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Review Article
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Allelochemicals as bioherbicides: Physiological mechanisms, resistance profiles, and commercial prospects

Norazua Zakaria[1,*], Afiq Aiman Saharudin[1], Mst. Motmainna[2], Mahmudul Hasan[3,*]

[1] Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[2] Laboratory of Climate-Smart Food Crop Production, Institute of Tropical Agriculture and Food Security, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[3] Institute of Plantation Studies, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

* Corresponding author: norazua@upm.edu.my; mdmahmudul@upm.edu.my

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Abstract: Weeds pose a serious threat to crops, causing greater yield losses than any other pest. Synthetic herbicides are potential tools for weed management, but their increasing and often indiscriminate use has caused human health problems, environmental pollution, herbicide resistance, and so on. Allelopathy-based bioherbicides offer more sustainable alternatives to synthetic herbicides for weed management that could be integrated into weed management strategies to reduce herbicide reliance. This systematic review, guided by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), aimed to synthesize current evidence on allelochemicals and their potential for bioherbicide development. A comprehensive search of Web of Science, Scopus, PubMed, and Google Scholar identified 112 studies meeting the inclusion criteria. The review covers synthetic herbicides for weed control, allelochemicals, bioherbicides development, currently available bioherbicides in the market and their impact on weed control and physiology, and potential factors influencing allelochemical efficacy. Allelochemicals impair weed growth through reduced nutrient uptake, reduced pigment synthesis, and alterations in stress-related hormones and reactive oxygen species accumulation. Several allelopathic species and their potential allelochemicals are highlighted as promising candidates for bioherbicide development, though variability in field efficacy and limited large-scale validation remain key limitations. Future research should focus on standardizing extraction and application methods and validating efficacy under field conditions. Clarifying the gene regulatory mechanisms underlying allelochemical biosynthesis and release will also be an important direction for future work. Overall, allelopathy-based bioherbicides represent a promising, sustainable tool for integrated weed management, though further mechanistic and applied research is needed before commercial adoption.

Keywords: allelochemicals, bioherbicides, efficacy, mode of action, sustainable agriculture

1. Introduction

Weed management is a crucial aspect of agriculture, landscaping, and ecosystem conservation, often relying on synthetic herbicides that raise concerns about environmental and human health impacts. Globally, total pesticide use in agriculture is 2.7 million tonnes of active ingredients (FAOSTAT, 2022). Yield losses due to weeds vary widely, depending on factors such as weed

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species, density, and management practices. Studies have reported rice yield reductions ranging from 5% to 82% due to weed competition (Rahman et al., 2017). For instance, losses attributed to grasses like *Echinochloa crus-galli* (L.) P. Beauv is estimated at 80%, while broad-leaved weeds account for 28% and sedges 10% (Garg et al., 2019). There have been reports of about 1800 weed species causing an annual economic loss of US$ 32 billion worldwide (Das et al., 2024).

Using herbicides to control weeds has long yielded benefits; however, the extended, heavy, and careless application creates problems, as it negatively impacts soil biodiversity, agricultural sustainability, and food safety (Hasan et al., 2023). Excessive dependence on chemical herbicides can harm the environment and promote the development of herbicide-resistant weeds, ultimately threatening the sustainability of agricultural production. Recently, there has been growing interest in developing bioherbicides from plant allelochemicals, which offer a natural alternative to synthetic herbicides to minimize their harmful impacts (Motmainna et al., 2023).

Although several reviews have discussed allelopathy, allelochemicals, and their potential applications in weed management, most have focused mainly on the ecological functions of allelopathy, mechanisms of allelochemical action, or specific groups of natural compounds. Comprehensive evaluation integrating allelochemical discovery, physiological mechanisms, identification approaches, formulation strategies, commercialization challenges, and prospects remains limited. In sustainable agriculture, bioherbicides offer the greatest opportunity for managing herbicide-resistant weed species and reducing reliance on synthetic herbicides; their use is becoming more popular, not as a full replacement for synthetic herbicides, but as a green alternative for sustainable weed control. Building on this rationale, this review provides a broader perspective by critically examining the transition of allelochemicals from natural plant defense compounds to practical bioherbicide candidates, exploring their ecological functions, mechanisms of action, identification approaches, and the biological, technical, economic and regulatory challenges affecting their practical application and commercialization.

2. Methodology

To ensure a comprehensive, transparent, and reproducible evaluation of the literature, this review adopted a Systematic Review approach guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines (Page et al., 2021) (Figure 1).

2.1 Search strategy and information sources

A comprehensive search was performed across primary electronic databases, including Web of Science, Scopus, PubMed, and Google Scholar, with the search executed in April 2026. For Google Scholar, the first 200 most relevant records retrieved using the predefined search terms were screened based on title and abstract relevance, following the recommendation that Google Scholar searches should focus on the most relevant ranked results due to its broad coverage and variable indexing. Records identified from Google Scholar were screened using the same inclusion and exclusion criteria applied to other databases, and eligible studies were considered for full-text assessment. The literature search targeted studies focusing on plant allelochemicals, bioherbicides, mode of action, and weed resistance. The search strategy utilized combinations of Boolean operators (AND, OR) with the following key terms: ("allelochemicals" OR "allelopathy") AND ("bioherbicide" OR "bio-based weed management") AND ("mode of action" OR "physiological mechanism") AND ("phytotoxicity" OR "weed suppression") AND ("herbicide resistance" OR "HRAC classification") AND ("sustainable agriculture").

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The review primarily considered peer-reviewed articles published between 2000 and 2026, covering the most relevant and recent advances in allelopathy, allelochemical characterization, and bioherbicide development.

2.2 Inclusion and exclusion criteria

The inclusion criteria were: (i) studies reporting allelochemicals with herbicidal or allelopathic activity; (ii) investigations describing mechanisms of action, physiological effects, efficacy, formulation, or commercialization of bioherbicides; (iii) studies addressing herbicide resistance and the potential role of allelochemicals in weed management; and (iv) peer-reviewed journal articles, books, and book chapters published in English. Exclusion criteria included conference abstracts lacking full-text availability, duplicate records, non-English publications, and studies not directly related to allelochemicals or bioherbicide development.

After database searching, duplicate records were removed. The remaining articles were screened based on title and abstract relevance. Full texts of potentially relevant publications were then assessed for eligibility according to the predefined criteria. Studies meeting the eligibility requirements were included in the final review and were synthesized according to themes including herbicide mechanisms, weed resistance, allelochemical sources, bioherbicide development, physiological responses, and factors affecting allelochemical production and efficacy.

2.3 Screening, eligibility, and data extraction

Articles identified through the database searches were manually compiled, and duplicate records were removed. Titles and abstracts were screened to assess relevance based on the predefined inclusion and exclusion criteria. Key data extracted included allelochemical identity, plant source, target weed species, physiological mode of action, and commercialization status. Disagreements regarding inclusion were resolved through mutual discussion and consensus among all authors.

