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THE POSITION OF ALLELOPATHY IN SUSTAINABLE AGRICULTURE

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Abstract: The escalating global population, coupled with the adverse environmental impacts of conventional farming-such as soil degradation, biodiversity loss, and herbicide resistance-necessitates a paradigm shift toward sustainable agricultural models. Modern agroecosystems require innovative, ecologically sound strategies to ensure long-term productivity and food security without compromising ecosystem health. Among these strategies, allelopathy emerges as a critical biochemical mechanism for natural weed suppression and the reduction of synthetic chemical dependency. This review evaluates the role of allelopathy within the framework of Integrated Weed Management (IWM) and sustainable intensification. It examines how allelochemicals -released through root exudation, leaching, and volatilization-can be harnessed through practical applications such as crop rotation, cover cropping, and the development of bioherbicides. While bio-based alternatives offer high specificity and low environmental persistence, their integration into large-scale systems requires a deeper understanding of molecular interactions and ecological dynamics. This paper concludes that leveraging allelopathic potential is essential not only for mitigating the crisis of herbicide resistance but also for fostering resilient, bio-diverse, and sustainable agricultural landscapes for future generations.

Keywords: Allelopathy, Sustainable agriculture, Integrated weed management, Bioherbicides, Allelochemicals, Agroecology

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1. Introduction

The rapid increase in the world's population necessitates a sustainable increase in food production. Global issues such as climate change, population growth, loss of biodiversity, and depletion of resources make it mandatory to reevaluate food production systems (Godfray et al., 2010). Although traditional farming methods have increased efficiency in the short term, they have led to serious long-term environmental problems, such as soil degradation, water pollution, loss of biodiversity, and greenhouse gas emissions (Foley et al., 2011). This shows that our current agricultural model isn't sustainable from an environmental, social, and economic standpoint. Issues like excessive use of chemical fertilizers and pesticides, soil contamination, depletion of water resources, and reduced biodiversity make a sustainable agriculture approach a necessity (Tilman et al., 2011).

In this context, sustainable agriculture is gaining increasing importance as an approach that targets the ecological, economic, and social sustainability of agricultural production. This approach not only to meet the food needs of the current generation but also ensures access to resources for future generations (Kamakaula, 2024). Sustainable agriculture stands out as a holistic approach that seeks to ensure both food security and the protection of ecosystems (Ikerd, 1993; Pretty, 2013; Farooq et al., 2019). It is fundamentally based on improving soil health by reducing the use of synthetic fertilizers and pesticides, using water resources efficiently, and preserving biodiversity (Lal, 2015). Simultaneously, it contributes to enhance the economic well-being of farmers and strengthen local food systems. This interdisciplinary field combines modern agricultural technologies with traditional knowledge to offer solutions that both protect the environment and ensure food security (Czyżewski and Kryszak, 2022).

One of the primary goals of sustainable agricultural systems is to ensure long-term productivity and economic viability while minimizing environmental impacts (Mkonda, 2021). These systems incorporate methods such as crop rotation, minimum tillage, organic fertilization, and biological pest control (Angon et al., 2023). These approaches enhance soil fertility while reducing reliance on chemical inputs (Shah and Wu, 2019; Shah et al., 2021; Belete and Yadete, 2023).

The objective of this review is to discuss the strategic role of allelopathy in modern sustainable agriculture and its potential as an ecological alternative to synthetic herbicides in the face of rising chemical resistance and environmental degradation.

2. Weed Management

Weeds are one of the most significant factors threatening agricultural productivity (Gharde et al., 2018). They lead to yield losses by competing with cultivated crops for water, light, and nutrients (Froud-Williams, 2002). To prevent these losses, humankind has used various methods since ancient times, ranging from simple hand weeding to mechanical tools and modern chemical herbicides (Woyessa, 2022). The discovery of synthetic herbicides in the mid-20th century revolutionized weed control. These chemicals became very popular because they offered a quick and effective solution (Mesnage et al., 2021). However, the excessive and unconscious use of herbicides over time has created serious environmental and agricultural problems (Rashid et al., 2010).

