oils from Artemisia, Eucalyptus, thyme, fennel, peppermint, citronella, and Satureja demonstrate their strong allelopathic and herbicidal activity, including inhibition of seed germination, reduced root and shoot growth, altered chlorophyll content, and induction of cellular damage in weeds. Compounds such as thymol, eugenol, and trans-cinnamaldehyde show consistent efficacy in both pre- and post-emergence applications, especially when delivered via nanoemulsions. Integrating plant-derived bioherbicides with nanotechnology-based formulations supports sustainable agriculture by improving weed control, enhancing crop efficiency, and minimizing environmental risks associated with conventional herbicides. Future research should focus on optimizing formulations, evaluating long-term ecological safety, and scaling field applications to fully realize the potential of these innovative, sustainable, and selective weed management strategies. Collectively, this integrated approach represents a viable, environmentally responsible solution to global weed management challenges. Despite their promising efficacy, the widespread adoption of these nano-carrier and essential-oil formulations will likely be constrained by regulatory approval processes and higher production costs, which must be carefully considered in real-world applications.

Acknowledgements

This article is based upon work from COST ACTION CA23123 – Non-chemical weed management in medicinal and aromatic plants (MAPs) (weedingMAPs), supported by COST (European Cooperation in Science and Technology).

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Chauhan, B.S. (2020) Grand Challenges in Weed Management. *Frontiers in Agronomy*, **1**, Article ID: 3. https://doi.org/10.3389/fagro.2019.00003

[2] Chauhan, B.S., Matloob, A., Mahajan, G., Aslam, F., Florentine, S.K. and Jha, P. (2017) Emerging Challenges and Opportunities for Education and Research in Weed Science. *Frontiers in Plant Science*, **8**, Article ID: 1357. https://doi.org/10.3389/fpls.2017.01537

[3] Islam, A.K.M.M., Karim, S.M.R., Kheya, S.A. and Yeasmin, S. (2024) Unlocking the Potential of Bioherbicides for Sustainable and Environment Friendly Weed Management. *Heliyon*, **10**, e36088. https://doi.org/10.1016/j.heliyon.2024.e36088

[4] van Evert, F.K., Fountas, S., Jakovetic, D., Crnojevic, V., Travlos, I. and Kempenaar, C. (2017) Big Data for Weed Control and Crop Protection. *Weed Research*, **57**, 218-233. https://doi.org/10.1111/wre.12255

[5] Ben Kaab, S., Fernández Pierna, J.A., Foncoux, B., Compère, P., Baeten, V. and Jijakli, M.H. (2024) Biochemical and Physiological Responses of Weeds to the Application of a Botanical Herbicide Based on Cinnamon Essential Oil. *Plants*, **13**, Article 3432. https://doi.org/10.3390/plants13233432

[6] Zawada, M., Legutko, S., Gościańska-Łowińska, J., Szymczyk, S., Nijak, M., Wojciechowski, J., *et al.* (2023) Mechanical Weed Control Systems: Methods and Effectiveness. *Sustainability*, **15**, Article 15206. https://doi.org/10.3390/su152115206

[7] Bayer Crop Science (2024) Cover Crop Management and Herbicide Program Selec-

tion Impact on Weed Suppression and Soybean Yields. Crop Science. https://www.cropscience.bayer.us/articles/bayer/cover-crop-management-and-herbicide-program-selection-impact-on-weed-suppression-and-soybean-yields

[8] Gerhards, R., Risser, P., Spaeth, M., Saile, M. and Peteinatos, G. (2023) A Comparison of Seven Innovative Robotic Weeding Systems and Reference Herbicide Strategies in Sugar Beet (*Beta Vulgaris Subsp. Vulgaris* L.) and Rapeseed (*Brassica napus* L.). *Weed Research*, **64**, 42-53. https://doi.org/10.1111/wre.12603

[9] Dong, F. and Zeng, W. (2024) Effects of Fall and Winter Cover Crops on Weed Suppression in the United States: A Meta-Analysis. *Sustainability*, **16**, Article 3192. https://doi.org/10.3390/su16083192

[10] Sosnoskie, L.M., Bill, K., Butler-Jones, A., Bouchelle, W.M. and Besançon, T.E. (2025) Deep Learning-Based Laser Weed Control Compared to Conventional Herbicide Application across Three Vegetable Production Systems. *Pest Management Science*, **81**, 4922-4936. https://doi.org/10.1002/ps.8912

[11] Campos, E.V.R., Ratko, J., Bidyarani, N., Takeshita, V. and Fraceto, L.F. (2023) Nature-Based Herbicides and Micro-/Nanotechnology Fostering Sustainable Agriculture. *ACS Sustainable Chemistry & Engineering*, **11**, 9900-9917. https://doi.org/10.1021/acssuschemeng.3c02282

[12] Bratovcic, A. (2025) Exploring Non-Chemical Methods for Sustainable Weed Management. *International Journal of Agriculture and Environmental Research*, **11**, 129-153. https://doi.org/10.51193/ijaer.2025.11109