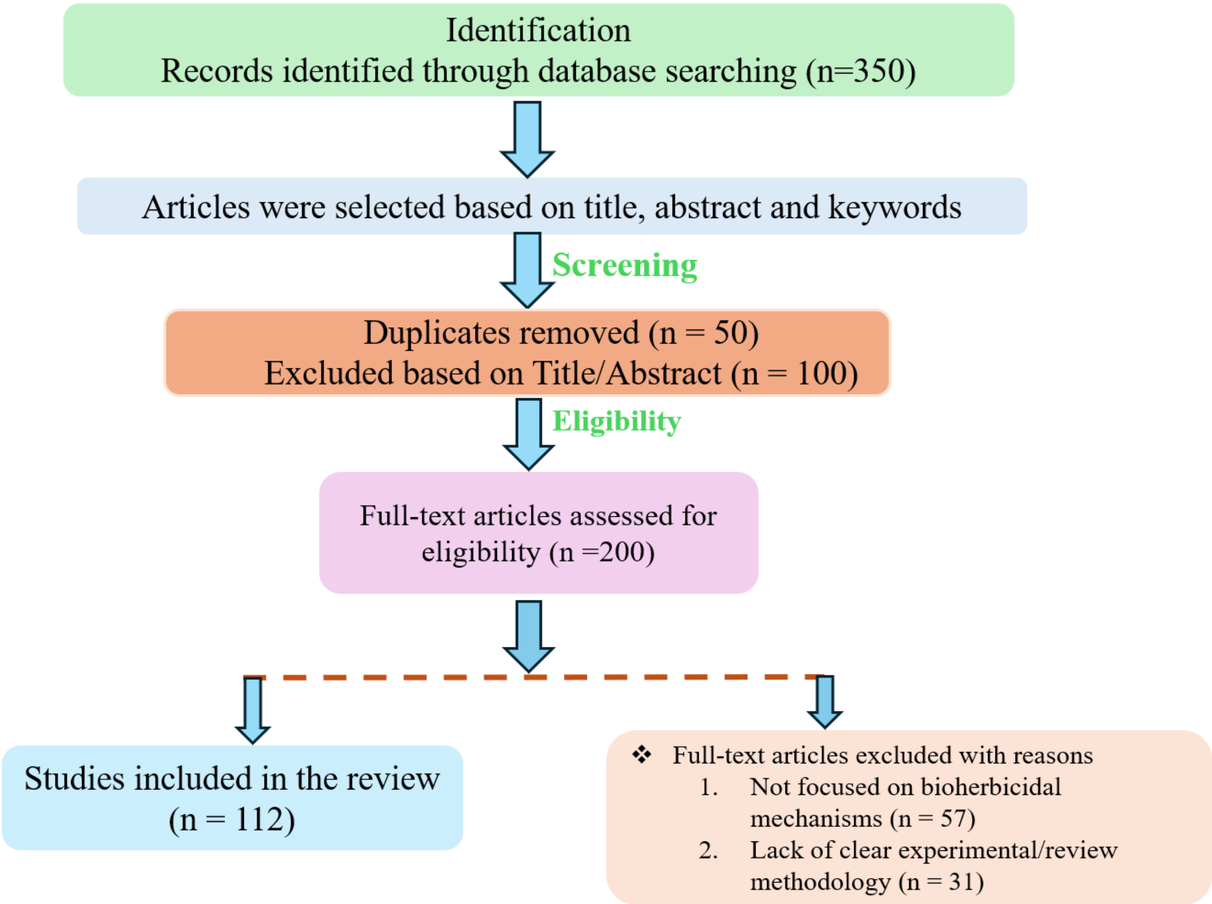

Figure 1. A PRISMA-based flow diagram.

3. Mechanisms and Injury Symptoms of Major Herbicides

Herbicides have become indispensable in agricultural practices over the past century, playing a crucial role in enhancing crop productivity to meet the demands of a growing global population. Currently, herbicides account for approximately 47.5% of total pesticide usage worldwide (FAOSTAT, 2022), with nearly 2,000 compounds developed for diverse agroecosystems. Herbicides are applied either to the soil before weed emergence (pre-emergence application) or directly to the foliage of emerged weeds (post-emergence application), depending on the target species' growth stage. The availability of diverse herbicide groups enables selective weed control with minimal impact on crop plants (Motmainna et al., 2025a).

In Malaysia, approximately 80% of the pesticides used were herbicides. FAOSTAT (2022) reports that, in Malaysia, herbicide active ingredients were used in approximately 34,084 and 56,430 tonnes in 2006 and 2016, respectively. Because of monoculture production, rubber, rice, and oil palm are the main crops that rely heavily on herbicides. While propanil, 2,4-D, quinclorac, bensulfuron, cyhalofop-butyl, and pyrazosulfuron are widely used in rice fields, active chemicals such as glyphosate, glufosinate, triclopyr, metsulfuron, and fluazifop are frequently employed in oil palm and rubber plantations (Casimero et al., 2023). Table 1 presents herbicide classification by mode of action and common injury symptoms.

While this mode of action framework is a standard tool for classifying herbicides, relying on it for field diagnosis has its limits. Visually, different chemical classes often produce identical damage. For example, both photosystem II inhibitors and pigment-synthesis inhibitors can cause chlorosis and necrosis. Furthermore, most of the mechanism data in Table 1 come from controlled, single-active-ingredient lab studies. How reliably these symptoms appear in real-world fields, where weeds routinely face herbicide mixtures, sublethal doses, and environmental stress, presents a significant challenge for field diagnosis.

4. Weed Resistance Profiles and HRAC Classification

Herbicide resistance is the innate capacity of specific weed biotypes within a population to withstand a herbicide treatment that would, in ordinary circumstances, efficiently control that weed population. Herbicide-resistant weeds have evolved due to the extensive, ongoing use of the same herbicides. Herbicide-resistant weeds and their modes of action are presented in Table 2. Consequently, the prevailing view is that weeds evolve resistance to herbicides. This mutation typically results in a change in plant metabolism or in a gene that imparts resistance to a specific herbicide or to a class of herbicides with similar modes of action.

Although Table 2 reflects the broad scope of herbicide resistance across HRAC groups, the supporting evidence is unevenly distributed. Resistance reporting heavily favours high-intensity crops such as rice, offering limited insight into other agroecosystems. Moreover, while Table 2 primarily summarises single herbicide resistance, field biotypes increasingly exhibit multiple resistances across several distinct modes of action. Consequently, how well this data represents the true evolutionary dynamics of resistant weed populations worldwide remains uncertain.