The continuous use of the same herbicides has led to the development of genetic resistance within target weed populations. This resistance reduces the efficacy of herbicides and forces farmers to use even more chemicals, creating a dangerous and costly cycle (Owen and Zelaya 2005; Renton et al., 2014). Weed management stands out as one of the most critical and challenging processes in achieving this goal. While synthetic herbicides, commonly used in conventional agriculture, offer an effective solution (Nath et al., 2024), the negative impacts of these chemicals on soil, water, and biodiversity (Tibbett et al., 2020) conflict with the principles of sustainability. In this context, organic and sustainable agriculture approaches have developed alternative strategies to reduce or completely eliminate herbicide use. For example, cultural control techniques, such as tillage methods, rotational systems, and the use of cover crops, provide effective ways to suppress weed populations (Teasdale and Zimdahl, 2018).

However, each of these methods has its own limitations and application challenges. Therefore, weed management in modern agriculture requires the development of integrated and multi-faceted approaches that not only preserve yield but also support ecosystem health. The advancement of ecologically intensive agro-ecosystems requires a synergistic approach that combines a rigorous understanding of ecosystem dynamics with the integration of indigenous agricultural knowledge. Given the capacity for advanced weed management to enhance crop yields, there is a critical need to develop and implement weed control technologies that are simultaneously economically viable and environmentally sustainable (Nath et al., 2024). Because of these growing problems, farmers and scientists are now looking for better ways to control weeds. It is clear that relying only on chemicals is not a long-term solution. Therefore, a more balanced approach called Integrated Weed Management (IWM) has become very important (Harker and O'Donovan, 2013). This approach combines different methods together to keep weeds at a low level while protecting nature (Scavo and Mauromicale, 2020).

2.1. Allelopathic Interactions Within the Soil Matrix

The soil environment acts as the primary theater for allelopathic interactions, serving not merely as a passive medium but as a dynamic regulatory filter. The transition of an allelochemical from a "donor" plant to a "target" organism is governed by a complex interplay of adsorption, desorption, and degradation (Inderjit, 2005). These processes determine the bioavailability and persistence of phytotoxins, which ultimately dictates their ecological impact. Soil properties such as texture, organic matter (SOM) content, and pH significantly influence the mobility of specialized metabolites. Phenolic acids, for instance, tend to bind strongly to clay particles and organic complexes through hydrogen bonding and van der Waals forces. High SOM content often reduces the immediate phytotoxicity of allelochemicals by sequestering them; however, this can also create a long-term "reservoir" effect, where chemicals are slowly released back into the soil solution (Fadiji et al., 2025). Furthermore, soil pH affects the ionization state of allelochemicals, particularly organic acids, thereby altering their solubility and uptake by neighboring root systems.

Microbial activity represents perhaps the most critical determinant of allelopathic efficacy, as soil microorganisms can act as either detoxifiers or activators of allelochemicals. In many instances, soil bacteria and fungi rapidly metabolize phytotoxins, utilizing them as carbon sources and thus mitigating their inhibitory effects on target plants (Blum, 2011). Conversely, microbial transformation can sometimes increase toxicity; for example, certain non-toxic glycosides released by plants are converted into potent aglycones by microbial enzymes within the rhizosphere. This two-way relationship between secondary metabolites and the physical, chemical, and biological characteristics of the soil matrix determines the final level of phytotoxicity (Scavo et al., 2019). Consequently, the stability and activity of these compounds are highly sensitive to microbial imbalances and chemical interventions, such as the application of herbicides or fungicides which can disrupt the competitive balance and influence their potential for natural weed control and crop resistance (Polyak and Sukcharevich, 2019).

As our understanding of these intricate soil-matrix interactions at the macro environmental level grows, modern molecular research has bridged the gap between ecology and biotechnology. By characterizing allelochemical properties and identifying the genes and proteins responsible for their biosynthesis, it is now possible to manipulate these traits through gene silencing, overexpression, or the introduction of new transgenes. This molecular precision provides a critical foundation for developing sustainable agroecosystems (Kumar et al., 2024). However, the interaction between allelochemicals and the soil environment often results in plant soil feedbacks (PSF). Continuous accumulation of specific metabolites can lead to "soil sickness," a form of autotoxicity that limits productivity in monocultures and forest plantations (Huang et al., 2013). Moreover, allelochemicals can shift the microbial community composition, favoring pathogens or suppressing beneficial mycorrhizal fungi, which indirectly influences the competitive balance between native and invasive species.

