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Allelopathy in sustainable agronomy: A natural mechanism for weed management: A review

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Abstract

Allelopathy, defined as the biochemical interaction among plants mediated through the release of secondary metabolites known as allelochemicals, has gained considerable attention as an eco-friendly and sustainable approach for weed management in modern agriculture. The increasing prevalence of herbicide-resistant weed species, coupled with environmental concerns such as soil degradation, biodiversity loss, and contamination of water resources, has necessitated the exploration of alternative weed control strategies. Allelochemicals, including phenolics, terpenoids, alkaloids, and flavonoids, exert inhibitory or stimulatory effects on neighboring plants by influencing physiological and biochemical processes such as germination, nutrient uptake, and photosynthesis. These compounds are released into the environment through various pathways, including root exudation, leaching, volatilization and residue decomposition, thereby affecting weed dynamics in agroecosystems. This review comprehensively synthesizes recent advances in the mechanisms of allelopathy, its agronomic applications, and its integration into sustainable weed management systems such as crop rotation, intercropping, cover cropping, and mulching. Furthermore, the development of allelochemical-based bioherbicides is critically evaluated as a promising alternative to synthetic herbicides. Despite its potential, challenges such as environmental variability, inconsistent field performance, and limited commercialization remain significant barriers. Future prospects include molecular breeding, genetic engineering, and the integration of allelopathy into precision agriculture systems. Overall, allelopathy represents a vital component of integrated weed management (IWM) and contributes significantly to the advancement of sustainable agronomy.

Keywords: Allelopathy, allelochemicals, sustainable agriculture, weed management, bioherbicides, integrated weed management, crop rotation, cover crops

Introduction

Weeds are one of the most critical biotic factors in agroecosystems, negatively affecting crop yield and quality and leading to substantial economic losses in agriculture globally (Singh *et al.*, 2021) [53]. Weed-induced yield reduction may vary between 45% and 95% based on the crop species, weed species, environmental conditions and management strategies (Scavo and Mauromicale, 2021; Shittu *et al.*, 2025) [38, 41]. Chemical control of weeds has traditionally been dependent on synthetic herbicides, which have proved effective but have also brought about numerous negative effects, such as environment contamination, development of herbicide resistance, and soil health impairment (Hussain *et al.*, 2021; Duke, 2020; Schulz *et al.*, 2024) [21, 39]. The development of herbicide-resistant weeds has added pressure for sustainable and more environmentally benign approaches to weed management (Choudhary *et al.*, 2023; Dang, D. T. 2025; Cheng *et al.*, 2024) [8, 12].

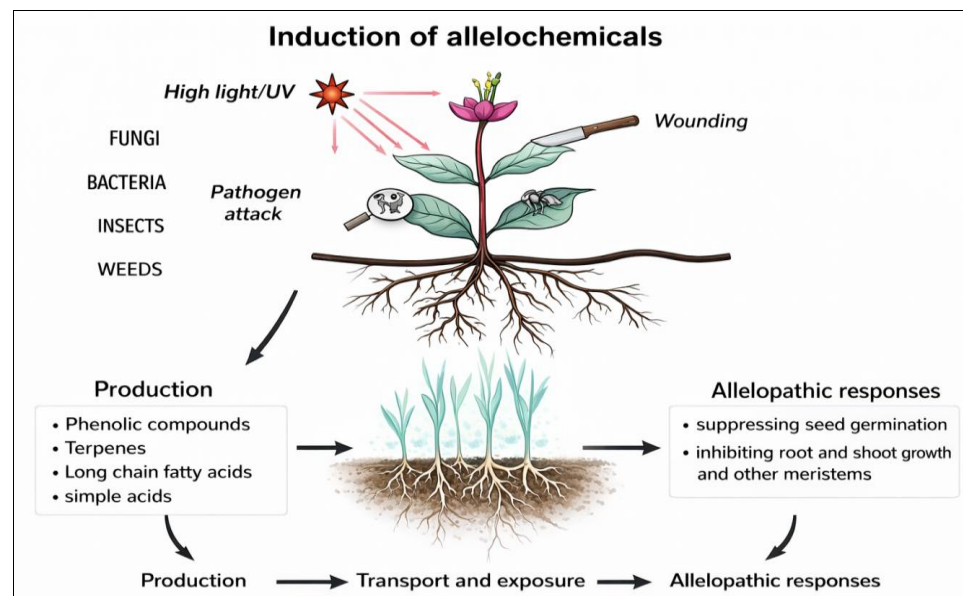
Allelopathy, the chemical interaction among plants through the release of bioactive allelochemicals, has become a significant natural process for weed control (Murthy *et al.*, 2025; Butnariu and Koirala, 2025; Blum, 2022) [54, 4]. These allelochemicals effect growth and development of plants at physiological and biochemical level and thereby affect the plant community (Singh *et al.*, 2021; Schulz *et al.*, 2024; Kong *et al.*, 2024; Latif *et al.*, 2022) [53, 39]. In contrast to synthetic compounds, allelopathy presents an eco-friendly and sustainable solution