5. Allelopathy in Weed Management

5.1 Allelopathy and allelochemicals

Allelopathy refers to chemical interactions among living organisms in an ecosystem. Allelopathy is the mechanism by which a plant influences the inhibition or stimulation of surrounding plants through the release of secondary metabolites known as allelochemicals (Schulz & Tabaglio, 2024; Motmainna et al., 2021a). Allelochemicals are created by a living being that, when released into the environment, affects the physiology of other species. Microbes produce allelochemicals during decomposition, and plants produce them as secondary metabolites. In plants, allelochemicals can be found in leaves, stems, flowers, fruits, seeds, and roots. These compounds are released into the environment through several pathways (Figure 2), including volatilization, leaching, root exudation, residue decomposition, and guttation/injury exudate (Shadab et al., 2026; Motmainna et al., 2021b). Plants release volatile organic compounds into the air that impact surrounding plants or deter herbivores. Allelochemicals are washed off plant surfaces into the soil by irrigation, rain, or dew, potentially affecting seed germination and plant growth. Additionally, allelochemicals are directly introduced into the soil via root exudation and can influence surrounding plants and the soil environment. During decomposition, decaying plant material releases allelochemicals that can affect the soil nutrient cycle and microbial communities. Allelochemicals are released from plant fluids or wounds that may affect the surrounding plants and environment. These pathways focus on the significant strategies by which plants and microorganisms use allelochemicals to mediate ecological interactions (Kong et al., 2024; Xie et al., 2021).

Despite clear documentation of individual release pathways, such as volatilization, root exudation, and leaching, their relative impacts in situ are rarely quantified. Few studies quantify how much each pathway actually contributes under real field conditions. Most evidence is based on controlled experiments that isolate one mechanism at a time. In natural environments, however, these pathways operate simultaneously and continuously interact with soil chemistry and microbes, making it difficult to determine which mechanism drives the observed allelopathic effects.

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Table 1. Herbicides classification based on mode of action with common injury symptoms.

Herbicides	Mode of action	Inhibition/ Disruption	Symptoms	References
Cyhalofop-butyl, Diclofop, Fenoxaprop, Quizalofop-P, Clethodim, Sethoxydim	Acetyl CoA carboxylase (ACC) inhibitors	Fatty acid synthesis	Leaf yellowing, growth cessation, and necrosis	Takano et al., 2020
Imazapyr, Imazapic, Imazethapyr, Pyrithiobac, Flucarbazonesodum, Bensulfuron, Mesosulfuron, Metsulfuron, Diclosulam, Metsulfuron-methyl + chlorimuron-ethyl	Acetolactate (ALS) synthase inhibitors	Branched-chain amino acid biosynthesis	Stunted growth, chlorosis, purpling, and necrosis	Motmainna et al., 2025b
Benefin, Ethalfluralin, Pendimethalin, Prodiamine, Trifuralin, Dithiopyr, Thiazopyr	Microtubule assembly inhibitors	Disruption of mitosis by inhibiting spindle formation	Swollen root tips, inhibition of root elongation, and abnormal seedling development	Lickfeldt et al., 2019
2,4-D, MCPA, Dichlorprop, MCPB, Dicamba, Picloram, Clopyralid, Triclopyr, Quinclorac	Synthetic auxins	Hormonal disruption of growth regulation	Twisting (epinasty), stem swelling, leaf cupping, callus formation, and tissue necrosis	Grossmann, 2010
Atrazine, Ametryn, Bentazon Propanil, Diuron, Bromoxynil, Ioxynil, Simazine, Metribuzin	Photosynthetic inhibitors at Photosystem II Site	Disruption of electron transport, ROS formation, membrane destruction	Interveinal chlorosis, leaf desiccation, and necrosis	Battaglino et al., 2021
Butylate, EPTC, Thiobencarb, Cycloate, Pebulate, Prosulfocarb, Molinate, Triallate, Vernolate	Lipid synthesis inhibitors	Membrane lipid biosynthesis	Inhibition of shoot and root development, malform seedlings, and failure to emerge	Gronwald, 1991
Glyphosate	EPSP (5-enolypyruvylshikimate-3-phosphate), Synthase Inhibitors	Aromatic amino acid biosynthesis	Gradual yellowing and wilting, especially in actively growing tissues	Hasan et al., 2024a
Glufosinate	Glutamine-synthesis inhibitors	Nitrogen metabolism and ammonia detoxification	Rapid chlorosis (yellowing), tissue necrosis, and plant desiccation	Takano & Dayan, 2020
Amitrole, Norflurazon, Clomazone	Carotenoid biosynthesis inhibitors/pigment synthesis inhibitors	Pigment production, bleaching and oxidative damage	Leaf bleaching (white/yellow tissue) starting from new growth; necrosis	Sandmann, 2002
Diquat, Paraquat, Acifluorfen, Fomesafen, Lactofen, Flumiclorac, Oxadiazon	Cell membrane disruptors or PPO inhibitors	ROS-mediated lipid peroxidation and cell membrane destruction	Rapid leaf spotting, bronzing, wilting, and necrosis	Barker et al., 2023

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Table 2. Herbicide-resistant weeds and mode of action.

Resistant weeds	Active Ingredient	Mode of Action	HRAC group	References
Eleusine indica (L.) Gaertn	Fluazifop-butyl Fenoxaprop-P-ethyl Fluazifop-P-butyl Haloxyfop-R-methyl Propaquizafop Quizalofop- P-tefury Haloxyfop-methyl Butroxydim	Inhibition of acetyl-CoA carboxylase	1	Deng et al., 2019
Leptochloa chinensis (L.) Nees.	Quizalofop-ethyl Fenoxaprop-ethyl Profoxydim			
Limnocharis flava (L.) Buchenau., *Sagittaria guayanensis* Kunth., *Bacopa rotundifolia* (Roxb.) Wettst., *Limnophila erecta* (Thunb.) Blume., *Monochoria vaginalis* (Burm.f.) C. B. Clarke	Bensulfuron-methyl	Inhibition of acetolactate synthase	2	Pan et al., 2025
B. rotundifolia, *L. erecta*	Pyrazosulfuron-ethyl			
B. rotundifolia, L. erecta, Clidemia hirta (L.) D. Don	Metsulfuron-methyl			
L. erecta	Cinosulfuron,			
Oryza sativa L. var. *sylvatica*	Imazapyr			
Oryza sativa L. var. *sylvatica*	Imazapic			
M. vaginalis, *Fimbristylis miliacea* (L.) Vahl., *E. crus-galli*	Bispyribac-sodium			
M. vaginalis, F. miliacea., E. crus-galli	Penoxsulam			
F. miliacea	Pyribenzoxim Pyrazosulfuronethy			
F. miliacea, Sphenoclea zeylanica Gaertn., *L. erecta, L. flava., S. zeylanica*	2,4-D	Auxin mimics	4	Todd et al., 2020
E. crus-galli	Quinclorac			
L. chinensis, *E. crus-galli*	Propanil	PSII inhibitors - serine 264 binders	5	Sahid et al., 2011

