

Review

Allelopathic Interactions in Vegetable Production Systems: Current Knowledge and Future Perspectives

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Abstract

The need to investigate ecological and sustainable approaches to weed management, as well as to reduce the negative environmental impact of chemical herbicides, is becoming increasingly important in modern agriculture and land management. Among alternative strategies, allelopathy is a natural mechanism by which particular plant species release bioactive compounds that can influence the germination, growth, and development of neighboring plants. Harnessing allelopathic interactions offers an opportunity to develop environmentally friendly alternatives to synthetic herbicides and helps preserve ecological balance within agroecosystems. This review examines the potential of allelopathic plant-derived substances for weed control in agricultural systems, with particular emphasis on managing weed populations in vegetable crops and gardens in urban and peri-urban areas. This study introduces the concept of allelopathy with definitions and general information. Subsequently, the paper analyzes the phenomenon's presence at the plant level, its interactions, and the extracts obtained from allelopathic plants. The paper focuses on essential oils and fatty acid-derived compounds, such as pelargonic acid, which have demonstrated significant inhibitory effects on weed germination and biomass accumulation. Overall, the presented results establish a scientific basis for developing bioherbicides and support implementing sustainable, environmentally responsible horticultural practices.

Keywords: allelopathy; allelochemicals; essential oils; plant extracts; bioherbicides; organic crops

1. Introduction

Over the last two decades, the expansion of urban and peri-urban areas has generated increasing interest in food production within limited spaces, particularly through private gardens and small-scale horticultural systems. These systems address the need to combine functionality with sustainability; however, the land used is often unsuitable for cultivation and requires substrate improvement and frequent soil interventions. In this context, there is a growing need to develop crop management and protection methods that are effective, accessible, and compatible with the natural functioning of ecosystems, without generating long-term ecological imbalances [1,2].

Agroecosystems are complex structures in which living organisms interact through competition and cooperation, and intensified human intervention has, over time, led to soil degradation, the emergence of plant diseases, and the development of weed and pest resistance to conventional control methods [3–7]. Within plant communities, competition for resources results in the hierarchization of species, favoring those with high adaptive



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capacity. In vegetable cropping systems, this competition is particularly pronounced, with weeds negatively affecting crop development through resource competition and chemical interference [8].

Vegetable crops are of significant importance from both nutritional and economic perspectives. Yet, they are highly vulnerable to weed infestation, especially under conditions of short crop rotations, high crop value, and limited herbicide availability, particularly in organic agriculture [9,10]. The use of insufficiently fermented compost, undecomposed plant residues, or contaminated fertilizers contributes to weed emergence and spread, with many species exhibiting high reproductive capacity, ecological adaptability, and long-term seed viability [11–15]. Problematic species, such as common ragweed (*Ambrosia artemisiifolia*) and creeping thistle (*Cirsium arvense*), cause direct yield losses and facilitate the persistence of diseases and pests within agroecosystems. These species are highly adaptable to essential resources, such as water, light, and nutrients. They also form extensive root systems and produce a large number of viable seeds. These characteristics allow them to colonize crops and persist in the soil rapidly. These species are also often host plants for numerous pathogens and insect pests, thereby contributing to biotic pressure on crops over multiple growing seasons.

In this context, allelopathy—defined as chemically mediated inhibitory or stimulatory interference between organisms—has gained renewed attention as a potential component of ecological weed management strategies. From its initial conceptualization to modern Ecophysiological and agroecological interpretations, allelopathy has been examined as a mechanism by which plants release secondary metabolites that can influence the germination and growth of other species [16–18]. Practical interest in this phenomenon arises from the persistent gap between the ecological need to reduce chemical inputs and the actual pressure exerted by weeds and pests on crops, particularly in horticultural systems [19].

Vegetable cropping systems represent a particularly relevant framework for applying allelopathic principles for several reasons. The frequent integration of cover crops, mulches, biofumigation practices, and intercropping creates conditions conducive to allelopathic processes, which may complement physical weed suppression and ecological regulation within agroecosystems [19–21]. Numerous cultivated species and cover crops, especially those belonging to the *Brassicaceae* and *Alliaceae* families, as well as cereals such as rye and sorghum, are associated with well-characterized secondary metabolites, including glucosinolates, isothiocyanates, benzoxazinoids, and phenolic compounds, with documented inhibitory potential against weeds [22–25].

Nevertheless, the effectiveness of allelopathic processes is strongly influenced by genotype, pedoclimatic conditions, residue management practices, and interactions with soil microbiota, which explains the variability of results reported under laboratory and field conditions [26–29]. Recent literature emphasizes that allelopathy may produce both beneficial and undesirable effects, depending on crop sequence and ecological context, highlighting the need for critical evaluation before its integration into routine agricultural practices [30–32].

In Romania and the broader region, growing interest in allelopathy is reflected in both conceptual and applied research focusing on vegetable cropping systems, intercropping technologies, and the use of plant-derived extracts, underscoring the potential of this concept for developing locally adapted, sustainable management strategies [8,33–35]. However, the available information remains fragmented across disciplines, which justifies the need for a structured synthesis focused explicitly on vegetable production systems [36].

