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**Review Article****Biological alternatives to herbicides: Unlocking the potential of bioherbicides and plant-based alternatives**Amir Afzal¹, Sairah Syed¹, Taimoor Hussain¹, Khalida Hamid Abbasi¹, Muhammad Farooq Ahmad¹, Arsalan Wasif¹, Wardah Muzzafar², Nadeem Ahmad¹¹ Barani Agricultural Research Institute, Chakwal, Punjab, Pakistan.² Groundnut Research Station, Attock, Punjab, Pakistan.**ABSTRACT**

The agricultural sector is under growing pressure to improve crop yields and production efficiency in order to meet the escalating demands for food worldwide. Weeds, crop pathogens, and insect pests remain major biotic constraints, with weeds persistently ranked among the most detrimental factors limiting crop yields. Weeds pose a persistent challenge in crop husbandry, competing aggressively with cultivated plants for essential growth resources including soil moisture, nutrients, and sunlight. Such competition reduces crop yields besides affecting biodiversity. Conventional weed management practices rely heavily on synthetic herbicides, have raised serious concerns. These concerns include environmental contamination, the evolution of herbicide-resistant weed populations, and harmful impacts on non-target organisms such as pollinators and beneficial soil microorganisms. Therefore, there is a growing demand to explore sustainable weed management alternatives that safeguard agronomic productivity while preserving ecological balance. Conventional herbicide-based weed management has raised concerns due to environmental contamination, the emergence of herbicide-resistant weed biotypes, and detrimental impacts on non-target organisms. These challenges have accelerated the search for sustainable weed management strategies. Biological approaches, such as bioherbicides derived from fungi, bacteria, and allelopathic plants, provide environmentally friendly options consistent with the principles of sustainable agriculture. Among these, essential oils—rich in phytotoxic terpenoids—demonstrate fortified potential as natural alternatives due to their selectivity and minimal environmental impact. Biological approaches suppress weeds through natural allelopathic and microbial mechanisms, enhance agro-biodiversity, improve soil health leading to reduced reliance on synthetic herbicides. The present article underscores the potential of integrating bioherbicides and other allelopathic agents into weed management programs to boost sustainable crop production systems and strengthen ecological resilience.

Keywords: Bioherbicides; eco-friendly weed management; integrated weed management; allelopathy; weed resistance management; environmental safety of herbicides.

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INTRODUCTION

Wheat, cotton, rice, sugarcane, maize, and vegetables represent the cornerstone of agricultural production in many agrarian economies, serving as primary sources of nutrient, fibre, and raw materials for industries contributing substantially to national economic growth (Ahmad, 2019; Ahmad et al., 2017). Yet the area allocated to crop cultivation is steadily declining worldwide, driven by escalating population pressures, rapid urbanization, and the transition of agricultural land to non-agricultural usage (Mehrabi, 2023). The global agricultural sector is facing pressure to enhance crop production in order to meet the escalating food security needs of a growing population in the present century (Khan et al., 2022). Although substantial

advancements have been achieved in agricultural technologies, to realizing optimal crop productivity (Baz et al., 2025; Juroszek and von Tiedemann, 2013). These biotic stressors not only compete with crops for sunlight, water, and nutrients, but also inflict direct physiological and pathological damage, ultimately diminishing both the quantity and quality of harvestable yields (Gharde et al., 2018; Dixit et al., 2024).

Weeds are a significant and persistent challenge in crop husbandry and natural ecosystems, competing with crops for critical resources such as moisture, nutrients, and light (Horvath et al., 2023; Kuar et al., 2024). This competition not only decreases crop harvests (Boutagayout et al., 2024) but also impacts biodiversity, disrupting ecosystem functioning (He et al., 2024). They are widely recognized as a primary constraint on agricultural productivity, contributing to an estimated 25–40% reduction in crop yields each year (Fahad et al., 2013). Broadly defined, a weed is any unwanted plant species that establishes itself within cultivated fields, where it competes with crops for essential resources such as light, water, nutrients, and space (Merfield, 2025). Various agronomic factors — including deep sowing, poor soil aeration, restricted light penetration, soil compaction, and nutrient deficiencies — often create environments conducive to weed proliferation while simultaneously weakening crop performance (Elmahdi, 2016).