E. indica, Hedyotis verticillata (L.) Lam.	Glyphosate-isopropylammonium	Inhibition of enolpyruvyl shikimate phosphate synthase	9	Baek et al., 2021
E. indica	Glufosinate-ammonium	Inhibition of glutamine synthetase	10	Jalaludin et al., 2017
E. crus-galli	Pretilachlor	Inhibition of very long-chain fatty acid synthesis inhibitors	15	Busi et al., 2014
Conyza sumatrensis (Retz.) E. Walker., *H. verticillata*, *E. indica*	Paraquat	PS I electron diversion	22	Zobiole et al., 2019

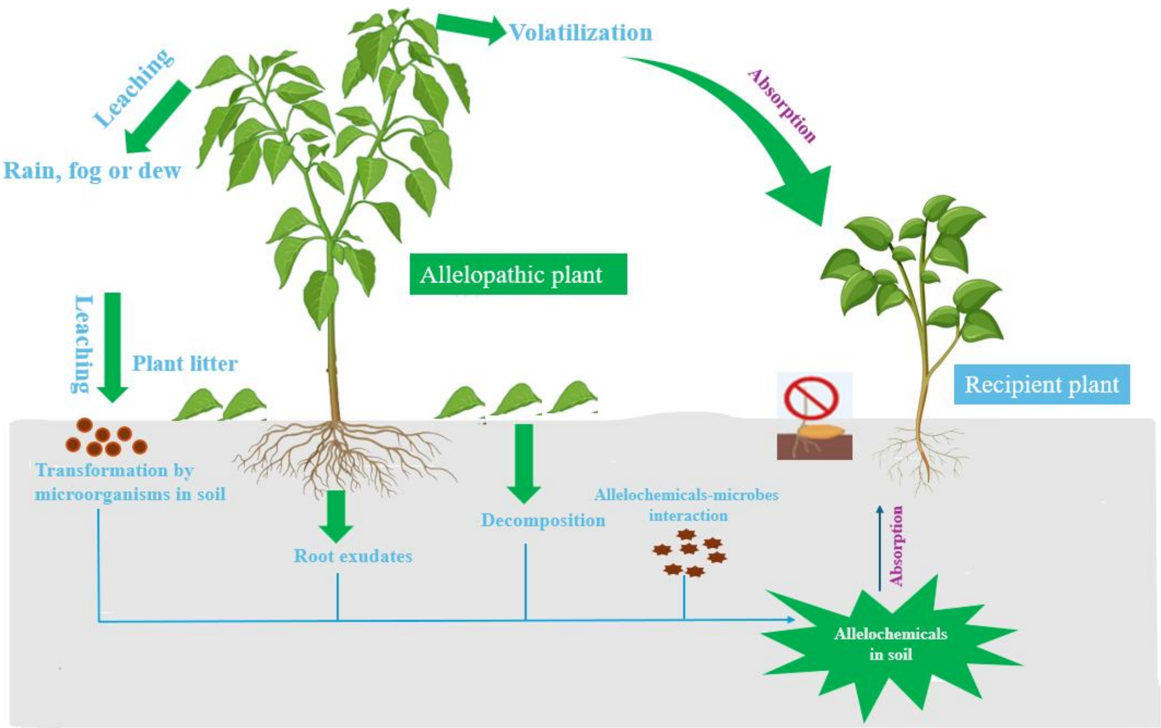

Figure 2. Release of allelochemicals.

5.2 Sources, structures, and activity of allelochemicals

Allelopathy is an important, environmentally benign means of eradicating weeds and safeguarding crops. Researchers are exploring how to use allelochemicals effectively in farming to protect the environment by controlling weeds in environmentally friendly ways and by developing new green agrochemicals (Arora et al., 2024; Hasan et al., 2024b; Motmainna et al., 2021c). Allelochemicals are often referred to as green compounds because of several advantages over synthetic herbicidal compounds. First of all, allelochemicals have a wide range of structures, making them good candidates as lead compounds for the development of new bioherbicides. Secondly, allelochemicals are typically water-soluble and non-halogenated, contributing to their environmental compatibility, application, and efficacy. Thirdly, unlike many synthetic herbicidal compounds, allelochemicals tend to have a shorter half-life, thereby reducing their persistence and potential environmental toxicity (Pantović, 2025; Kostina-Bednarz et al., 2023; Hickman et al., 2023; Macías et al., 2019). Several strategic approaches are necessary to identify herbicidal potential natural compounds, such as sourcing purified compounds, exploring previously untapped biological resources, and utilizing ethnobotanical knowledge to select potential compounds. Historically, from plant-based allelochemicals, a number of herbicides, such as cinmethylin, glufosinate, mesotrione, and dicamba have been developed (Nornasuha & Ismail, 2017). After appropriate validation, phytotoxic extracts can be effectively incorporated into integrated weed management systems. Moreover, chemical modification of allelochemicals can enhance their bioactivity against target weeds as well as maintaining key beneficial attributes. Table 3 represents the impact of allelochemicals on weed control.

A major limitation across the studies summarized in Table 3 is their reliance on purified compounds applied at concentrations far exceeding those naturally released by donor plants in the environment. Furthermore, experimental conditions vary considerably, ranging from simple Petri-dish germination assays to soil-based pot experiments. This methodological inconsistency complicates comparisons of compound efficacy and raises questions regarding the extent to which these findings translate to field-relevant concentrations under natural soil conditions. Moreover, because most studies focus on a limited number of model or crop species, the broader spectrum of activity, including potential effects on non-target and beneficial plant species, remains insufficiently understood.

5.3 Allelochemicals in bioherbicide development

Bioherbicides represent a promising alternative to traditional chemical herbicides, utilizing natural organisms or their derivatives to manage weeds. Figure 3 shows the schematic diagram of bioherbicide development, detailing the step-by-step process from initial plant discovery to the final commercial formulation. The process begins with selecting parts (leaves, stems, or roots) of an allelopathic plant, which undergo extraction and purification. The active compounds are subsequently identified through analytical techniques such as high-performance liquid chromatography (HPLC), liquid chromatography–mass spectrometry (LC-MS), and gas chromatography–mass spectrometry (GC-MS) to detect and characterize potential allelochemicals (Xie et al., 2021). These candidate compounds are then subjected to bioassays across laboratory, glasshouse, and field settings to evaluate their biological efficacy. Understanding their mode of action reveals that these allelochemicals induce the production of reactive oxygen species (ROS), triggering lipid peroxidation and biochemical pathways involving key enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). This oxidative stress leads to significant physiological suppression, including marked decreases in photosynthetic rate, stomatal conductance, transpiration rate, and chlorophyll pigment content, ultimately validating the formulation for large-scale bioherbicide production (Abbasi et al., 2026).