to protect the environment and the ecosystem (Scavo and Mauromicale, 2021; Thang *et al.*, 2023; Narwal, 2000) [38, 45, 31]. Thus, the application of allelopathy in sustainable weed control is now widely accepted as an approach to address modern agronomic problems (Rithiga *et al.*, 2024; Ghosh *et al.*, 2026; Sreekanth *et al.*, 2024; Harker *et al.*, 2021) [55, 42, 20].

2. Concept and History of Allelopathy

The concept of allelopathy was first introduced by Hans Molisch in 1937, who described it as the chemical interactions between

plants that influence their growth and development (Singh *et al.*, 2021; Chauhan, 2022; Ulas *et al.*, 2025; Creamer *et al.*, 1996) [6, 53, 10]. The term is derived from the Greek words “allelon,” meaning “each other,” and “pathos,” meaning “suffering,” which collectively describe the mutual biochemical interactions among plants (Scavo and Mauromicale, 2021; Tarrant *et al.*, 2024; Basdemir, and Ozkan, 2026) [38, 44, 2]. Over time, the concept has evolved to include both inhibitory and stimulatory effects of plant-derived chemicals on neighboring plants (Murthy *et al.*, 2025; Wianeki, 2025) [54, 50].



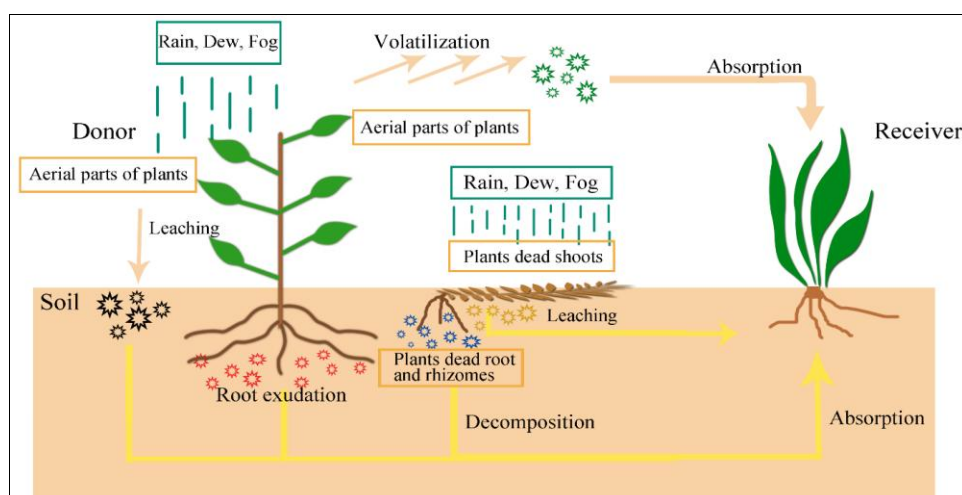
(Sources: Choudhary *et al.* 2023) [8]

Fig 1: Schematic representation of allelochemical induction and their role in suppressing weed growth through allelopathic interactions.