2.2. Allelopathy and Bio-based Strategies: A New Era in Weed Management

The widespread and intensive use of synthetic herbicides in modern agriculture has led to significant challenges, most notably the rapid evolution of herbicide-resistant weed biotypes (Mucheri et al., 2024). Beyond resistance, growing concerns regarding chemical residues in food chains and their negative impacts on environmental health have forced the scientific community to seek sustainable and eco-friendly alternatives (Yu et al., 2024). These efforts have shifted the focus toward integrated weed management strategies, including biological control, allelopathy, and the development of bioherbicides (Scavo and Mauromicale, 2020).

Bioherbicides are defined as weed control agents derived from living organisms, such as specialized pathogenic fungi (mycoherbicides), bacteria, or plant extracts (Roberts et al., 2022; Pantović et al., 2023). The first evidence of bioherbicide development was documented in the mid-1970s with the discovery of mycoherbicides. Unlike conventional chemicals, bioherbicides offer high specificity toward target weeds and degrade rapidly in the environment, thereby minimizing non-target toxicity. Bioherbicides serve as reliable, sustainable, and environment-friendly weed control agents that utilize host-specific plant pathogens to manage weeds without the negative ecological impacts associated with chemical pesticides (Aneja et al., 2017). Bioherbicides inhibit weed growth by disrupting cell membrane integrity and essential biochemical processes, leading to impaired nutrient absorption, reduced pigment synthesis, and the induction of oxidative stress through reactive oxygen species (ROS) development. Despite their sustainability benefits, bioherbicides face significant challenges for large-scale application due to their short environmental persistence, high production costs, and potential toxicity to non-target organisms (Hasan et al., 2021).

To overcome these technical constraints, recent advancements in formulation chemistry have focused on enhancing the stability and efficacy of allelopathic compounds. Microencapsulation and nanotechnology-based delivery systems have emerged as pivotal strategies to shield active ingredients from rapid environmental degradation, thereby extending their persistence in the soil (Sabarivasan and Murali Arthanari, 2025; Bhati et al., 2026). Furthermore, the integration of synergistic adjuvants can significantly lower application rates and production costs by improving the adherence and penetration of bioherbicides on target weed surfaces. Implementing solid-state fermentation (SSF) techniques also offers a cost-effective pathway for large-scale production, utilizing agricultural by-products as substrates (Bastos et al., 2017). By refining these delivery and manufacturing processes, the gap between the ecological potential of bioherbicides and their commercial viability can be bridged, ensuring safer and more precise weed management (Cordeau et al., 2016).

Allelopathy represents a complex biochemical interaction where plants release secondary metabolites, known as allelochemicals, into the environment. These substances are released through root exudation, leaching, or volatilization and can inhibit the germination and growth of competing weed species. Utilizing the allelopathic potential of cover crops or mulch is increasingly recognized as a natural and effective tool for weed suppression in organic and conservation tillage systems (Dang Xuan et al., 2025). This phenomenon is a cornerstone of ecological balance and offers significant potential for enhancing weed suppression and sustainable farming systems (Cheng and Cheng, 2015; Scavo et al., 2018).

Allelopathy represents a direct negative interaction where weeds and crops influence each other through the release of biochemicals (Farooq et al., 2011). While a specific crop may possess allelopathic properties, its inhibitory effects are often selective and may not impact every weed species in a field. Conversely, when weeds exhibit allelopathy, the impact on the crop can be particularly severe because the chemical influence is concentrated on a single target species (Scavo and Mauromicale, 2021). These interactions primarily occur through root exudates from living plants or the decomposition of crop residues. Specific crops, including maize, sorghum, wheat, barley, rye, and mungbean produce residues that naturally suppress the growth of certain weeds (Farooq et al., 2011; Lertmongkol et al., 2011). Integrating these natural defenses into global weed management practices offers a sustainable alternative to synthetic herbicides, positioning biological interference as a cornerstone of future agricultural success. Beyond traditional methods, a significant area of research involves developing bio-herbicides derived directly from plant allelochemicals (Li et al., 2010). One innovative strategy is "biological replacement," where non-harmful plants are used to outcompete invasive species.