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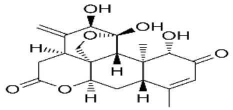
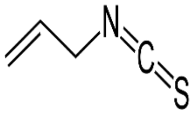
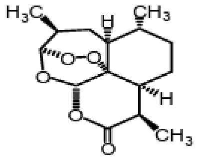
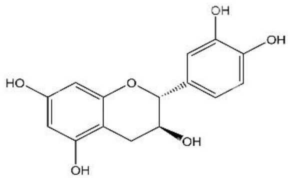
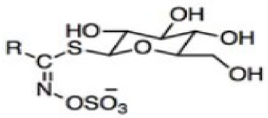
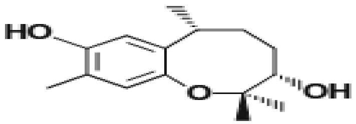
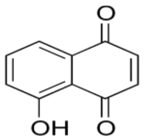
Table 3. Effects of allelochemicals on receiver species.

Allelochemical	Structure	Source	Sensitive species	References
Ailanthone		*Ailanthus altissima* (Mill.) Swingle	*Lepidium sativum* L., *Raphanus sativus* L., *Digitaria sanguinalis* (L.) Scop., *Portulaca oleracea* L., *Veronica persica* Poir., *Stellaria media* (L.) Vill., *Matricaria chamomilla* L., *Centaurea cyanus* L., *Achillea millefolium* L.	Caser et al., 2020
Allyl isothiocyanate		*Alliaria petiolata* (M.Bieb.) Cavara & Grande	*Cyperus esculentus* L., *Amaranthus palmeri* S.Watson,	Cipollini, 2016
Artemisinin		*Artemisia annua* L.	*Phalaris minor* Retz., *Panicum repens* L., *Silybum marianum* (L.) Gaertn. *D. sanguinalis*	Saad et al., 2013
Catechin		*Centaurea stoebe* Tausch	*Potentilla arguta* Pursh., *Centaurea maculosa* Lam., *Lycopersicon esculentum* Mill., *Gaillardia aristata* Pursh., *Arabidopsis thaliana* (L.) Heynh., *Ocimum basilicum* L.	Duke et al., 2009
Glucosinolates		*Brassica* spp.	*D. sanguinalis, A. palmeri*	Turk et al., 2003
Heliannuols		*Helianthus annuus* L.	*Sida spinosa* L., *D. sanguinalis, Amaranthus album* L.	Rawat et al., 2011
Juglone		*Juglans nigra* L.	*Sinapis arvensis* L., *Cirsium arvense* (L.) Scop., *Papaver rhoeas* L., *Lamium amplexicaule* L.	Topal et al., 2007

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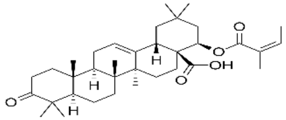
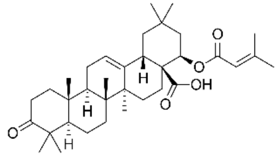
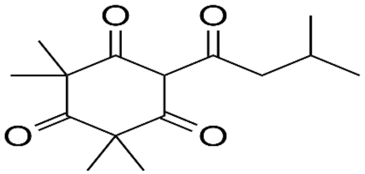
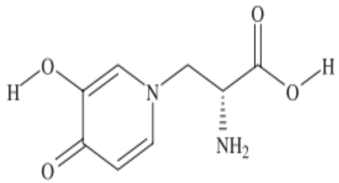
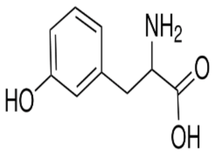
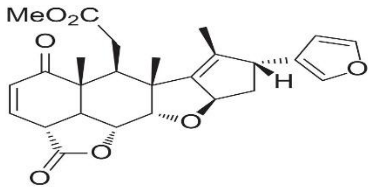
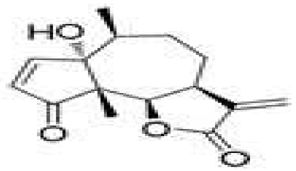
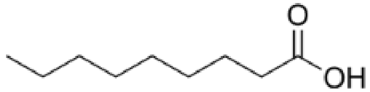
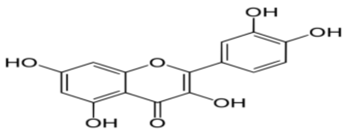
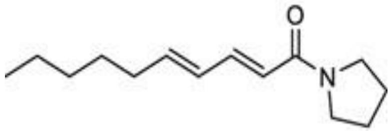
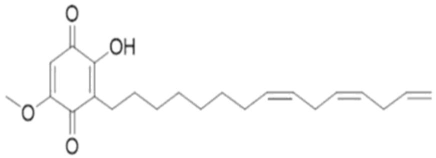
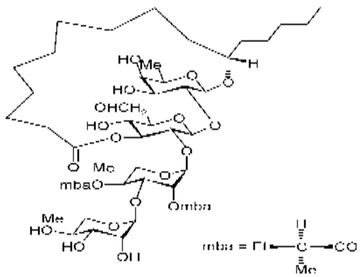
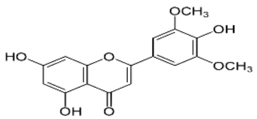
Lantadene A and lantadene B	 Lantadene A  Lantadene B	*Lantana camara* L.	*Bidens pilosa* L. *Eichhornia crassipes* (Mart.) Solms	Kato-Noguchi & Kurniadie, 2021
Leptospermone		*Callistemon citrinus* (Curtis) Skeels	*E. crus-galli, Amaranthus retroflexus* L., *Abutilon theophrasti* Medik., *Convolvulus arvensis* L., *Sesbania exaltata* (Raf.) Cory	Singh, 2017
Mimosine		*Leucaena leucocephala* (Lam.) de Wit	*B. pilosa, Mimosa pudica* L., *Lolium multiflorum* L.	Kato-Noguchi & Kurniadie, 2022
M-tyrosine		*Festuca* spp.	*A. thaliana*	Huang et al., 2012
Nimbolide B		*Azadirachta indica* A.Juss.	*Lepidium sativum* L., *E. crus-galli*	Kato-Noguchi et al., 2014

Parthenin		*Parthenium hysterophorus* L.	*Avena fatua* L., *Asphodelus tenuifolius* Cav., *Lolium rigidum* Gaudin	Motmainna et al., 2021d
Pelargonic acid		*Brassica napus* L.	*A. retroflexus, P. oleracea, A. fatua, Erigeron bonariensis* L.	Ganji & Andert, 2024
Quercetin		*Cleome rutidosperma* DC.	*E. crus-galli, F. miliacea, L. chinensis, C. iria*	Motmainna et al., 2024
Sarmentine		*Piper longum* L.	*Brassica kaber* (DC.) Wheeler, *A. retroflexus*, *Chenopodium album* L., *Cyperus difformis* L., *E. indica*	Huang et al., 2010
Sorgoleone		*Sorghum bicolor* (L.) Moench	*P. minor, Coronopus didymus* (L.) Sm., *Cyperus rotundus* L., *Solanum nigrum* L., *A. retroflexus, Ambrosia artemisiifolia* L., *Cassia obtusifolia* L.	Głąb et al., 2017
Tricolorin A		*Ipomoea tricolor* Cav.	*Triticum vulgare* Vill., *Lolium multiflorum* Lam. *Trifolium alexandrinum* L., *Physalis ixocarpa* Brot. ex Hornem.	Pereda-Miranda et al., 1993
Tricin and Momilactone B	 Tricin	*Oryza sativa* L.	*E. crus-galli*	Kato-Noguchi et al., 2008