Therefore, this paper aims to provide an integrated analysis of allelopathy and allelopathic substances, with emphasis on their role in the ecological control of weeds and pests in vegetable crops. The study seeks to link biochemical mechanisms with practical

applications, identify methodological limitations, and highlight relevant research directions for sustainable and organic agriculture, with applicability at the farm scale.

2. Conceptual Framework of Allelopathy

Allelopathy is a biological phenomenon specific to plants (Figure 1) in which biochemical substances produced by one plant interact with or inhibit nearby plants through phenolic compounds, volatile compounds, or alkaloids, creating both positive and negative effects. Plants that can influence the growth and development of other plants by releasing these compounds into the environment are called allelopathic plants [12].

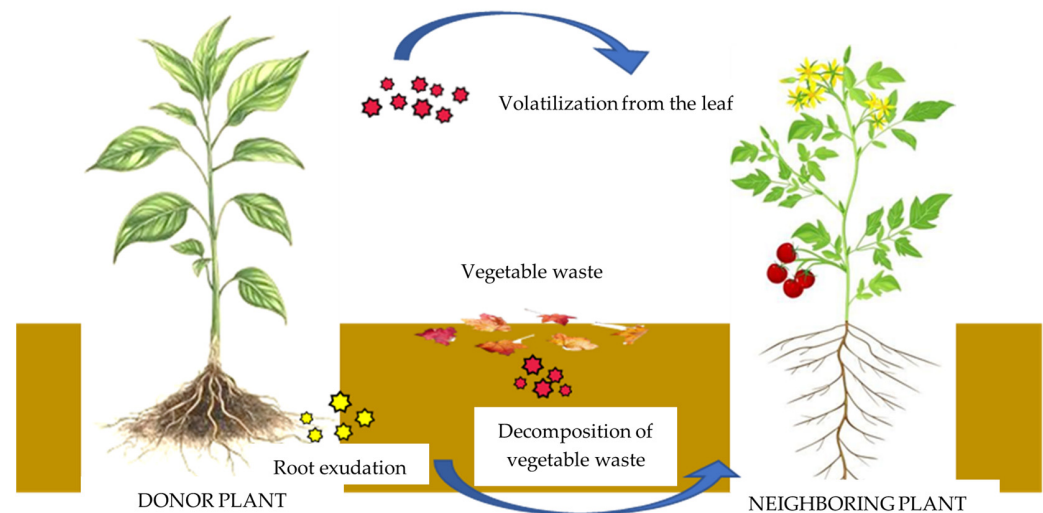


Figure 1. The phenomenon of allelopathy [37].

Rice, in his monograph on allelopathy, offers a more complex definition that encompasses the direct and indirect effects of plants on one another and on those around them. In the same sense, other researchers have closely examined the phenomenon of allelopathy and ruled out the idea of plant competition, finding that allelopathic effects alter plant development [1,17].

Allelopathy can also be defined as the phenomenon of biochemical interference between plants, whereby a plant species releases secondary compounds (allelochemicals) into the environment that influence the development of other species. These compounds are often secondary metabolites such as phenols, alkaloids, or terpenoids. Roots, released as vapors or resulting from the decomposition of plant debris, can inhibit the germination, growth, or reproduction of target plants. Unlike classical competition, where limited environmental resources (sunlight, water, and mineral nutrients) are exploited, allelopathy directly introduces inhibitory chemicals into the soil and air, affecting the physiology of competing plants (Table 1). However, both processes can limit the growth of coexisting species; allelopathy acts by releasing toxins into the ecosystem, while simple competition reduces the concentration of resources available to plants [11,18,38–40].

Competition between plants is also an exploratory mechanism, as each species tries to capture abiotic resources from the environment as efficiently as possible. This causes plants to develop morphological and physiological strategies to collect light (through extended leaves and shade-avoidance reactions), water, and nutrients from the soil (through extended root systems) as easily as possible. Unlike allelopathy, this type of interaction does not involve the release of toxic substances. Classical competition is based purely on resource consumption, thus shaping the vertical structure and spatial distribution of vegetation [41].

Table 1. Physiological mechanism based on allelopathic compounds [42–46].