Crops, predominantly cereals, are most vulnerable during their early phases of development to weed competition when fast weed establishment and destructive biomass accumulation outcompete young crop plants (Asghar and Kataoka, 2021). The level of yield damages caused by weeds varies extensively, ranging from 18-80%, depending on the crop species, population of weed, and the effectiveness of management strategies. Mean yield reductions attributable to weed infestations span between 20% and 76% across different cropping systems (Gharde et al., 2018; Asghar et al., 2024).

Traditional approaches of weed management rely primarily on agrochemicals (Shrestha et al., 2021). Global expenditures on crop protection products are projected to rise from \$70.47 billion in 2024 to \$75.3 billion in 2025, reflecting an estimated annual growth rate of 6.3% (Crop Protection Chemicals Global Market Report, 2025). This trend underscores the persistent reliance on chemical inputs as a principal strategy for safeguarding crop health and maintaining the stability of global food production systems. Notably, cereals and grain crops comprise approximately 47% of the total agrochemical market, highlighting the substantial dependence on chemical solutions to secure agricultural yields (Size, 2024). However, application of synthetic herbicides, have raised severe concerns (Varah et al., 2019; Schütte et al., 2017). These comprise contamination of ecosystem, developing resistance against herbicide (Islam et al., 2024), and influence aggressively non-target organisms such as pollinators and useful soil microorganisms (Ankit et al., 2021). Therefore, there is developing demand to investigate sustainable alternatives that can ensure agronomic productivity and maintain ecological balance.

Biological weed management has developed as a promising and environmentally friendly approach to confronting these challenges (Nayak et al., 2024). Biological weed management aligns with ecological agriculture by sustainably suppressing weeds through living organisms or their by-products, while preserving soil health, maintaining agro ecosystem functions, and reducing reliance on synthetic herbicides. By decreasing reliance on synthetic herbicides, it promotes the development of organic and low-input farming systems, lowers production costs, and mitigates environmental and human health risks (Benbrook et al., 2021; Kavva and Nisarga, 2025). This approach employs natural organisms—including weed-specific insects, pathogens, grazing animals, and allelopathic plants—to suppress or eliminate targeted weed species (Rakshit et al., 2021).

The significance of weed management research harnessing biological tools lies in its potential to address key agronomic constraints while supporting biodiversity conservation. Beyond weed suppression, this approach promotes onfarm biodiversity, augments soil physicochemical and biological properties, and strengthens climate resilience. Integrating biological weed management into broader weed control strategies aligns with global imperatives for resilient food systems and long-term food security (Sims et al., 2018). This analysis elucidates the mechanisms, and restrictions of biological weed management, emphasizing its potential to harmonize modern agronomic practices that sustain natural and agroecosystems.

MATERIALS AND METHODS

The research was anchored in a thorough and systematic sorting of synchronous scholarly literature (Afzal et al., 2024; Jonker & Pennink, 2010), combining peer-reviewed studies, technical reports, and evidence-based findings to explain advancements, mechanisms, and practical applications in biological weed management. Data were sourced from reputable and high-impact scholarly databases such as Google Scholar, PubMed, Science Direct, and Springer Link,

complemented by authoritative research reports, government documents, and proceedings from national and international scientific conferences.

Selected Keywords

include biological weed management, pathogen-mediated weed suppression, biocontrol agents for invasive species, allelopathic interactions in weed ecology, and integrated weed management frameworks were exploited to ameliorate the literature search and determine the recovery of high-relevance publications. Emphasis was placed on research outputs during the past fifteen years that provided rigorous empirical evidence, detailed mechanistic insights, and validated field-level applications of biological agents. Publications exhibiting methodological limitations, insufficient experimental proof, or incidental relevance to the scope of biological weed management were omitted to hold the scientific integrity and precision of the review. Key information, comprising targeted weed species, variety of biological agents, and economic practicability, was extracted and analyzed to determine tendency, status, and gaps in knowledge.

Outcome

The literature review delivered a comprehensive knowledge concerning effectiveness, restrictions, and forthcoming potential of biological weed management. The data generated was beneficial establishing basis for recommendations and further research opportunities. The data generated provided a robust basis for development of evidence-based recommendations, facilitating informed decision-making, and recognizing key research gaps to guide future research aimed at ameliorating precision, efficiency, and sustainability in the related field.