Studies on allelopathy were mainly limited to the laboratory in the earlier days, but progress has now been made to extend the level of application of allelopathic principles to field agronomy and sustainable agricultural systems (Schulz *et al.*, 2024; Rebong *et al.*, 2024) [39]. Contemporary research highlights the importance of the allelochemical involvement in the ecological functioning of plant communities and the control of the weed flora (Choudhary *et al.*, 2023; Li *et al.*, 2024) [8]. In addition, allelopathy is being considered as an essential element of agroecological approaches that seek to minimize dependence on synthetic inputs (Rithiga *et al.*, 2024) [55].

3. Mechanisms of Allelopathy

Allelopathy is a multifaceted phenomenon at both biochemical and ecological levels, it includes production, release and action of allelochemicals into the environment (Choudhary *et al.*, 2023; Dayan *et al.*, 2025) [8, 13]. These processes restrict the growth and development of plants through inhibition of physiological activities including cell division, nutrient absorption, and photosynthesis (Murthy *et al.*, 2025; Tamang *et al.*, 2025) [54, 43].



(Sources: Scavo and Mauromicale, 2021) [38]

Fig 2: Pathways of allelochemical release, transport, and absorption in plant-plant interactions within the soil-plant system

3.1 Release Pathways

Allelochemicals enter the surroundings through invasion root exudates, leaching, volatilization, and decomposition of plant residues (Schulz *et al.*, 2024) [39]. Root exudation is also the most important pathway by which allelochemicals are released directly into the rhizosphere to interact with soil microbes and other plants in the vicinity (Choudhary *et al.*, 2023; Isman, 2023) [8, 22]. The process of leaching, rain wash away the allelochemicals on plant surface and bring them down onto soil, where they have an effect on seed germination and seedling growth (Scavo and Mauromicale, 2021; Xu *et al.*, 2021) [38, 52]. Volatilization is a release of volatile compounds into the air that can have an impact on other plants in the proximity without coming in contact with soil (Murthy *et al.*, 2025; Kakar *et al.*, 2023) [54]. Residue decomposition also plays a role, where less breaking down plant material, releases allelochemicals that remain in the soil and affect the plants that follow (Rithiga *et al.*, 2024; Ravlic *et al.*, 2022) [55].

3.2 Types of Allelochemicals

Allelochemicals are heterogeneous and comprise various groups of organic chemicals such as phenolics, terpenes, alkaloids, and flavonoids (Singh *et al.*, 2021; Sarkar *et al.*, 2012) [53]. Phenolic compounds including ferulic acid and coumarin can act as inhibitors of seed germination and radicle growth (Murthy *et al.*, 2025; Halecki *et al.*, 2022) [54]. Terpenoids, for example cineole, inhibit respiration in plants (Biddington and Windsor, 1993) and when dissolved in water predicted to be plant growth reducing agents (Choudhary *et al.*, 2023) [8]. Alkaloids (including quinine), interfere with the metabolism and the enzymes of the target plant (Scavo and Mauromicale, 2021; ANGRIWAN *et al.*, 2025) [38]. Flavonoids like catechin promote oxidative stress and subsequent cell death and growth suppression (Schulz *et al.*, 2024) [39].

3.3 Physiological Effects on Weeds

Allelochemicals are known to act on weeds by modifying the physiological activities, such as seed germination, root growth and enzyme activity (Murthy *et al.*, 2025) [54]. These substances can block cell proliferation through mitotic interference leading to the depression of plant growth (Choudhary *et al.*, 2023; Clunes *et al.*, 2022) [8]. To top it all, allelochemicals can influence photosynthesis by modulating chlorophyll production and the electron transport chain (Singh *et al.*, 2021) [53]. Solutes uptake among them nucleotides and glucose metabolism is affected by the allelochemical, as in Osmoetal. Allelochemicals can also change permeability of membranes and ion transport processes (Schulz *et al.*, 2024) [39], so that nutrient absorption is compromised. In addition, these substances influence the balance of plant hormones, which causes malformations of growth and development (Kong and Liu, 2022) [7].