In Bangalore, India, researchers successfully managed the invasive weed *Parthenium hysterophorus* by introducing competitive ruderal flora. Several species showed strong inhibitory effects, including: *Tagetes minuta* and *Mirabilis jalapa*, *Tephrosia purpurea* and various *Cassia species*. Notably, *Cassia sericea* was identified as the most effective species for naturally replacing and suppressing *Parthenium* (Bashar et al., 2021). The ability of crops to suppress weeds is often a combination of physical growth advantages and chemical defenses. For instance, barley demonstrates superior competitiveness compared to wheat, largely due to its rapid root development during the first three weeks after sowing. This physical advantage is bolstered by the presence of gramine, a natural allelochemical that inhibits weed growth (Maver et al., 2020). Similarly, sorghum utilizes chemical interference through the production of hydrocyanic acid (HCN). Found within its shoots and foliage, this compound is highly effective against specific weed species such as *Abutilon theophrasti*, *Amaranthus hybridus*, *Setaria viridis*, and *Bromus pectinatus* (Zhou et al., 2025). In the case of maize, the allelopathic effect is primarily driven by root exudates. These chemical secretions allow maize to naturally limit the growth of common weeds like *Chenopodium album* and *Amaranthus retroflexus* (Zambelli et al., 2025). By understanding these natural defense systems, agriculture can transition toward more sustainable, bio-based weed management.

Despite extensive research into resource competition and global environmental shifts, the specific role of allelopathy remains a comparatively understudied driver of ecological processes within grassland and forest ecosystems (Hierro and Callaway, 2021). The synergistic interaction between specialized metabolites (such as terpenoids and phenolics) and signaling chemicals allows plants to dynamically regulate inter- and intraspecific interactions, thereby driving the structural productivity and compositional developmentof forest and pasture communities (Xu et al., 2023). Historically, the study of plant plant interactions in terrestrial ecosystems has highlighted allelopathy as a key driver of community structure. The classic paradigm involves *Juglans nigra*, which facilitates a competitive advantage by releasing the phytotoxic compound 1,4-naphthoquinone (juglone), a process documented to inhibit the development of neighboring flora over millennia (Soderquist, 1973). The role of volatile terpenes as agents of allelopathic interference was documented in the 1960s, specifically regarding the inhibition of grassland species by neighboring shrubs within the coastal regions of Southern California (Muller et al., 1964). Research has documented premature mortality in paper birch (*Betula papyrifera* Marsh) when cultivated in mixed-species plantations alongside black walnut (*Juglans nigra* L.), likely due to the latter's allelopathic influence (Rietveld et al., 1983). Evidence suggests that allelopathy is a fundamental characteristic of forest ecosystems worldwide. Reports of allelochemical production are geographically and taxonomically diverse, encompassing Australian *Eucalyptus* sp. (Lovett, 1986), boreal conifers (Mallik, 2003), and various tropical and temperate species (McKey et al., 1978; Williamson et al., 1992). The extensive nature of this phenomenon is underscored by Coder and Warnell's (1999) compilation, which details allelopathic activity in over one hundred different tree species. While allelopathy is a well-established strategy for weed suppression within agricultural and agroforestry frameworks, its potential as a restoration tool specifically regarding the ability of indigenous arboreal species to mitigate the proliferation of invasive exotics remains significantly under-researched (Cummings et al., 2012).

Sustainable agroecosystem management increasingly relies on allelopathic mechanisms to minimize environmental impacts. Through techniques like intercropping, cover cropping, and the application of bioherbicides, allelopathy facilitates a transition toward greener agricultural frameworks. This review explores the significant allelopathic capacity found across various plant types, from forest species to common agricultural weeds, highlighting their role in modern sustainable intensification.

3. Conclusion

Chronic systemic issues within modern agriculture, such as environmental degradation and the proliferation of herbicide-resistant biotypes, mandate a transition toward nature-based intervention strategies. Allelopathy stands at the forefront of this shift, acting as a pivotal mechanism to mitigate chemical dependency and fortify agro-ecosystem stability. Beyond facilitating the innovation of bio-based herbicides, the exploitable potential of allelochemicals synergizes with sustainable agronomic practices, including residue management and diversified cropping systems. Elucidating the molecular pathways of these interactions and embedding them within Integrated Weed Management (IWM) frameworks will be essential for safeguarding global food security and fostering an ecologically sustainable agricultural legacy.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	F.B.	A.İ.Ö.
C	70	30
D	70	30
S	80	20
DCP	70	30
DAI	70	30
L	70	30
W	70	30
CR	80	20
SR	70	30

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

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