Introduction to Bioherbicides

Bioherbicides are biologically derived weed suppression agents originating from living organisms such as phytopathogenic fungi, rhizobacteria, and other beneficial microorganisms, which exert allelopathic or pathogenic bioactivity against targeted weed species. Numerous higher plants inherently biosynthesize a range of secondary metabolites, collectively known as allelochemicals, which function as autotoxic or allelopathic compounds by interfering with cellular metabolism, hormonal balance, and enzymatic pathways, thereby suppressing germination, growth, and competitive vigor of co-existing plant species within the rhizosphere niche. These mechanisms, often governed by quantitative and qualitative variations in allelochemical release, play a pivotal role in interactions in plants and can be harnessed strategically for sustainable and integrated weed management (IWM) within diversified cropping systems (Bailey, 2014). This ecologically compatible mechanism of action offers a sustainable strategy for weed suppression, ensuring the preservation of crop productivity, maintenance of soil physicochemical integrity, and enhancement of agroecosystem resilience and stability (Sherwani et al., 2015). A significant advantage of bioherbicides is their inherent biodegradability, resulting in low environmental persistence and making them highly suitable for ecologically sensitive production systems, such as organic farming, precision agriculture, peri-urban horticulture, and riparian buffer zones, where minimizing synthetic chemical inputs is imperative. Upon application, these agents undergo rapid microbial degradation within the soil matrix, ensuring no accumulation of phytotoxic residues in the soil profile, surface water, or atmospheric environment, thereby maintaining ecological safety and agroecosystem integrity (Raza et al., 2025). (Figure 1)

However, bioherbicides typically exhibit a slower mode of action than synthetic herbicides and may require multiple applications across phenological stages to achieve threshold-level weed suppression (Marrone, 2024). Despite these constraints, bioherbicides exhibit strong potential as integral components of Integrated Weed Management (IWM) frameworks, where they can be combined with cultural, mechanical, and chemical tactics to improve weed control while maintaining soil microbiome diversity and increasing agroecological resilience (Raju, 2025). Evolving the utility of bioherbicides in modern agronomic systems imposes genotypic screening of weeds for susceptibility, formulation optimization, and multi-locational field trials to confirm reliability of performance under different edaphic and climatic conditions (Pathak et al., 2019). With continued improvement, bioherbicides can serve as a foundation of climate-smart, sustainable crop production systems, aligning with universal aims for reduced pesticide dependency and improved agro-biodiversity conservation.

Understanding the Physiological Impact of Bioherbicides on Weeds for Integrated Weed Management

Weed management remains a major challenge in crop production systems (Kavya and Nisarga, 2025; Nath et al., 2024). Integrated weed management (IWM) strategies incorporating bioherbicides are becoming prominent as environmentally sustainable alternatives to chemical herbicides. Bioherbicides—typically derived from plant extracts, allelochemicals, or beneficial microorganisms—offer potential for controlling weed populations by disrupting key physiological processes in target species. Synthetic herbicides that eradicate weeds through chemical toxicity, but

bioherbicides inhibit them by interfering with physiological processes, including nutrient assimilation, photosynthesis, respiration, and hormonal regulation (Triolet et al., 2020). Despite escalating research interest, the discipline of specific physiological responses of weeds to bioherbicidal agents has not been addressed sufficient (Becerra-Alvarez et al., 2025). Plant-derived extracts can be absorbed by weed seeds, where they disrupt essential cellular processes. These effects include disruption of cell membranes, inhibition of mitosis, and suppression of amylase activity, DNA damage, and interference with various biochemical pathways. Such disruptions often delay or completely inhibit seed germination (Hassan et al., 2022). Furthermore, weed growth is primarily suppressed through reduced root cell division leading to decreased nutrient uptake, inhibition of chlorophyll synthesis, and altered manufacture of plant hormones essential for normal development (Raza et al., 2025). Exposure to these compounds also induces the accumulation of reactive oxygen species (ROS) and stress-related hormones, thereby disrupting the plant's normal antioxidant defense mechanisms (Gill, S.S. and Tuteja, 2010).