4. Role of Allelopathy in Sustainable Agronomy

Allelopathy is important for sustainable agriculture, as it can reduce the reliance on synthetic herbicides and maintain ecological stability (Rithiga *et al.*, 2024) [55]. Allelopathy through use of natural plant products reduces environmental pollution while improving soil quality (Schulz *et al.*, 2024; Dang Xuan *et al.*, 2025) [39, 11]. It also promotes the conservation of biodiversity, providing different plant and microbial communities (Scavo and Mauromicale, 2021) [38]. In addition, allelopathy is in conformity with the principles of organic farming where natural inputs and ecological processes are promoted. Therefore, allelopathy has been gaining importance as

a crucial aspect of the integrated weed management (IWM) systems (Murthy *et al.*, 2025; Uyun *et al.*, 2024) [54, 48].

5. Agronomic Applications

Allelopathy can be effectively utilized in various agronomic practices to enhance weed management and crop productivity (Scavo and Mauromicale, 2021) [38].

5.1 Crop Rotation

Crop rotation with allelopathic crops is also a promising option in sustainable weed management. It operates by interfering in the lifecycle of weeds, so that they are unable to maintain growing and reproducing. Over the years, this seeps into the soil to have an increasingly smaller number of weed seeds (Rithiga *et al.*, 2024; Gao *et al.*, 2024) [55, 16]. Allelopathic plants secrete bioactive compounds that suppress the germination and growth of weeds. As a result, without high dependence on herbicides, the weed pressure naturally decreases. Research has demonstrated that such rotations are beneficial for uniting crop production and the health of the soil. For example strong allelopathic effect of rice-wheat cropping system on weed infestation. It produces an environment that is bad for weeds to take hold. Therefore, crop sequence with allelopathic plants provides a green and economical weed management tactic.

5.2 Intercropping

Systems of intercropping allelopathic and non-allelopathic crops will be a best option for weed control. In these production systems, allelopathic crops emit phytotoxic compounds that suppress weed seed germination and seedling growth, while companion crop makes good use of the resources in the soil and air. The net effect of these interactions is a greater overall suppression of weeds than monocropping (Murthy *et al.*, 2025) [54]. Furthermore, intercropping can contribute to effective utilization of light, water, nutrient and other resources. This results in improved crop growth and yield. The heterogeneous plant canopy also tempers favorable conditions for weed germination. Hence, there is diminished weed pressure without over-reliance on chemical herbicides. Hence, intercropping with allelopathic plants can be considered as a green and sustainable solution for enhancing crop productivity and weed management (Choudhary *et al.*, 2023; Guo *et al.*, 2024) [8, 18].

5.3 Cover Cropping

Cover crops, including rye and mustard, are important contributors to sustainable weed control via their allelopathic activity. These cover crops exude allelochemicals that are capable of suppressing weed seed germination and inhibiting weed growth in its early stages. Thus, the weed seed rain is also diminished dramatically. Cover crops also provide chemical suppression of weeds, as well as physical ground cover (which reduces the amount of light available for weed growth). This makes them even more effective against the undesirables in a garden. The cultivation of such cover grasses contributes to a decreased dependence on chemical-based herbicides. And they also help with improved soil health and retention of moisture. Therefore, allelopathic cover crops can be introduced in cropping systems in an environment-friendly way to reduce weed pressure in the following crop (Schulz *et al.*, 2024) [39].