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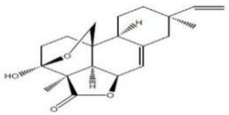
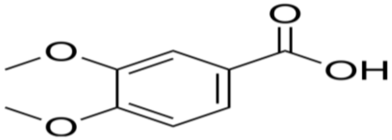
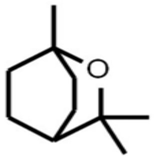
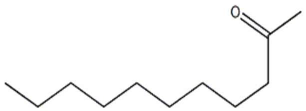
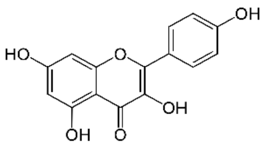
	 Momilactone B			
Veratric acid		*Digitaria sanguinalis* (L.) Scop.)	*Glycine max* (L.) Merr., *Triticum aestivum* L., *Zea mays* L.,	Zhou et al., 2013
1,8-cineol		*Eucalyptus* spp.	*L. rigidum*, *R. sativus*, *Ageratum conyzoides* (L.) L., *E. crus-galli*, *P. oleracea*	Qiu et al., 2010
2-undecanone		*Solanum habrochaites* S. Knapp and D.M. Spooner	*Euphorbia hirta* L., *Cyperus iria* L., *Axonopus compressus* (Sw.) P.Beauv., *A. conyzoides, E. indica, F. miliacea*	Hasan et al., 2021a
Kaempferol		*Borreria alata* (Aubl.) DC.; *Mimosa pigra* L.	*E. crus-galli*	Motmainna et al., 2025c

A key benefit of allelochemicals in bioherbicide development is their potential to introduce new or multiple modes of action. It can help to mitigate herbicide resistance often caused by target-site changes (Hasan et al., 2021b; Motmainna et al., 2021e). Few modes of action have been introduced since 1980, partly due to the heavy reliance on glyphosate, which is now widely resistant. Only one herbicide with a novel mechanism known as Tetflupyrolimet, which has been commercialized since then, though some older compounds like Cinmethylin and Aclonifen were later found to act through unique pathways (Dayan et al., 2019). Table 4 presents plant-based commercial bioherbicides developed from allelochemicals with their mode of action.

Table 4. List of commercially available plant-based bioherbicide.

Name	Active ingredient	Selectivity	Mode of action	References
Avenger® Weed Killer	d-limonene-70%	Non-selective and contact	Cell damage, dehydration	Verdeguer et al., 2020
Barrier H	Citronella oil-22.90%	Non-selective and contact	Rapid dehydration, necrosis	Clay et al., 2005
Beloukha®	Pelargonic acid-51.98%	Non-selective and contact	Disrupt cell membrane, necrosis	Muñoz et al., 2020
BioWeed™	Pine oil-680 g/L	Non-selective	Damage cell membrane, necrosis	Maes et al., 2021
GreenMatch™ EX	d-limonene-50%	Non-selective and contact	Waxy cuticle damage	Avila-Adame et al., 2008
WeedLock®	2 undecanone-10%	Non-selective	Cellular damage and oxidative stress	Hasan et al., 2022
Weed Slayer®	Eugenol-6%	Non-selective; contact and systemic herbicide	Damage cell membrane, affect root system	Verdeguer et al., 2020
WeedZap®	Clove oil-45% and Cinnamon oil-45%	Non-selective	Cell structure disrupts and damage	Verdeguer et al., 2020

New promising molecules continue to be discovered (Hasan et al., 2025), but their successful development and commercialization remain constrained by several major challenges**.** A key limitation is the high cost of production, as many allelochemicals possess complex chemical structures that require sophisticated extraction, purification, or synthesis processes. In addition, variability in efficacy under field conditions, limited environmental persistence, formulation difficulties, and regulatory requirements can further hinder their large-scale adoption. These economic and technical constraints become particularly significant when competing with relatively inexpensive conventional herbicides. For example, the bioherbicide *Colletotrichum gloeosporioides* f.sp. *malvae*, developed for the control of *Malva pusilla*, was ultimately withdrawn from the market due to commercial and economic limitations (Cordeau et al., 2016). Consequently, despite considerable research progress, the transition of allelochemicals from laboratory discovery to practical weed management solutions remains a substantial challenge. Without a change in approach, current progress may not be sufficient to

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keep pace with the increasing evolution of herbicide-resistant weeds. Allelochemical interactions are also important because some compounds may act synergistically, enhancing weed control efficacy. Furthermore, certain allelochemicals may inhibit detoxification or resistance-related enzymes in resistant weed populations, thereby restoring susceptibility to herbicides. Although plants have likely evolved to produce such combinations naturally, the underlying mechanisms, consistency of responses under field conditions, and potential for commercial application remain poorly understood and require further investigation.

5.4 Challenges and barriers to the commercialization of allelochemical-based bioherbicides

5.4.1 Economic feasibility

Economic viability remains a major consideration in the development and commercialization of allelochemical-based bioherbicides. The processes involved in the discovery, extraction, purification, and formulation of bioactive compounds can be costly, often leading to higher production costs than those associated with established synthetic herbicides, which benefit from mature manufacturing technologies and economies of scale (Mungwari et al., 2025). Consequently, unless a bioherbicide offers clear advantages in efficacy, resistance management, environmental safety, or regulatory acceptance, competing with widely available synthetic herbicides on cost alone may be challenging. This economic constraint remains a significant barrier to the large-scale adoption of many promising bioherbicide candidates.

5.4.2 Formulation technologies

Successful commercialization of allelochemicals depends not only on their biological activity but also on effective formulation technologies. Many allelochemicals are volatile, unstable, or poorly soluble in water, making it difficult to maintain consistent performance under field conditions (Sharma & Sharma, 2025). Appropriate formulation techniques, such as encapsulation, emulsification, and the use of adjuvants, can improve their stability, shelf life, and compatibility with existing spraying equipment (Kumar et al., 2024). However, developing such formulations requires specialized expertise and infrastructure. As a result, large agrochemical companies with established formulation technologies are often better positioned to commercialize promising allelochemicals, whereas academic researchers and small start-up companies frequently need industrial partnerships or licensing agreements to bring their products to market.