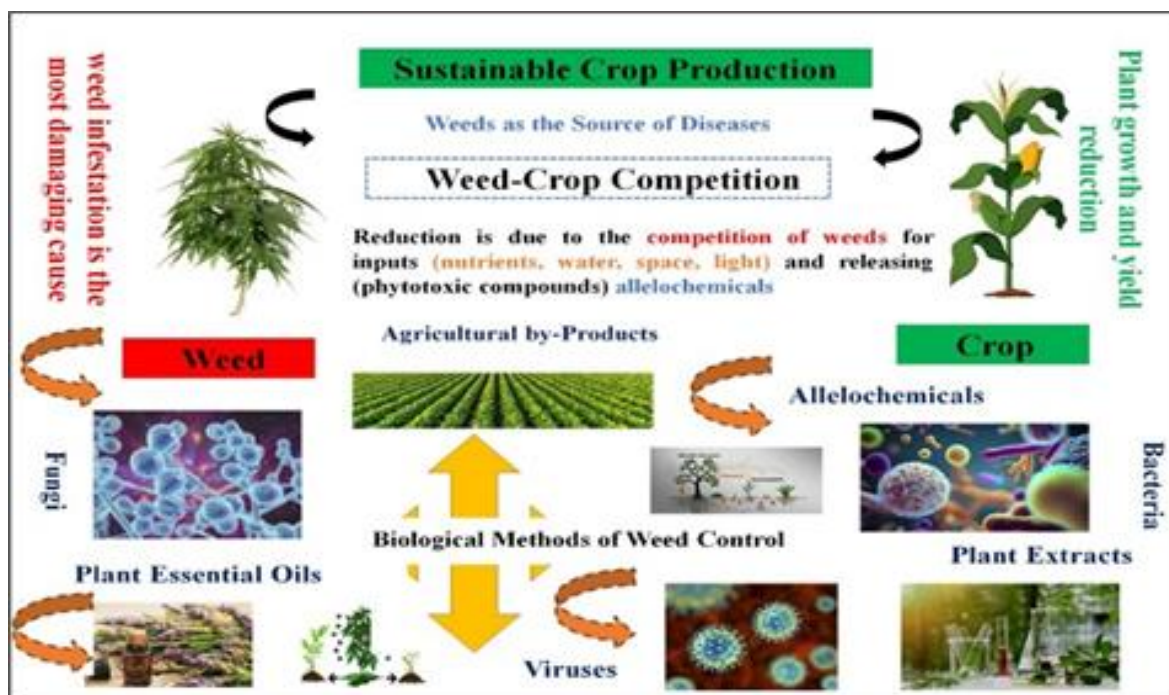


Figure 1. Schematic overview showing how bioherbicides fit into integrated weed management, and the different ways they act on weeds (Islam et al., 2024).

Microbial bioherbicides control weeds through varied yet comparably detrimental mechanisms, such as inducing pathogenic infections, impairing physiological functions, and disrupting growth processes critical to weed persistence (Arya and Pandey, 2024). These microbes colonize intercellular spaces, penetrating deeper tissues such as the root cortex, where they release toxins that disrupt cell division and impair normal physiological functions (Bordin et al., 2021). In some cases, microbial metabolites trigger disease symptoms such as necrosis and chlorosis, further suppressing weed growth by reducing photosynthetic capacity, inhibiting gibberellin activity, and elevating levels of reactive oxygen species (ROS), abscisic acid, and ethylene (Roberts et al., 2022). Understanding these mechanisms is crucial for enhancing the efficacy of bioherbicides as vital tools within integrated weed management systems, ultimately supporting sustainable crop production.

Categories of Bioherbicides

Bioherbicides are increasingly recognized as essential components of integrated weed management (IWM) strategies (Islam et al., 2024). Derived from diverse biological sources—such as fungi, bacteria, and plant-based compounds—they exhibit a wide spectrum of modes of action and application techniques (Cheng et al., 2022). By offering an environmentally sustainable alternative to synthetic herbicides, bioherbicides help mitigate ecological risks and promote the balance and resilience of agroecosystems (Hasan et al., 2021).

While their efficacy varies with weed species, environmental factors, and application methods, bioherbicides play a significant role in advancing sustainable weed management (Duke et al., 2022). They align with the principles of

sustainable agriculture by minimizing chemical residues, preserving soil health, and enhancing biodiversity (Srimathi, 2024).