Plant Name	Scientific Name	Active Compounds	Mode of Action	Effects
Basil	<i>Ocimum basilicum</i> L.	Eugenol, estragole, linalool, cineol	Destruction of the cell membrane, inhibition of cell division, and disruption of photosynthesis	Reduced the growth rate of nearby plants
Thyme	<i>Thymus vulgaris</i> L.	Thymol, carvacrol	Inhibition of water absorption in the plant, inhibition of cellular respiration, and disruption of protein synthesis in the soil	Destruction of common weeds and limitation of their development in crops
Wild thyme	<i>Thymus serpyllum</i> L.	Tannins, thymol, carvacrol, organic acids, ethanol	Reduced germination rate, inhibition of root elongation	Reduced the growth rate of nearby plants
Lavander	<i>Lavandula angustifolia</i> Mill.	Linalyl acetate, lavandulil, linalool, camphor	Inhibition of germination, damage to the root system, inhibition of shoot development, antifungal effects, repellent effects against pests	Reduced the growth rate of nearby plants, assisting in pest control in crops
Mint	<i>Mentha piperita</i> L.	Flavonoids, volatile acids, polyphenols, menthone	Repellent effects against pests, inhibition of germination	Reduced the growth rate of nearby plants, assisting in pest control in crops
Oregano	<i>Origanum onites</i> L.	Carvacrol, thymol	Inhibition of germination and blockage of photosynthesis	Reduced the growth rate of nearby plants
Rosemary	<i>Rosmarinus officinalis</i> L.	Rozmarinic acid, carnosol	Inhibition of germination by blocking cellular respiration	Reduced the growth rate of nearby plants
Sage	<i>Salvia officinalis</i> L.	Camphor, cineole, phenolic acid, salvinol	Slowing seedling growth and root elongation, inhibition of seed germination, antibacterial and antifungal effects in the soil	Destruction of common weeds and limitation of their development in crops, and elimination of crop pests

Allelochemicals are chemical compounds produced by plants, microorganisms, or animals that are released into the environment through mechanisms such as root exudation, volatilization from aerial parts, leaf washing by precipitation, or decomposition of plant debris. Once in the environment, these compounds can significantly influence the growth, development, germination, metabolism, or behavior of other organisms, including plants, microorganisms, and insects [18,47–49].

Types of allelochemicals:

- Phenolic compounds (phenolic acids, flavonoids, tannins, quinones) such as ferulic acid, p-coumaric acid, vanillic acid, juglone, act on membrane permeability, inhibiting cell division and elongation, also block enzymes involved in germination and photosynthesis, generating oxidative stress. The effects of these compounds are evidenced by direct contact with tissues or by altering the root microenvironment [46,50].

- Terpenoids (essential oils: mono- and sesquiterpenes) such as cineole, camphor, pinene, limonene—volatile or easily leached substances; affect membrane integrity, ion transport, and mitochondrial activity; can inhibit germination or primary growth by blocking cell division [43,51–53].
- Alkaloids such as caffeine, nicotine (in particular species), and other tertiary alkaloids are considered allelochemicals that interact through enzymes and receptors, disrupt protein synthesis and energy metabolism, and can be toxic at low concentrations, affecting germination and early development [54,55].
- Benzoxazinones (benzoxazinoids), such as DIMBOA, BOA (in wheat, corn, rye), or similar derivatives, represent a class of heterocyclic chemical compounds (C₈H₇NO₂) consisting of a benzene ring fused to an oxazine ring containing a carbonyl group (C=O). Structurally, they are benzoxazine derivatives. They act through compounds released into the soil as precursors or degradation products; they inhibit the growth of weeds and certain microorganisms by blocking essential metabolic pathways and by direct toxicity to the roots [56,57].
- Cyanogenic glycosides and isothiocyanates (derived from glucosinolates), a good example for this is the cyanogenic glycosides (HCN release) and isothiocyanates from Brassicaceae. They act by degrading and releasing reactive agents (cyanide, isothiocyanates) that inhibit cellular respiration and key enzymes and exert antimicrobial effects, thereby reducing the competitiveness of sensitive species [24,26].
- Fatty acids and aliphatic compounds (aldehydes, ketones) such as pelargonic acid and sorgoleone (root exudate specific to sorghum), which act by destabilizing the membrane, causing loss of cell integrity and local dehydration, sorgoleone strongly inhibits the absorption and growth of roots of other species [44,58–64].
- Saponins and steroids from various medicinal plants. The mode of action is by disrupting the permeability of cell membranes (pore formation), also affecting the absorption of nutrients, and may have antifungal/antibacterial effects [52].
- Non-protein amino acids, peptides, and purines-mimosine, caffeine (purine), etc., which interfere with nitrogen metabolism, protein synthesis, or enzyme function, blocking germination by inhibiting key metabolic steps.

3. Sources of Allelopathic Compounds in Vegetable Systems

Allelopathy in vegetable cropping systems arises from diverse chemical interactions among cultivated crops and associated plant species introduced through cover cropping, mulching, or intercropping. From a practical standpoint, allelopathic effects with the highest agronomic relevance are those mediated by secondary metabolites released through plant residues or biomass management, rather than by low-dose root exudation alone. Consequently, understanding allelopathy in vegetables requires integrating chemical identity, release pathways, biochemical mode of action, and field-scale context (Table 2) [20,65,66].

Table 2. Allelopathic action of vegetable species [8,21,22,57,67–69].

Species	Allelochemical Class	Release Pathway	Primary Target	Evidence Level	Notes
<i>Brassicaceae</i> spp. (cabbage, Mustard)	Glucosinolates → ITCs ¹	Residue incorporation	Weeds, Pathogens	Field + greenhouse	Strongly management- dependent
<i>Allium</i> spp.	Organosulfur Compounds	Residues, tissue disruption	Pathogens	Greenhouse > field	Short persistence

Table 2. Cont.