5.4 Mulching and Green Manuring

Mulching with allelopathic plants residues represents a promising approach to weed control in cropping systems. When decomposing these residues allelochemicals are released that

reduce the germination of weed seeds and growth of seedlings. This natural weed-suppressing activity reduces weed pressure and competition among crops. And mulching helps retain soil moisture and soil temperature. Green manuring, on the other hand, provides fertility to the soil and also helps in weed control. Green manure rotations contribute to greater soil organic matter and nutrient availability in the soil. At the same time, their

allelopathic effect inhibits the emergence and growth of weeds. This double advantage makes green manuring a viable agronomic option. Generally, both mulching and green manuring are environmentally friendly weed control methods which also protect soil health (Rithiga *et al.*, 2024; Scavo and Mauromicale, 2021)^[55, 38].

Table 1: Allelopathic crops and their effects

Crop	Allelochemicals	Target Weeds	Effect
Rice	Momilactones	Barnyard grass	Germination inhibition
Wheat	Phenolic acids	Broadleaf weeds	Growth suppression
Sorghum	Sorgoleone	Grasses	Root inhibition
Mustard	Glucosinolates	Multiple weeds	Toxic effects

6. Allelopathy in different cropping systems

Allelopathy is important in various tillage systems for weed management and crop production. It results in the production of bioactive substances that inhibit weed germination and growth, thereby decreasing crop-weed competition (Fenibo *et al.*, 2025)^[53]. Cereal grains, such as wheat and rice, have a strong allelopathic potential, that is largely responsible for the natural weed control (Scavo and Mauromicale, 2021)^[38]. Similarly, oilseed crops including mustard and sunflower release the

strong allelochemicals which suppress the weed germination and growth (Rithiga *et al.*, 2024)^[55]. Moreover, grasses and legumes act as dual suppressors of soils weeds and legumes also improve soil fertility via biological nitrogen fixation. This enhances soil quality and reduces reliance on chemical inputs (Murthy *et al.*, 2025)^[54]. Hence, allelopathic crops contribute to a sustainable and environmentally friendly approach in farming systems for weed management and productivity improvement.

Table 2: Methods of Using Allelopathy in Agriculture

Method	Description	Benefits
Intercropping	Growing crops together	Weed suppression
Crop rotation	Sequential cropping	Break weed cycle
Mulching	Residue cover	Soil protection
Bioherbicides	Extract-based products	Eco-friendly

7. Allelopathy Vs Synthetic Herbicides

Allelopathy is considered a substitute to synthetic herbicides with higher sustainability level due to its environmental and eco-friendly characteristic in agroecosystem management (Scavo and Mauromicale, 2021; Schulz *et al.*, 2024)^[38, 39]. In contrast to traditional herbicides, which are synthetic chemicals that may persist in soil and water and cause contamination of the environment for extended periods of time, allelochemicals are natural products that are biodegraded swiftly by microorganisms and other natural processes, substantially decreasing EC of phenolic compounds to the environment (Choudhary *et al.*, 2023; Dayan & Duke, 2023)^[8, 13]. While synthetic herbicides have been heavily implicated for the emergence of herbicide-resistant weed species that pose a serious threat to crop productivity and sustainability globally, allelopathic interactions are known to be multi-modal in their nature, and the presence multiple mechanisms of action against a target species makes the evolution of resistance less likely. In addition, soil biology at the rhizosphere and beyond is regulated by allelopathy, leading to a positive impact on soil health and the environment, while synthetic herbicides have been reported to negatively influence soil microorganisms and the nutrient cycling process (Schulz *et al.*, 2024; Inderjit, 2021)^[39]. But despite these benefits, allelopathic responses are generally influencedand sometimes even obscured by environmental conditionssuch as soil type, moisture and temperature, which affect the emission, activity and uptake of allelochemicals (Murthy *et al.*, 2025; Kong, 2022)^[54]. Besides, the effect of allelochemicals is slow relative to synthetic herbicides that initiate rapid and uniform weed control under field conditions, rendering allelopathy less predictable for fast weed suppression (Chauhan, 2022; Singh *et al.*, 2023)^[6f].