The following sections outline the major categories of bioherbicides, emphasizing their mechanisms of action, efficacy, and potential roles in advancing weed management within contemporary agronomic practices.

1. Microbial bioherbicides

Microbial bioherbicides employ living organisms—such as specific strains of fungi, bacteria, or viruses—that suppress weed growth through a variety of mechanisms (Harding and Raizada, 2015; Boyette and Hoagland, 2015; Gu et al., 2023). These beneficial microbes can directly inhibit weed development or induce pathogenic effects, ultimately reducing weed populations. Microbial bioherbicides effectively target weeds throughout their growth cycle, disrupting vital physiological functions. This multifaceted action underscores their promising role in developing sustainable and environmentally responsible weed management strategies (Triolet et al., 2020; Cheng et al., 2022).

A major advantage of microbial bioherbicides is their relatively lower research and development costs compared to synthetic herbicides, positioning them as a cost-effective and accessible option for weed control in agronomic systems. Moreover, while herbicide-resistant weed populations is emerging continuously commonly, there are no documented cases of resistance developing against microbial bioherbicides (Duke, 2024). This is primarily due to the complex and multifaceted biological interactions mechanisms, which make resistance development slow compared to chemical-based herbicides.

A prominent example of microbial bioherbicide application is in Africa, where a commercially existing mycoherbicide, developed through targeted laboratory selection, is used successfully to control the parasitic weed *Striga hermonthica*. This weed poses a significant menace to cereal crops such as sorghum, maize, and millet, and the mycoherbicide represents a sustainable, environmentally friendly alternative to synthetic herbicides (Duke, 2024).

2. Plant extract bioherbicides

Plant extract-based bioherbicides are derivative from specific plant parts such as leaves, roots, or seeds and comprise compounds with characteristic herbicidal properties. These bioherbicides leverage bioactive plant constituents to interfere with weed metabolism, disrupt development, and prevent growth. Prominent examples consist of extracts from neem, clove, cinnamon, parthenium weed, and vinegar, all of which have demonstrated strong herbicidal activity in several studies (Chakraborty and Ray, 2021; Bashar et al., 2022).

A well-documented example is the exploitation of extracts from *Sorghum bicolor*. These extracts possess phytotoxic ability and suppress weed populations without negatively impacting crop yields (Dayan et al., 2009). Finding of work conducted confirmed that sorghum water extracts decreased the biomass of *Echinochloa crus-galli* by up to 40%, which corresponded to an 18% proliferation in rice yield (Weston et al., 2013). Such discoveries underscore the practical potential of plant extract bioherbicides as biologically friendly tools within integrated weed management (IWM) strategies.

3. Biocontrol agents

Certain stubborn weed species often survive conventional herbicide treatments by quickly developing genetic resistance over time (Pedroso and Moretti 2025). This resistance reduces efficiency of herbicide, complicating weed control and threatening crop productivity. This highlights a foremost disadvantage of exclusively be dependent on on herbicides to control weeds (Ulas et al., 2025). In contrast, biological control delivers a different and appreciated approach. This strategy employs living organisms—such as insects, nematodes, or fungi—to manage weeds naturally. These biological agents function as the natural enemies of weeds, either by directly feeding on them or by disrupting their growth and reproductive cycles (Khan et al., 2025). These biological controls utilize diverse modes of action, reducing the prospect of resistance development and encouraging more sustainable, long-term weed management in farming systems (Villavicencio-Vásquez et al., 2025).

Biocontrol methods are predominantly effective for management of hostile or aggressive weeds and are valuable especially in natural ecosystems where chemical interventions may not be applicable or environmentally sustainable (Schwarzländer et al., 2018; Neal, 2024). Likewise, biocontrol agents offer a dynamic and durable solution; as the target weed population increases, the population of biocontrol agents frequently increases in parallel, exerting constant and sustained pressure to suppress weed proliferation over time.