Species	Allelochemical Class	Release Pathway	Primary Target	Evidence Level	Notes
<i>Fabaceae</i> spp.	Phenolics, flavonoids	Residues, Exudates	Weeds (indirect)	Field (mixed)	Effects often indirect
<i>Solanaceae</i> spp.	Glycoalkaloids, Phenolics	Residues	Weeds, pathogens	Greenhouse	Risk of autotoxicity
<i>Rye</i> spp.	Benzoxazinoids, Phenolics	Mulch, residues	Weeds	Field	High biomass advantage
<i>Sorghum</i> spp.	Sorgoleone, phenolics	Roots, residues	Weeds	Field + greenhouse	Warm-season systems

ITCs¹—isothiocyanates derived from *Brassicaceae*.

Among the vegetable crops, *Brassicaceae* (e.g., cabbage, mustard, radish, perennial wall-rocket) offer the best-documented and best-understood mechanistic allelopathic system. Their biological activity is mainly determined by glucosinolates and their enzymatic hydrolysis products, especially isothiocyanates (ITCs). These compounds are generated when plant tissues are destroyed, and myrosinase enzymes come into contact with glucosinolates in the presence of moisture. In plant systems, this process is deliberately exploited through biofumigation, where fresh *Brassicaceae* biomass is incorporated into the soil before planting [24,28,29].

Isothiocyanates are highly reactive molecules that can disrupt cell membranes, inhibit enzyme activity, and induce oxidative stress in germinating weed seeds and soil pathogens. Field studies indicate that their suppressive effects are strongest in the early stages of weed emergence, particularly against small-seeded annual weeds, and under conditions that promote rapid hydrolysis and temporary soil sealing (adequate moisture, incorporation of fine residues). However, the effectiveness of *Brassicaceae*-mediated allelopathy is highly variable, as ITCs have a short lifespan and their bioavailability is strongly influenced by soil texture, organic matter content, microbial activity, and climatic conditions. Thus, although *Brassicaceae* vegetables represent the most “usable” allelopathic system in vegetables, their success depends more on precise management than on species selection [70].

Allium crops, such as onions, garlic, and leeks, have the potential to contribute to the allelopathic effect in vegetable gardens, mainly through the organosulfur compounds they contain. These compounds include thiosulfinates, which are derived from S-alk(en)yl-L-cysteine sulfoxides. These compounds are produced quickly following tissue damage and exhibit strong antimicrobial activity. In vegetable rotations or intercropping systems, residues of *Allium* and sulphur compounds derived from their roots can suppress soil pathogens locally and influence microbial communities [19,35].

However, the allelopathic contribution of *Allium* species to weed suppression under field conditions is less consistent than that of the *Brassicaceae* family. The high reactivity and short persistence of sulphur compounds limit their spatial and temporal range of action, making them more relevant for localised pathogen suppression or as part of integrated crop rotations than as standalone weed management tools [21,26,29].

In *Fabaceae* (e.g., beans, peas, vetch, clovers), allelopathic effects are primarily associated with phenolic acids, flavonoids, and related secondary metabolites released through residues and root exudates. Unlike *Brassicaceae*, *Fabaceae* rarely produce a single dominant allelochemical with strong biocidal properties. Instead, their allelopathic influence is typically moderate and often intertwined with other ecological processes, including nitrogen enrichment, changes in microbial communities, and altered crop–weed competition dynamics [8,28].

In vegetable crops, *Fabaceae* are more accurately viewed as facilitators of indirect allelopathy, where chemical effects interact with improved soil structure and biological activity. Field evidence suggests that weed suppression attributed to *Fabaceae* is often due to the combined impact of residue cover, shading, and altered nutrient availability rather than to direct phytotoxicity alone.

Allelopathic effects in *Solanaceae* (tomato, pepper, eggplant, potato) are linked to glycoalkaloids, phenolic compounds, and terpenoids. These metabolites can exhibit phytotoxic and antimicrobial properties, particularly in laboratory and greenhouse studies. However, their practical application in vegetable systems is constrained by the risk of autotoxicity, carry-over effects in rotations, and inconsistent persistence in soil [57].

As a result, *Solanaceae* residues are seldom used intentionally for allelopathic weed control. Instead, their chemical effects are best interpreted within a broader residue management and rotation framework, where both beneficial and detrimental impacts must be considered.

The effects and allelopathic potential of some vegetable species such as sweet potato (*Ipomoea batatas* L.), are known for its content in phenolic compounds and flavonoids, pepper (*Capsicum annuum* L.), rich in capsaicinoids and polyphenols, dill (*Anethum graveolens* L.), parsley (*Petroselinum crispum* Fuss.) and fennel (*Foeniculum vulgare* Mill.), aromatic plants containing essential oils and terpene derivatives, as well as carrot (*Daucus carota* L.) and onion (*Allium cepa* L.) [50,71], known for the presence of phenolic compounds and sulfur substances, were investigated. Laboratory studies analyzed the extracts and found that they can have both inhibitory and stimulatory effects on plant germination and growth, depending on the species, concentration, and application conditions.