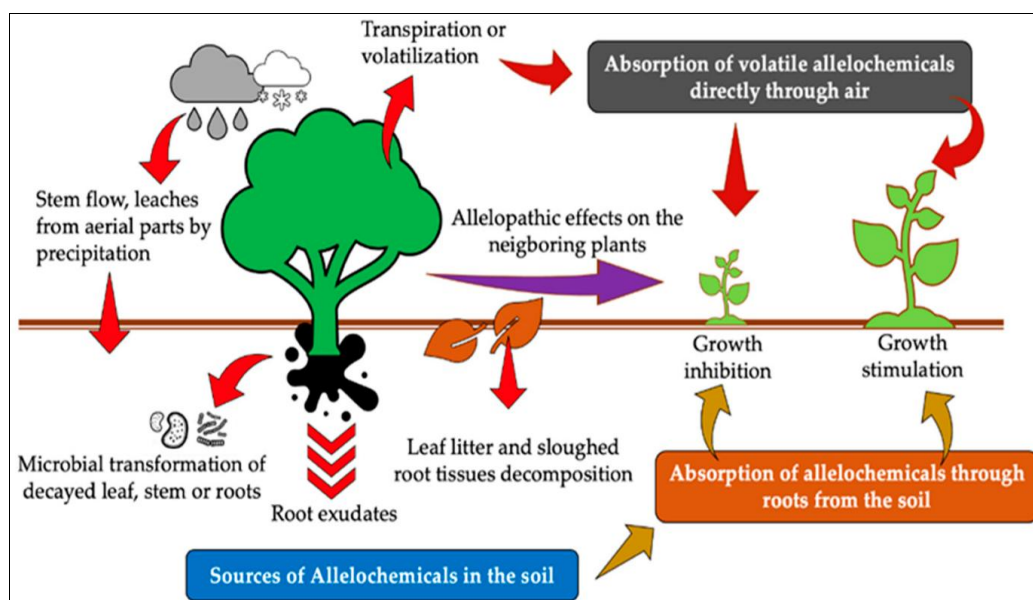
Hence, although allelopathy presents a safer and more sustainable approach, its combination with other weed management measures is required to ensure dependable and efficient weed control (Scavo and Mauromicale, 2021; Schulz *et al.*, 2024)^[38, 39].

8. Bioherbicides and Allelopathy

Bioherbicides founded on allelochemicals constitute a novel and rapidly evolving strategy for the sustainable weed control in the contemporary agri-industry (Dayan *et al.*, 2021; Duke, 2022)^[13]. Plant secondary metabolites-based bioherbicides have many beneficial attributes such as biodegradability, less toxicity, and limited persistence in environment as compared to traditional synthetic herbicides (Cantrell *et al.*, 2022; Rajakumar *et al.*, 2025)^[33]. Natural products frequently display specific toxicity for a weed species, so it reduces injury to other crops and beneficials, wound that is numerous in generalist chemical herbicides (Macias *et al.*, 2023; Verdeguer *et al.*, 2021). Recent advances in analytical chemistry, metabolomics and biotechnology have enabled the discovery, isolation and structure elucidation of allelochemicals with herbicidal potential and the development of such products for commercial use (Choudhary *et al.*, 2023; Dayan and Duke, 2023)^[8, 13]. Also, novel methods such as nano-formulations and encapsulations have been developed to enhance the stability, effectiveness, and delivery of allelochemical-based bioherbicides in field environments (Singh *et al.*, 2024; Rajakumar *et al.*, 2025)^[33]. However, issues such as high production cost, short storage period and variable efficiency in field still restrict the widespread commercialization of bioherbicides despite these progresses (Duke, 2022; Schulz *et al.*, 2024)^[39]. However, it is

foreseen that the further investigations and technological development will allow a better practicability and acceptance of these allelopathy-derived bioherbicides in the context of

sustainable agricultural production (Dayan *et al.*, 2021; Macias *et al.*, 2023)^[13].