4. Seed-based bioherbicides

During the critical phases of crop germination and growth during early stage, seed-based bioherbicides offer a targeted approach for weed management. These bioherbicides consist of crop seed treatments with specific biological agents or natural compounds prior to sowing (Radhakrishnan et al., 2018). The treatment reliefs shelter developing seedlings

by decreasing competition from adjacent weed flora, thereby enabling better crop establishment and primary vigor (Schwarzländer et al., 2018). Seed-based bioherbicides are expected to play progressively noteworthy role in sustainable weed management practices, and in the conservation of natural ecosystems (Irshad and Cheema, 2004). As component of the wider category of bioherbicides, seed-based applications underscore the usefulness and eco-friendly nature of biological weed control strategies. These procedures harness natural organisms or bioactive compounds with diverse modes of action, ranging from inhibition of weed seed germination to suppression of early weed development. Careful selection of bioherbicides agents and following accurate application protocol are indispensable, taking into account weed species, cropping pattern, and environmental circumstances for optimum and sustainable consequences.

5. Allelochemicals as natural bioherbicides

Allelochemicals have attracted attention as an ecologically friendly and sustainable alternative to synthetic herbicides for controlling weeds. Scientists have documented numerous allelochemicals with established bioherbicidal properties. These compounds have exposed the potential to suppress broad range of weeds efficiently, comprising together broad and narrow leaved species. Their targeted action makes them an excellent preference for weed control in crop husbandry and environmental conservation, offering solutions that are not only effective but also safer for ecosystems. One of the key advantage of allelochemicals is their natural origin, which means they are typically less damaging to non-target organisms and contribute to decreasing chemical residues in the environment. With ongoing research and development, there is great potential to evolve original bioherbicides based on these compounds. Such novelties could lead to more effective, safe, and cost-efficient weed management tools, ultimately supporting the objectives of sustainable agriculture and integrated weed control strategies (Soltys et al., 2013).

Examples of Allelochemicals for Sustainable Weed Control: Composition, Sources, and Targets:

Several natural compounds derived from plants reveal bioherbicidal properties and have been recognized for their potential usage in weed management. Avenacin A-1, a triterpenoid saponin extracted from oats (*Avena sativa*), has revealed inhibitory effects on many broadleaves weed species (Mugford and Osbourn, 2012). Juglone, chemically known as 5-hydroxy-1,4-naphthoquinone, is a well-known allelochemical created by black walnut trees (*Juglans nigra*) and is active against a extensive range of weed species (Liu, et al., 2022). Likewise, coumarins, specifically 2H-1-benzopyran-2-one, produced from mulberry (*Morus alba*), reveal herbicidal potential against many weeds (Khamare et al., 2022). Another potent compound, sorgoleone (2-hydroxy-5-methoxy-3-alkyl-1,4-benzoquinone), is sourced from sorghum (*Sorghum bicolor*) roots and is known to suppress the development of both narrow and broadleaf weeds (Jesudas et al., 2014). Also, caffeic acid (3,4-dihydroxy-cinnamic acid), produced from *Parthenium hysterophorus*, has revealed effectiveness in controlling specific grassy weeds such as crabgrass and goose grass (Bashar et al., 2022). Phenethyl mustard oil (2-phenylethyl isothiocyanate), derived from mustard plants, also shows wide-spectrum herbicidal activity against various weeds (Petersen et al., 2001). Catechin, a flavonoid [(2R,3S)-2-(3,4-dihydroxyphenyl)-3,4-dihydro-2H-chromene-3,5,7-triol], derived from a range of plant species, has been particularly effective against broadleaf weeds (Inderjit et al., 2008). Lastly, eucalyptol (1,8-cineole or 1,3,3-trimethyl-2-oxabicyclo [2.2.2] octane), originally derived from eucalyptus trees, has been branded for its phytotoxic effects on several weed species (Puig et al., 2019).

6. Essential oils for eco-friendly weed control

Essential oils (EOs) are natural, volatile phytochemicals extracted from different plant organs, including vegetation, inflorescences, fruits, seeds, bark, roots, and sporadically whole plants (Almarie, 2022). In weed science, EOs are documented for their prospective in developing eco-friendly bioherbicidal formulations, aligning with the principles of sustainable and climate-smart agronomy (Almarie et al., 2016; Subramanian, 2025). Gas chromatography–mass spectrometry (GC–MS) profiling is routinely employed to explain the chemical composition of EOs, with eucalyptol (65.1%) and α -pinene (15.3%) frequently recognized as dominant allelochemicals in numerous species (Wesołowska et al., 2019). As described by Ali et al. (2015), EOs are chiefly enriched with terpenoids—particularly monoterpenes and sesquiterpenes—that reveal phytotoxicity, disrupting germination, seedling vigor, and competitive growth of a broad spectrum of weed taxa. These bioactive properties underscore their importance as potential allelopathic agents for integration into sustainable weed management strategies and precision agronomic systems.