Defining allelopathic relationships among different vegetable species is necessary because, through their biochemical structures, these vegetables produce allelochemicals that can influence the development of other species, including weeds in crops. These interactions become especially evident in associated crops, where both compatibility phenomena, determined by tolerance to certain bioactive substances, and repellency or inhibition effects, generated by plants' sensitivity to compounds released into the environment, can be observed [72].

4. Effects of Allelopathy on Weed and Pest Dynamics

Studies covering the effects of allelopathy on weeds have been analyzed in different areas at different stages and through various approaches in light of the complexity of this phenomenon, highlighting several types of effects, namely, through substances produced from acids [44,54,57–60], essential oils [42–44], aqueous extracts (Figure 2) [50,73–76], and microorganisms, bacteria or fungi [77] by direct application to the vegetative parts of plants, placed on the soil as fresh or decomposed compost [6], incorporated into the soil, or even through the roots of secretory plants cultivated in combined crops capable of synthesizing substances with inhibitory effects [9].

The allelochemical substances discovered and studied have demonstrated the possibility of introducing them into organic crop systems, with positive effects on inhibiting weed seed germination and on plant growth and development.

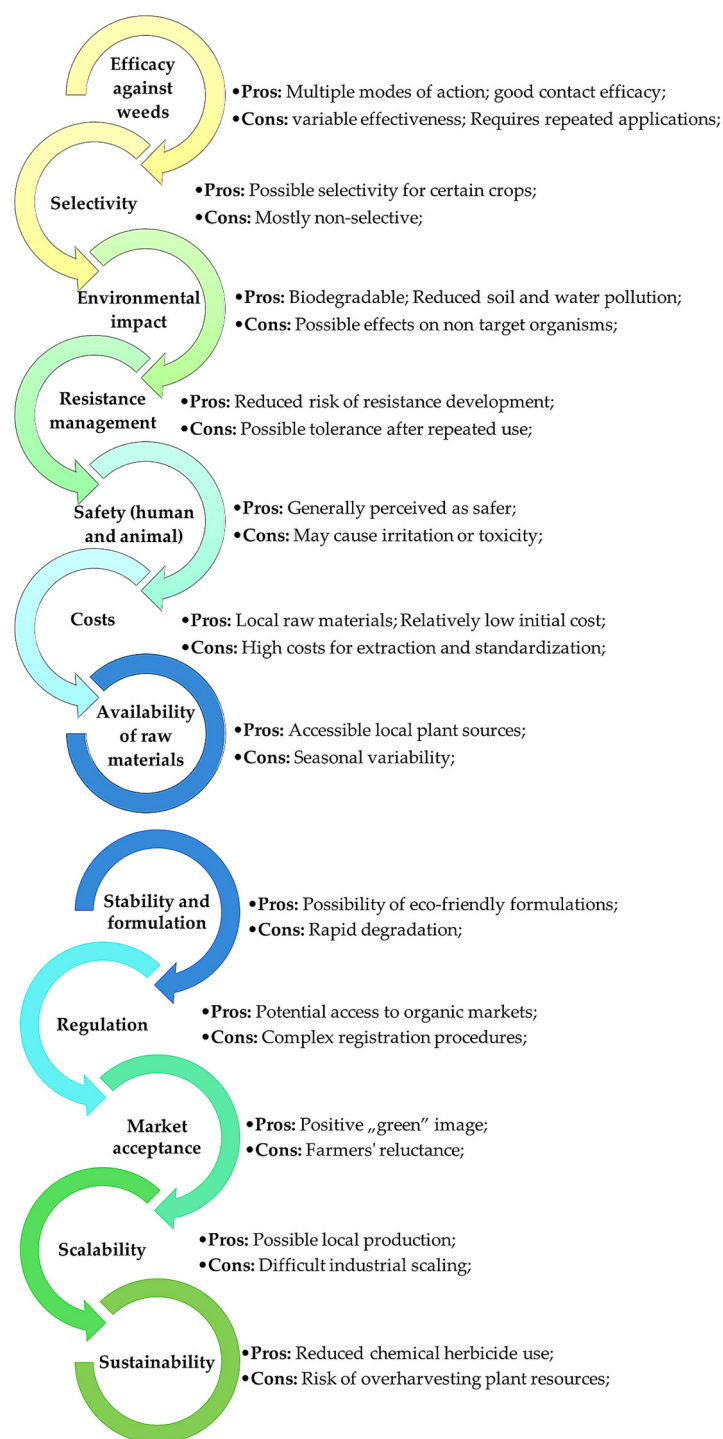


Figure 2. The benefits of using aqueous extracts in allelopathy.