(Sources: Schulz *et al.* 2024)^[39]

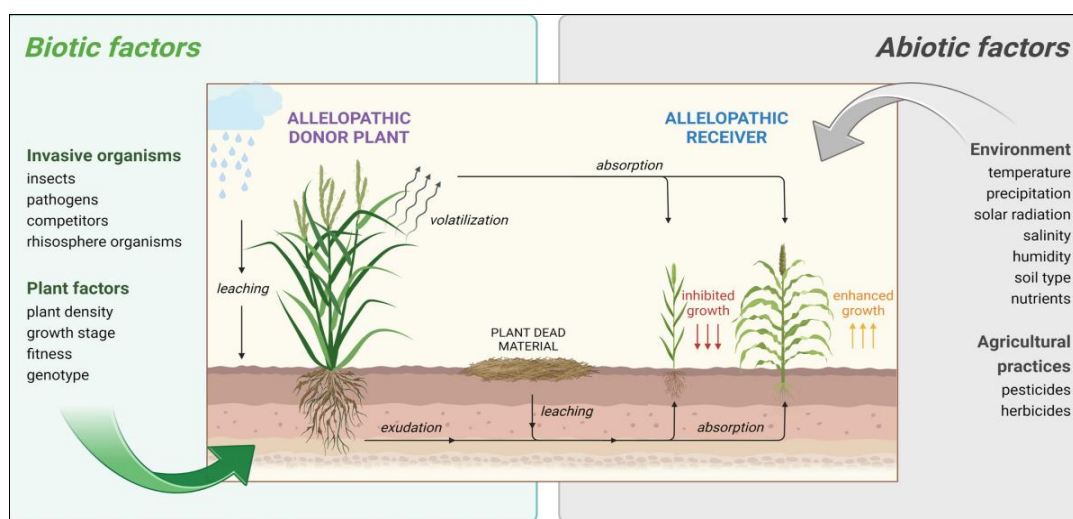
Fig 3: Sources, pathways, and effects of allelochemicals in plant-plant interactions within agroecosystems.

9. Factors Affecting Allelopathy

A complex interaction of environmental, biological, and genetic factors, which influence the synthesis, release, and activity of allelochemicals, affect the outcomes of allelopathy in the agroecosystems (Schulz *et al.*, 2023; Choudhary *et al.*, 2023)^[8]. Soil texture, pH, organic matter content and cation exchange capacity are the soil attributes which influence the adsorption, mobility, persistence and bioavailability of allelochemicals, as well as their subsequent phytotoxic effect on weeds (Blum, 2021; Inderjit, 2021). Temperature, rainfall, and light intensity are climate factors known to strongly affect the production and emission of plant allelochemicals, and the degradation and transformation in soil and in the environment (Singh *et al.*, 2022).

Soil microorganisms are indeed crucial in allelopathic

relationships, and can degrade or metabolize the allelochemicals, attenuating their effects, or, conversely, biotransform them into more toxic metabolites that potentiate weed suppression (Kong, 2022; Murthy *et al.*, 2025)^[54]. Moreover, plant genotype is an important factor affecting the amount and types of allelochemicals produced and some crops have stronger allelopathic activity than others (Wu *et al.*, 2023; Rithiga *et al.*, 2024)^[55]. Allelopathic effects are also influenced by agronomic practices including irrigation, fertilization and crop management as these affect plant growth and soil conditions (Chauhan, 2022; Schulz *et al.*, 2024)^[6, 39]. Hence, an understanding of these parameters is critical to maximize the potential of allelopathy for sustainable weed control systems (Scavo and Mauromicale, 2021)^[38].



(Source: Kong, 2022)

Fig 4: Schematic representation of allelopathic processes showing the role of environmental (abiotic) and biological (biotic) factors in regulating allelochemical release, transport, and plant response.