5.4.3 Registration requirements

Regulatory approval is another important factor affecting the commercialization of allelochemicals. Although many countries offer simplified or faster registration procedures for biopesticides than for synthetic pesticides, companies must still generate extensive data on product efficacy, safety, and environmental impact. Collecting these data can take several years and requires significant financial investment. For small companies and academic spin-offs, the cost of meeting regulatory requirements can be a major challenge (Raza et al., 2025). As a result, even promising products may initially be launched in only a limited number of countries or regions before expanding into larger markets.

5.4.4 Market acceptance

Market acceptance is another important factor influencing the commercial success of allelochemical-based products. Farmers are more likely to adopt bioherbicides when they provide reliable weed control, are cost-effective, and can be easily integrated into existing farming practices (Dolianitis et al., 2025). However, many bioherbicides have a narrower weed-control spectrum, require more precise timing of application, or are more expensive than conventional herbicides. These limitations can reduce farmer adoption despite their environmental and resistance-management benefits. As a result, bioherbicides are currently used mainly in niche markets, such as organic farming and integrated resistance-management programmes, rather than as large-scale replacements for conventional herbicides (Raza et al., 2025).

5.4.5 Industrial investment

Investment from industry plays a crucial role in determining whether promising allelochemicals reach the market. Large agrochemical companies have the resources and expertise needed for product development, formulation, regulatory approval, and distribution. However, they often focus on conventional herbicides because these products generally offer larger markets and more predictable financial returns. As a result, many promising allelochemicals discovered through academic research struggle to secure the investment needed for commercial development (Xuan et al., 2025). Their progress often depends on licensing agreements, biopesticide companies, or public–private partnerships. Therefore, the availability of financial and industrial support can be just as important as the allelochemical's biological effectiveness in determining its commercial success.

5.5 Technical challenges in allelochemical-based bioherbicide development

5.5.1 Environmental instability and rapid degradation

Many natural compounds, particularly volatile terpenes and phenolics, break down rapidly often within hours to a few days under field conditions when exposed to sunlight, soil microbes, and hydrolysis (Anh & Xuan, 2025). This relatively short period of activity contrasts with synthetic herbicides, which are often designed to provide extended residual control over several weeks. As a result, bioactive compounds may require repeated applications, potentially reducing their economic advantages.

5.5.2 Field-performance variability

Allelochemical activity is highly sensitive to soil type, moisture, temperature, and local microbial communities (Fadiji et al., 2025; Li et al., 2013), leading to unpredictable results between trial sites and seasons. Since most studies are conducted under controlled laboratory or greenhouse conditions, the effectiveness of these compounds under diverse field environments remains uncertain, limiting their progression from proof-of-concept studies to practical agricultural applications.

5.5.3 Formulation difficulties

Many allelochemicals are hydrophobic, volatile, or chemically unstable in water. Achieving adequate solubility, spray coverage, and rainfastness requires specialized delivery systems such as encapsulation or nanoformulations (Niu et al., 2026; Hasan et al., 2025). These requirements add high cost and technical complexity compared to standard synthetic formulations.

5.5.4 Limited shelf life

The stability of formulated bioherbicides remains a significant challenge, as many bioactive molecules are susceptible to oxidation and microbial degradation during storage (Duke et al., 2024; Campos et al., 2023). This instability can shorten product shelf life, complicate storage and distribution, and undermine grower confidence when batch-to-batch performance varies.

5.5.5 Potential non-target effects

Many allelochemicals exert their effects through broad mechanisms, such as membrane disruption and oxidative stress, rather than acting on a specific molecular target (Iqbal et al., 2025). This non-specific mode of action raises concerns regarding potential off-target effects on crop seedlings, beneficial soil microorganisms, and aquatic ecosystems through environmental runoff. However, comprehensive ecotoxicological assessments remain limited for most candidate compounds.

5.5.6 Regulatory hurdles

Obtaining regulatory approval requires extensive evaluations of safety, efficacy, and environmental fate. The substantial costs and lengthy timelines involved in generating these regulatory data packages pose significant barriers for academic researchers and small startups, often delaying the translation of promising bioherbicide candidates into commercial products.

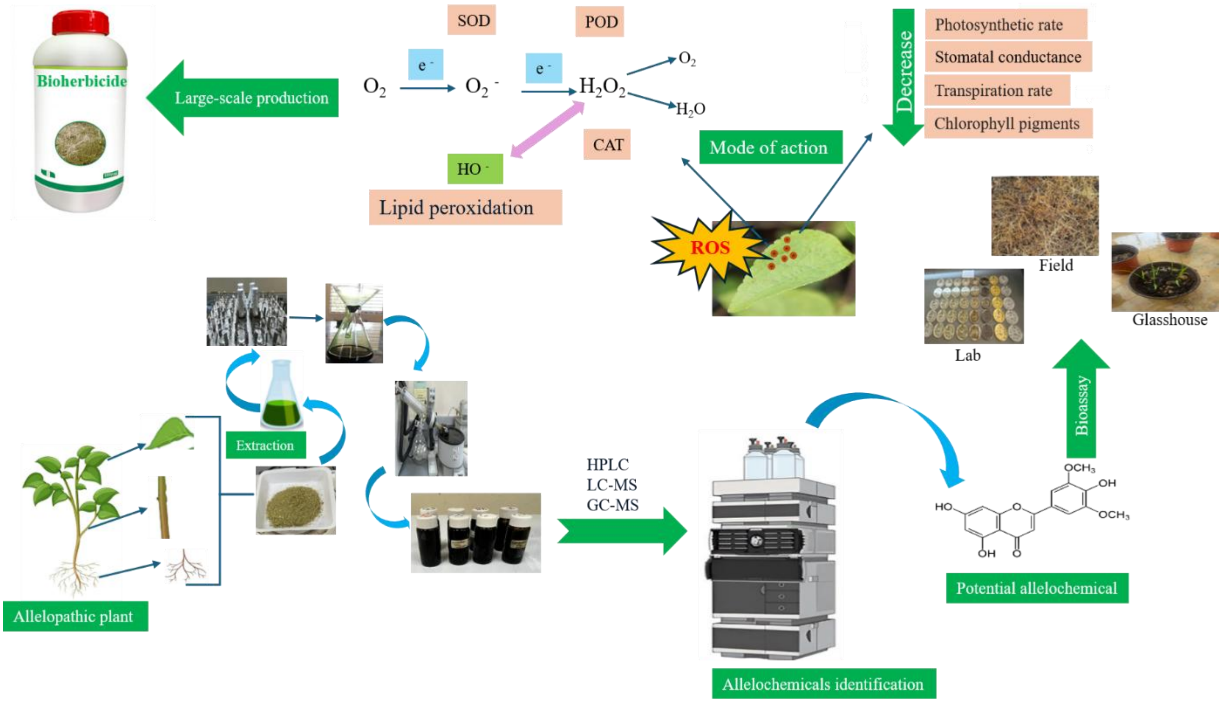

Figure 3. Schematic diagram of bioherbicide development.