In vegetable crops, aqueous plant extracts can also play a favorable role. These are solutions obtained by extracting chemical compounds with allelopathic potential from various plant parts, such as leaves, roots, stems, or seeds, using water as the solvent. These extracts contain a wide range of allelochemicals, including phenolic acids, flavonoids, alkaloids, terpenes, and sulfur compounds, substances known for their ability to influence the physiological processes of neighboring plants. *Lantana camara* L. is recognized as a medicinal plant used in traditional products due to its therapeutic properties; however, it also contains high levels of allelochemicals that confer allelopathic activity. Aqueous extracts obtained from vegetative tissues and callus of *Lantana camara* L. have shown variable allelopathic effects on seedlings of *Capsicum annuum* L., *Daucus carota* L., *Zea mays*

L., and *Sorghum bicolor* Moench., as well as on weed species such as *Brassica campestris* L. and *Ipomoea aquatica* Forssk [46,50].

Based on these findings, *Lantana camara* L. can be classified as an invasive and noxious species, as its allelopathic potential affects both vegetable and forage plants. Although it demonstrates inhibitory effects on weed species, its use also has potential negative consequences for cultivated vegetable crops [76].

The allelopathic effects of essential oils have been extensively investigated as sustainable alternatives for weed and pest management in agricultural systems. Essential oil extracted from basil (*Ocimum basilicum* L.) is effective against several problematic weed species, including *Agropyron repens* (L.) P. Beauv., *Setaria viridis* (L.) P. Beauv., *Amaranthus retroflexus* L., and *Echinochloa crus-galli* (L.) P. Beauv., when applied foliarly at different concentrations, provided surprising weed control results 10 days after application [43].

The bioherbicidal activity of basil is associated with its main active constituents, such as eugenol, which disrupts cell membrane integrity, estragole and linalool, which inhibit cell division and plant development, and camphor and cineole, which interfere with photosynthetic processes and limit physiological exchanges. In addition to foliar applications, basil can suppress weed growth in associated cropping systems by releasing allelochemicals into the soil through root exudates. However, basil essential oil can also exert phytotoxic effects on certain vegetable crops, including lettuce, negatively affecting seed germination and early seedling development [51,73,78–80].

The allelopathic potential of essential oils has been evaluated through laboratory and field studies to determine their applicability in both vegetable and agricultural cropping systems, for essential oils derived from aromatic and medicinal plants, such as coriander, oregano, rosemary, thyme, sage, mint and lavender, have been identified as weed growth inhibitors by inhibiting cell division and seed germination by acting on essential processes with the help of tannins, aldehydes, ketones, esters and ethers but also through volatile compounds contained and released through the roots at soil level but also by their volatilization during precipitation. In controlled laboratory experiments, essential oils obtained by steam distillation can be applied to weed seed substrates at different concentrations. The results indicate that the inhibitory effects increase in efficiency with increasing concentration, with optimal results observed especially in dicotyledonous species such as sesame and cowpea [42,81].

Similar allelopathic responses were observed following the application of the essential oils of *Cymbopogon citratus* (L.) Spreng. and *Ocimum gratissimum* L., in which the primary constituents citral, eugenol, and cineole significantly affected initial germination, total germination, and the germination rate index in species such as lettuce and related species. These effects led to reduced seed vigor and early plant development, highlighting the role of essential oils in regulating weed-crop dynamics [82].

In addition, essential oils derived from *Juniperus* spp. can be applied to broadleaf weed species present in field crops, acting by burning the plants and destroying the leaves, thereby inhibiting photosynthesis [53,60].

Pelargonic acid is increasingly used as a contact herbicide due to its antibacterial properties and its immediate inhibitory effects on plant growth, contributing to the prevention of infestations and the control of certain pathogens, as well as to the control of weeds in crops. Its mode of action involves the destruction of plant cell membranes and the inhibition of photosynthesis, while also exhibiting sanitizing activity against diseases and pests [59]. Based on a saturated nonanoic fatty acid [58], naturally present in plants of the *Pelargonium* family in esterified form, it is mainly used in urban and peri-urban areas to eliminate weeds in small vegetable crops, landscaped areas, and fruit orchards on private properties. In

liquid form, it can also be incorporated into the soil to act on weed roots and pests that overwinter there.

Pelargonic acid has been tested for its effects on weed growth and seed development in monocotyledons such as *Agropyron repens* (L.) P. Beauv., *Lolium rigidum* Gaud., and *Avena sterilis* L. [44], both individually and in combination with two essential oils, namely citrus oil (lemon or lemongrass) and manuka oil (tea tree). Combined treatments can produce stronger inhibitory effects, achieving up to 96% reductions in plant biomass following foliar applications. The general efficacy of pelargonic acid has been demonstrated in various laboratory and field studies; however, it also has disadvantages, such as rapid decomposition in soil and low efficacy in large agricultural crops. Its effects are being tested on a small scale [44,83].