10. Limitations and Challenges

Although allelopathy holds immense promise for providing a polyherbicide in the weed management arsenal for sustainable agriculture, allelopathic interactions are complex and dynamic, and multiple factors limit its application in modern farming systems (Schulz *et al.*, 2024; Murthy *et al.*, 2025) ^[39, 54]. One of the major hurdles is that allelopathic effects vary under field conditions and are affected by environmental factors, including soil type, climate, and microbial activity, thus making it difficult to predict results (Choudhary *et al.*, 2023; Inderjit, 2021) ^[8]. Another issue is the selectivity of allelochemicals which may also influence the growth of non-target crops, thus restricting its use in mixed cropping system (Singh *et al.*, 2023; Macias *et al.*, 2023).

In addition, the mode of action of these compounds is comparatively slow when compared to synthetic herbicides, which decreases the efficacy of control in terms of rapid weed suppression in high-input agricultural systems (Chauhan, 2022; Murthy *et al.*, 2025) ^[6, 54]. And to complicate things further, standardized formulations are scarce and large-scale commercial products have yet to emerge, also making for rather bountiful hurdles to upscaling allelopathy-based technology (Duke, 2022; Dayan & Duke, 2023) ^[13]. Moreover, the intricacy of allelopathic relationships and the challenge to separate individual allelochemicals under field conditions adds another layer of difficulty for their application (Kong, 2022; Schulz *et al.*, 2024) ^[27, 39]. Thus, it is necessary to investigate these problems by means of interdisciplinary science and technologically innovative to take advantages of allelopathy in the green agriculture.

11. Future Prospects

In the future, allelopathy research will likely be directed toward modern biotechnological and agronomic tools that could improve its potential and application in sustainable weed management (Dang Xuan, 2025; Schulz *et al.*, 2024) ^[39, 11]. Molecular breeding and genetic engineering have the potential to lead for the production of crop plants with enhanced allelochemic potential, which could suppress weeds as efficiently as the chemical analogs (Wu *et al.*, 2023; Singh *et al.*, 2024) ^[51].

The application of precision agriculture in allelopathy, through digital technologies and data-driven decision-making, could also enhance the application of allelopathy by fine-tuning the timing of allelopathic activities (Schulz *et al.*, 2024) ^[39]. Emerging strategies such as nano-formulated bioherbicides and controlled-release formulations are anticipated to enhance the stability, efficacy, and delivery of allelochemicals into various environmental matrices (Rajakumar *et al.*, 2025; Dayan *et al.*, 2021) ^[33, 13].

Moreover, microbial allelopathy, or utilizing soil microorganisms to produce or stimulate production of allelochemicals, is an exciting new research area (Rajakumar *et al.*, 2025; Kong, 2023) ^[33]. Advancements in metabolomics, genomics, and systems biology will also lead to further understanding of the processes of allelopathy and related weed management systems (Dang Xuan, 2025) ^[11]. In general, these advances will be essential for fostering the integration of allelopathy into climate smart and sustainable agriculture systems (Schulz *et al.*, 2024) ^[39].

12. Conclusion

Allelopathy is a potential and environmentally sustainable method for weed control, which reveals good compatibility with

the concepts of ecological and organic agriculture. Reducing dependence on synthetic herbicides, allelopathy aids in the reduction of environmental pollution, the protection of biodiversity, as well as the enhancement of soil health, which collectively supports the sustainability of agriculture. The management of weeds through allelopathic means can be optimized when introduced into other agronomic practices such as crop rotation, intercropping, and cover cropping, all of which could offer a complete system for weed control. However, issues such as variability in field performance, restricted commercialization, and inadvertent impacts on non-target crops need to be resolved through further research and technological development. Advances in biotechnology, precision farming and bioherbicide formulation will also be anticipated to improve the use and effectiveness of allelopathy in the future farm systems. Thus, in the context of emerging environmental and agricultural challenges, allelopathy has great potential to be a crucial element of integrated weed management and sustainable agronomy.

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