6. Factors Affecting Allelochemical Production and Efficacy

Plants use allelochemicals as an important defence mechanism against both biotic and abiotic stress factors. The production, release, and effectiveness of allelochemicals are influenced by environmental conditions; however, not all stress factors stimulate allelochemical production, and their effects depend on plant species, stress intensity, and duration of exposure. The release of allelochemicals is commonly triggered by nutrient limitation, herbivore damage, and competition with neighboring plants rather than by physical injury or exogenous hormone application alone (Shan et al., 2023). Recent studies indicate that the controlled induction of stress responses, including exposure to competitive signals, nutrient limitation, shading, and stress-related signalling molecules, may enhance allelochemical production and improve weed-suppression potential. For example, anthropogenic shading of *Cynara cardunculus* L. increased the concentration of phytotoxic sesquiterpene lactones, although excessive stress negatively affected plant performance (Scavo et al., 2020). Similarly, the application of signalling compounds such as cis-jasmone and jasmonic acid has been reported to stimulate allelochemical production in crops including *T. aestivum*, *S. bicolour*, *O. sativa*, and *Solanum tuberosum* L. (Pickett et al., 2007). When plants experience competition for resources or nutrient-poor conditions, they modify their secondary metabolism and increase the production of defence compounds to improve survival and competitive ability.

6.1 Biotic factors

Biotic factors significantly affect the production and release of allelochemicals as organisms interact. Plants can detect neighbouring competitors via root exudates or volatile signals, triggering metabolic changes that increase the production of defensive compounds (Pierik et al., 2013). Herbivory and plant–plant interactions can also stimulate allelochemical synthesis, while autotoxicity helps regulate population density and genetic diversity. For example, germination of *Ambrosia trifida* L. and *A. artemisiifolia* can be inhibited by their own allelochemicals (Su et al., 2022). Similarly, root interactions between *O. sativa* and *E. crus-galli* in rice fields can induce the release of momilactones, which suppress the growth of competing plants (Estiati, 2019).

However, a major challenge is that allelochemical production is strongly influenced by biotic interactions and environmental conditions, leading to considerable variability in their synthesis, release, and effectiveness. Such variability can limit the consistency and predictability of allelopathic effects under field conditions, making it difficult to fully exploit allelochemicals for sustainable weed management.

6.2 Abiotic factors

Abiotic environmental conditions enhance the synthesis and release of allelochemicals in plants. All phytotoxic secondary metabolites function as true allelochemicals unless they persist in the environment at biologically effective concentrations for a certain duration. Under ideal conditions, such as full sunlight and sufficient soil nutrients, plants tend to allocate resources toward growth and reproduction. However, under stressful conditions, chemical defence mechanisms like allelochemical production become more prominent.

Abiotic stress can trigger the expression of enzymatic genes, leading to an increase in the production and release of volatile organic compounds, particularly terpenes (Midzi et al., 2022). In higher plants, these volatile organic compounds also act as antioxidants, mitigating oxidative stress by scavenging reactive oxygen species (ROS) and helping protect cellular structures and photosynthetic functions (Hasan et al., 2024b). In algae, volatile organic compounds released under abiotic stress similarly help mitigate ROS and additionally play a role in interspecific communication to enhance defence against predators (Zuo, 2019).

Beyond these general stress responses, specific abiotic factors, such as salinity, heavy metals, and soil physicochemical properties, have been shown to directly modulate allelochemical production. For instance, exposure to heavy metals such as $CuCl_2$ and $FeCl_2$ in rice cultivation, particularly $CuCl_2$ has been demonstrated to enhance the synthesis and release of momilactone B, a phytotoxic allelochemical (Kato-Noguchi, 2009). Similarly, changes in soil pH and electrical conductivity (EC) have been reported to induce allelochemical release in various plant species (Al-Qthanin et al., 2024).

Notably, abiotic stressors rarely act in isolation, and combinations of stress conditions often exert a compounded or interactive effect on allelochemical generation. Naphthoquinone defensive metabolites from *Echium plantagineum* L., for example, are rapidly produced in response to concurrent stresses such as intraspecific competition, high temperatures, and drought (Skoneczny et al., 2019). When multiple stress types interact, they can create complex trade-offs: some combinations enhance the abundance of particular allelochemicals, while others suppress it. Thus, abiotic stressors whether acting singly or in combination can significantly increase allelochemical activity by promoting the production and release of these bioactive compounds.

6.3 Soil nutrient deficiency

Lack of certain nutrients, especially nitrogen (N) and phosphorus (P), is a major cause of plants to synthesize and release allelochemicals. Under nutrient-deficient conditions, allelopathic activity in *O. sativa* was increased, particularly when P was limited (Klinnawee et al., 2023). This suggests that nutrient shortage contributes to increased allelopathic activity in rice. Phosphorus deficiency increases allelochemical production and changes the composition of these compounds in ways that may make plants' phytotoxic effects even stronger. Under such stress, *E. crus-galli* exhibited reduced enzymatic activity and suppressed physiological functions, whereas *O. sativa* demonstrated a marked increase in phenylalanine ammonia-lyase activity and total phenol content in both root and leaf tissues (Wang et al., 2010). This indicates that *O. sativa* enhances allelochemical output under nutrient deficiency as a strategy to outcompete neighboring plants. Similarly, *H. annuus* has also been reported to produce significantly more allelochemicals under nutrient-limited conditions (Fujii et al., 2022), further supporting the role of nutrient stress in inducing allelopathic activity.

7. Conclusion and Future Direction

In light of the considerable advancements in the field of allelopathy, there remain numerous avenues for further investigation and refinement of both established and newly discovered allelochemicals. Future investigations ought to concentrate on the isolation and identification of novel allelopathic compounds. The effectiveness of these newly identified allelochemicals requires thorough testing across various environmental conditions. Should they prove effective, these allelochemicals may provide a substantial basis for advancing novel bioherbicides. Furthermore, it is imperative to focus on enhancing formulation techniques incorporating multiple surfactants, as these are pivotal to the efficacy of bioherbicide formulations. The use of allelochemicals in the agricultural sector faces obstacles due to their rapid degradation and relatively high production costs. To overcome these constraints, the chemical sector can make significant contributions to the development of more efficient formulation methodologies that are also economically viable. Additionally, several chemical and pesticide companies around the world are increasingly investing in the development of bioherbicides, contributing to their growing presence in the global market.

Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Author Contributions

Norazua Zakaria: Conceptualization, Methodology, Reviewing and Editing. **Afiq Aiman Saharudin:** Data curation, Writing- Original draft preparation. **Mst. Motmainna:** Visualization, Investigation, Reviewing and Editing. **Mahmudul Hasan:** Writing- Original draft preparation, Reviewing and Editing.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Ethics Statement

This study did not involve human participants, animal subjects, or identifiable personal data. Therefore, ethical approval was not required.

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