Environmental factors influence allelopathic interactions involving fatty acids and phenolic compounds. The decomposition of phenolic compounds and carbon in the soil, along with nutrient availability, can be strongly influenced by environmental temperature [6] (Table 3). Rising temperatures increase the rate of decomposition of phenolic compounds, thereby intensifying their allelopathic effects on plant development. Under these conditions, seed germination and plant growth are reduced, resulting in an inverse relationship between environmental temperature, phenolic compound activity, and plant development parameters [57].

Sorgoleone is an important allelopathic compound involved in weed suppression and is naturally produced by sorghum roots. It is released through the hydrophobic exudates of *Sorghum bicolor* Moench., roots, and has herbicidal effects on neighboring plant species. According to the chemical structure of sorgoleone, 2-hydroxy-5-methoxy-1,4-benzoquinone, it falls into the class of classical benzoquinones with a high content of phenolic compounds and lipid compounds. The biosynthesis of sorgoleone in soil is mediated in most cases by the enzyme CYP71AM1 and other cytochrome P450 monooxygenases [84,85].

Table 3. Substances involved. Effects on weeds [6,21,63,86].

Plant Species/Group	Main Allelopathic Compounds	Effects and Relevance of Vegetables Cropping Systems
Rye (<i>Secale cereale</i> L.)	Benzoxazinoids (DIBOA/DIMBOA * derivatives), phenolic compounds	Strong residue and mulch effects on weed emergence suppression; widely used as an allelopathic cover crop
Sorghum/sorghum–Sudangrass (<i>Sorghum</i> spp.)	Sorgoleone (root exudate), phenolic compounds	Significant weed suppression, particularly in warm-season systems; effects associated with both root exudation and residue decomposition
Buckwheat (<i>Fagopyrum esculentum</i> Moench.)	Phenolic compounds	Rapid soil canopy development and effective competition with weeds; possible additional allelopathic contribution
Marigold (<i>Tagetes</i> spp.)	Thiophenes	Allelopathic effects are mainly discussed in the context of nematode and soil-borne pathogen management
Aromatic species (e.g., <i>Lamiaceae</i>)	Terpenoids	Antimicrobial and insecticidal properties; primarily used as plant extracts rather than as field-applied residues

* DIBOA/DIMBOA—secondary compounds produced by cereals.

Also, its analogues resorcinol and related hydroquinones are continuously secreted throughout the growth period of sorghum plants, allowing their prolonged persistence in the rhizosphere for a persistent effect on weed plants and pests, its longer persistence

in the soil and the specific substances for synthesis and transport at the root-soil level frame sorgoleone as a potent allelochemical and with high potential for use compared to pelargonic acid for example (Table 4) [84,87–98].

Table 4. Comparative table of the effect of the substances Sorgoleone and Pelargonic acid [59–62,87].

Criterion	Sorgoleone	Pelargonic Acid
Origin and nature	Natural allelopathic compound produced by the roots of sorghum (<i>Sorghum bicolor</i> L.), of phenolic/benzoquinone * nature.	Saturated fatty acid (C9 *), commercially used as a contact herbicide.
Mode of action	Inhibits photosynthesis, cellular respiration, and other metabolic processes; complex action with multiple targets.	Destroys the cellular membranes of green tissues upon contact, causing rapid dehydration.
Type of action	Mainly preventive, inhibiting germination and the growth of young plants.	Contact herbicide with rapid and visible effects on young plants.
Spectrum of control	Effective against several weed species, with variable sensitivity among species.	Non-selective; affects all plants it comes into contact with.
Soil persistence	May persist locally in the upper soil layer, exerting a prolonged allelopathic effect.	Low persistence; degrades relatively rapidly in the environment.
Mobility and residues	Low mobility; potential impact on subsequent crops if not properly managed.	Low risk of long-term residues.
Availability and use	Mainly studied experimentally; limited commercial use.	Commercially available in various formulations.
Environmental impact	High potential for use in ecological weed control strategies; still under study.	Considered relatively safe when used according to label instructions, but may also affect non-target plants.

* C9—nonanoic acid; benzoquinone—yellow crystalline organic compound.

5. Experimental Approaches Used in Allelopathy Research

The experimental approach to allelopathy is an essential tool for understanding the mechanisms by which plant-produced chemical compounds influence the growth and development of other plants. Laboratory experiments enable the isolation, identification, and testing of allelochemicals, including essential oils, organic acids, aqueous extracts, and various secondary metabolites. In-depth laboratory studies provide relevant data on the inhibitory effects of allelochemicals and allelopathy, constituting the scientific basis for extrapolating the results to greenhouse and field experiments and for developing sustainable weed control strategies (Table 5).

Table 5. Allelopathy targets. Objectives and characteristics [90,91].

Target Group	Primary Objective	Main Allelopathic Effects	Most Sensitive Stage	Key Compounds/ Plant Sources	Limitations /Variability
Weeds	Suppression of weed emergence and early growth	Inhibition of seed germination Reduced radicle and root growth Early seedling vigor reduction	Pre-emergence to early post-emergence	Phenolics (rye, buckwheat), benzoxazinoids (rye), sorgoleone (<i>Sorghum</i>), isothiocyanates (<i>Brassicaceae</i>)	Strongly species-dependent Small-seeded annuals are more sensitive Perennials and large-seeded weeds are less affected

Table 5. Cont.