The phytotoxic properties of essential oils are expressed through multiple physiological and biochemical disorders within plants. These embrace leaf burn, chlorosis, inhibition of mitosis, stunted growth, chlorophyll degradation, membrane depolarization, suppression of cellular respiration, and oxidative damage (Hassan et al., 2021). Verdeguer et al. (2012) documented essential oils derived from *Cistus ladanifer* L. inhibited the germination and growth of several

weed species effectively, including *Portulaca oleracea* L., *Amaranthus hybridus*, *Coryza canadensis*, *Chenopodium album*, and *Parietaria judaica* L. (Hassan et al., 2021). These findings highlight the potential of essential oils as environment friendly alternatives for weed management.

The Promise of Bioherbicides in Integrated Weed Management

Bioherbicides, sourced from natural sources fungi and plants, deliver clear benefits over synthetic herbicides. Consequently, bioherbicides are emerging as a promising alternative to traditional chemical herbicides in sustainable farming because of their various benefits. Derived from natural materials, they support minimize the usage of injurious chemicals by decreasing reliance on chemicals and supporting biodiversity, making them a promising tool for sustainable crop husbandry and optimistic in preserving biodiversity and defending ecosystems (Hasan et al., 2021; Stefanski et al., 2020). Their selective mode of action agrees for accurate control of definite weed species, circumventing the buildup of toxic residues and conserving soil and water quality (Pacanoski 2015). Bioherbicides present minimal risks to human health and non-target organisms, in contrast to conventional herbicides. Their natural degradation into non-toxic compounds avoids environmental contamination and contributes to the fortification of soil and water resources (Pacanoski 2015). Moreover, with the increasing challenge of herbicide-resistant weeds, bioherbicides offer effective alternatives and can be integrated with other management practices—such as crop rotation and tillage—to improve overall weed control (Hasan et al., 2021; Pacanoski 2015). The use of bioherbicides represents a shift toward more sustainable and environmentally friendly farming practices, underscoring their potential to advance eco-friendly crop production in the future (Cordeau et al., 2016).

CONCLUSION

Among the diverse bioherbicides studied in this work, those derived from plant essential oils (EOs) stand out due to their potent phytotoxic properties and ecological benefits. Research has confirmed that EOs offer a highly viable and sustainable alternative to synthetic herbicides for effective weed management. Their natural origin, environmental safety, selective and targeted mode of action, and excellent compatibility with integrated weed management systems make essential oil-based bioherbicides particularly promising tools for advancing sustainable agriculture. Continued research and development efforts are crucial to optimize the efficacy, formulation, and commercial scalability of EO-based bioherbicides. By embracing these natural and effective solutions, the agricultural sector can move closer to achieving environmentally responsible, productive, and sustainable crop production systems.

AUTHOR'S CONTRIBUTION

The authors worked as team in the study. Nadeem Ahmad, providing essential technical support, resources, and valuable input to the discussion and granted the final approval of the submitted version. Amir Afzal led the conceptualization, supervision, and overall project administration, undertook the primary responsibility for manuscript preparation. Sairah Syed was engaged in data collection and developed the initial draft of the methodology section. Taimoor Hussain carried out the data analyses and contributed to the interpretation of results. Khalida Hamid Abbasi supported the work through an extensive literature review and validation of the generated data, whereas Muhammad Farooq Ahmad assisted in the accurate recording of data. Arsalan Wasif contributed to the structured presentation of results, and Wardah Muzzafar provided critical support in refining the manuscript through editing, formatting, and referencing.

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AVAILABILITY OF DATA AND MATERIAL

The datasets supporting this study are included in the article. Extended methodological details and raw data can be accessed by contacting the corresponding author, subject to ethical and institutional guidelines.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study did not involve human subjects or animal models. In accordance with institutional guidelines, ethical approval and informed consent requirements were formally waived for this research.

CONSENT FOR PUBLICATION

I, the undersigned, consent to the publication of my identifiable information.

CONFLICT OF INTERESTS

The authors declare there is no conflict of interest.

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