[13] Ocán-Torres, D., Martínez-Burgos, W.J., Manzoki, M.C., Soccol, V.T., Neto, C.J.D. and Soccol, C.R. (2024) Microbial Bioherbicides Based on Cell-Free Phytotoxic Metabolites: Analysis and Perspectives on Their Application in Weed Control as an Innovative Sustainable Solution. *Plants*, **13**, Article 1996. https://doi.org/10.3390/plants13141996

[14] Hasan, M., Ahmad-Hamdani, M.S., Rosli, A.M. and Hamdan, H. (2021) Bioherbicides: An Eco-Friendly Tool for Sustainable Weed Management. *Plants*, **10**, Article 1212. https://doi.org/10.3390/plants10061212

[15] Zhang, Z., Becerra-Alvarez, A. and Al-Khatib, K. (2025) Physiological Action of Bioherbicides in Weed Control: A Systematic Review. *Frontiers in Agronomy*, **7**, Article ID: 1633565. https://doi.org/10.3389/fagro.2025.1633565

[16] Kremer, R.J. (2019) Bioherbicides and Nanotechnology: Current Status and Future Trends. In: Koul, O., Ed., *Nano-Biopesticides Today and Future Perspectives*, Elsevier, 353-366. https://doi.org/10.1016/b978-0-12-815829-6.00015-2

[17] Bratovcic, A. (2022) Positive Aspects of Nanotechnology on Agricultural Sustainable Development: Application of Nanoparticles and Fibers for Increasing Agricultural Yield. *International Journal of Agriculture and Environmental Research*, **8**, 780-798. https://doi.org/10.51193/ijaer.2022.8606

[18] Duhan, J.S., Kumar, R., Kumar, N., Kaur, P., Nehra, K. and Duhan, S. (2017) Nanotechnology: The New Perspective in Precision Agriculture. *Biotechnology Reports*, **15**, 11-23. https://doi.org/10.1016/j.btre.2017.03.002

[19] Bratovcic, A. (2023) Green Synthesis of Various Nanostructures Containing Essential Oil and Silver Nanoparticles: Nanocomposites, Nanoemulsions and Nanoen-Capsules. *International Journal of Engineering Research and Applications*, **13**, 234-242.

[20] Chand Mali, S., Raj, S. and Trivedi, R. (2020) Nanotechnology a Novel Approach to Enhance Crop Productivity. *Biochemistry and Biophysics Reports*, **24**, Article 100821. https://doi.org/10.1016/j.bbrep.2020.100821

[21] Elmowafy, M., Shalaby, K., Elkomy, M.H., Alsaidan, O.A., Gomaa, H.A.M., Abdelgawad, M.A., *et al.* (2023) Polymeric Nanoparticles for Delivery of Natural Bioactive Agents: Recent Advances and Challenges. *Polymers*, **15**, Article 1123. https://doi.org/10.3390/polym15051123

[22] Pérez-de-Luque, A. (2023) Can Nanotechnology Improve the Application of Bioherbicides? *Pest Management Science*, **80**, 49-55. https://doi.org/10.1002/ps.7526

[23] Soltani Toularoud, A.A., Nasrollahi, S., Goli Kalanpa, E., Rouhi Kelarlou, T. and Nematollahzadeh, A. (2025) Toxicological Impact of Silver Nanoparticles on Soil Microbial Indicators in Contaminated Soil (Pot Experiment). *Nanotoxicology*, **19**, 216-231. https://doi.org/10.1080/17435390.2025.2454967

[24] Das, D., Ingti, B., Paul, P., Jamatia, J.P., Ete, T., Khan, T., *et al.* (2025) Soil Microbial Dynamics in Response to the Impact of Nanoparticles on Agricultural Implications. *Discover Soil*, **2**, Article No. 58. https://doi.org/10.1007/s44378-025-00087-8

[25] Taban, A., Saharkhiz, M.J. and Khorram, M. (2020) Formulation and Assessment of Nano-Encapsulated Bioherbicides Based on Biopolymers and Essential Oil. *Industrial Crops and Products*, **149**, Article 112348. https://doi.org/10.1016/j.indcrop.2020.112348

[26] Takeshita, V., Carvalho, L.B., Galhardi, J.A., Munhoz-Garcia, G.V., Pimpinato, R.F., Oliveira, H.C., *et al.* (2022) Development of a Preemergent Nanoherbicide: From Efficiency Evaluation to the Assessment of Environmental Fate and Risks to Soil Microorganisms. *ACS Nanoscience Au*, **2**, 307-323. https://doi.org/10.1021/acsnanoscienceau.1c00055

[27] Kaur, S., Singh, H.P., Mittal, S., Batish, D.R. and Kohli, R.K. (2010) Phytotoxic Effects of Volatile Oil from Artemisia Scoparia against Weeds and Its Possible Use as a Bioherbicide. *Industrial Crops and Products*, **32**, 54-61. https://doi.org/10.1016/j.indcrop.2010.03.007

[28] Saad, M.M.G., Gouda, N.A.A. and Abdelgaleil, S.A.M. (2019) Bioherbicidal Activity of Terpenes and Phenylpropenes against *echinochloa Crus-Galli*. *Journal of Environmental Science and Health*, *Part B*, **54**, 954-963. https://doi.org/10.1080/03601234.2019.1653121

[29] Benchaa, S., Hazzit, M. and Abdelkrim, H. (2018) Allelopathic Effect of *Eucalyptus citriodora* Essential Oil and Its Potential Use as Bioherbicide. *Chemistry & Biodiversity*, **15**, e1800202. https://doi.org/10.1002/cbdv.201800202

[30] Boukhalfa, R., Dimkpa, C.O., Deng, C., Wang, Y., Ruta, C., Calabrese, G.J., *et al.* (2024) Encapsulation in Silica Nanoparticles Increases the Phytotoxicity of Essential Oil from *thymus Vulgaris* in a Weed Species. *ACS Agricultural Science & Technology*, **4**, 1321-1331. https://doi.org/10.1021/acsagscitech.4c00580

[31] El Mahdi, J., Tarraf, W., Ruta, C., Piscitelli, L., Aly, A. and De Mastro, G. (2020) Bioherbicidal Potential of the Essential Oils from Different Rosmarinus Officinalis L. Chemotypes in Laboratory Assays. *Agronomy*, **10**, Article 775. https://doi.org/10.3390/agronomy10060775

[32] Taban, A., Rastegar, S., Nasirzadeh, M. and Saharkhiz, M.J. (2022) Essential Oil Composition and Comparative Phytotoxic Activity of Fennel, Summer Savory, Mexican Marigold and Feverfew: A Potential Bioherbicide. *Vegetos*, **35**, 502-510. https://doi.org/10.1007/s42535-021-00325-8

[33] Kaur, P., Gupta, S., Kaur, K., Kaur, N., Kumar, R. and Bhullar, M.S. (2021) Nanoemulsion of *Foeniculum Vulgare* Essential Oil: A Propitious Striver against Weeds of Triticum Aestivum. *Industrial Crops and Products*, **168**, Article 113601. https://doi.org/10.1016/j.indcrop.2021.113601

[34] Rys, M., Miastkowska, M., Sikora, E., Łętocha, A., Krajewska, A. and Synowiec, A. (2022) Bio-Herbicidal Potential of Nanoemulsions with Peppermint Oil on Barnyard Grass and Maize. *Molecules*, **27**, Article 3480. https://doi.org/10.3390/molecules27113480

[35] Somala, N., Laosinwattana, C. and Teerarak, M. (2022) Formulation Process, Physical Stability and Herbicidal Activities of *Cymbopogon Nardus* Essential Oil-Based Nanoemulsion. *Scientific Reports*, **12**, Article No. 10280. https://doi.org/10.1038/s41598-022-14591-2

[36] Singh, H.P., Batish, D.R. and Kohli, R.K. (2003) Allelopathic Interactions and Allelochemicals: New Possibilities for Sustainable Weed Management. *Critical Reviews in Plant Sciences*, **22**, 239-311. https://doi.org/10.1080/713610858

[37] Raveau, R., Fontaine, J. and Lounès-Hadj Sahraoui, A. (2020) Essential Oils as Potential Alternative Biocontrol Products against Plant Pathogens and Weeds: A Review. *Foods*, **9**, Article 365. https://doi.org/10.3390/foods9030365

[38] Ghasemi, G., Alirezalu, A., Jarrahi, A., Safavi, S.A. and Azadi, P. (2025) Unlocking the Bioactive Power of Satureja Sahendica Essential Oil against Saprophytic Fungi, Weeds, and Insect Pests. *Journal of Agriculture and Food Research*, **23**, Article 102177. https://doi.org/10.1016/j.jafr.2025.102177

[39] Kumar, A., Kanwar, R. and Mehta, S.K. (2025) Nanoemulsion as an Effective Delivery Vehicle for Essential Oils: Properties, Formulation Methods, Destabilizing Mechanisms and Applications in Agri-Food Sector. *Next Nanotechnology*, **7**, Article 100096. https://doi.org/10.1016/j.nxnano.2024.100096

[40] Wahba, T.F., Abd-Elatef, E.A. and Wahba, M.N. (2024) Field Effectiveness of Some Essential Oil Emulsions against the Whitefly Bemisia Tabaci (GENN.) That Infest Potato Plants in Egypt. *Journal of Plant Diseases and Protection*, **131**, 1451-1463. https://doi.org/10.1007/s41348-024-00944-8

[41] Sharifiyan, M., Mehrkhou, F. and Negahban, M. (2024) Sublethal Effects of Nanoformulated Mentha Pulegium L. Essential Oil on the Biological and Population Growth Parameters of the Greenhouse Whitefly, Trialeurodes Vaporariorum, (Hemiptera: Aleyrodidae). *Scientific Reports*, **14**, Article No. 27357. https://doi.org/10.1038/s41598-024-78249-x

[42] Somala, N., Laosinwattana, C., Chotsaeng, N. and Teerarak, M. (2023) Citronella Essential Oil-Based Nanoemulsion as a Post-Emergence Natural Herbicide. *Scientific Reports*, **13**, Article No. 20851. https://doi.org/10.1038/s41598-023-48328-6