Target Group	Primary Objective	Main Allelopathic Effects	Most Sensitive Stage	Key Compounds/ Plant Sources	Limitations /Variability
Soil-borne pathogens	Reduction of inoculum potential and disease pressure	Antimicrobial activity Enzyme and membrane damage Indirect suppression via microbiome shifts	Free-living or early infection stages	Isothiocyanates (<i>Brassicaceae</i>), phenolics, thiosulfonates (<i>Allium</i> spp.)	Narrow dose–time window Strong dependence on soil moisture and temperature Effects often transient
Nematodes	Suppression of population density and activity	Toxic effects on juveniles and eggs Interference with mobility and reproduction	Motile juvenile stages	Thiophenes (<i>Tagetes</i> spp.), isothiocyanates (<i>Brassicaceae</i>)	Species-specific responses Requires proper residue management Variable persistence in soil
Insect pests	Indirect regulation within IPM systems	Altered host plant quality Reduced herbivore performance Enhanced natural enemy interactions	Feeding and developmental stages	Terpenoids (aromatic plants), phenolics, sulfur-containing compounds	Weak direct allelopathic effects Mostly indirect and system-dependent Rarely effective as a stand-alone control

Essential oil derived from basil plants is an effective bioherbicide against *Agropyron repens* (L.) P. Beauv., *Setaria viridis* (L.) P. Beauv., *Amaranthus retroflexus* L., and *Echinochloa crus-galli* (L.) P. Beauv., plants. When applied to the leaves, it can significantly reduce weed biomass. In an experiment, five concentration variations were used, namely 0.8%, 1.6%, 3.2%, 6.4%, and 12.8% mg of pure extract, which, when applied after plant emergence, reduced plant biomass by up to 68% after foliar spraying. The results were recorded 10 days after treatment.

The effectiveness of essential oils has been tested in several ways, including laboratory experiments and in the outdoor environment (field studies), and they can bring major benefits to vegetable crops as well as large cereal crops. In a laboratory experiment, extracts from essential oils were obtained by steam distillation. For each extract, several concentrations were used, namely 3%, 6%, 10%, and 20%, which were applied to the substrate of the weed seeds. The allelochemicals derived from the aforementioned aromatic plants [42,43,55] are recognized in the paper as essential oils, volatile compounds, and etheric oils used in substances applied against weed seeds. The results obtained are presented in the study for each concentration, with the best and most accurate results being obtained at concentrations higher than 6%, and especially in dicotyledonous plants such as sesame and peas. The inhibitory effects were evident 14 days after germination, with an inhibition rate of 88% compared to the control group.

The potential of pelargonic acid to inhibit growth and reduce weed seed development in crops studied in [44] was remarkable, particularly against monocotyledonous weeds such as *Agropyron repens* (L.) P. Beauv., *Lolium rigidum* Gaud., and *Avena sterilis* L. Pelargonic acid was used on its own and in combination with two essential oils, one citrus lemon oil and one manuka or tea tree oil, with this combination achieving exceptional results of up to a 96% reduction in plant biomass after foliar application.

According to the study, the action of the compounds in pelargonic acid, together with lemongrass and manuka essential oils, was 90% effective. The same study (cited above) also found that lemongrass oil acts as a contact agent, whereas manuka oil acts systemically against common weeds in vegetable crops [58].

The *Nicotiana benthamiana* plants on which the tests were performed were obtained from the National Germplasm Resources Laboratory (Beltsville, MD, USA) and kept in growth chambers at temperatures of 24 °C, 16 h of light, and 8 h of darkness. The extraction

and identification of P450 and CYP71 enzymes were performed from isolated cells of *Sorghum bicolor* Moench, roots, using BLASTN and TBLASTN analyses [84].

This study focused on identifying and recognizing the enzymes involved, including fatty acid O-methyltransferase and alkylresorcinol. In the final stage of the study, cytochrome P450 enzymes were involved in the reactions, mediating dihydroxylation, which results in the production of dihydro-sorgoleone, which, once in the soil, oxidizes and eliminates the phytotoxic element called sorgoleone [92].

A study based on the expression of the effect of jasmonic acid (JA) and methyl jasmonates (MeJA) on sorgoleone synthesis in sorghum roots. The jasmonate content influenced sorgoleone content in the plant, increasing sorgoleone levels with increasing JA and MeJA concentrations compared to the level in untreated control plants. Lower treatment concentrations influenced the occurrence of root variation and the number of secondary roots and branches. Root weight also increased at a concentration lower than 5 μM , whereas development was inhibited with increasing concentrations of the two compounds JA and MeJA [87].

The study shows that sorghum roots and their development are directly influenced by jasmonates and methyl jasmonates at varying concentrations. At a concentration of 0.5 μM , development occurs with a slight increase in activity. In comparison, using a dose above 1 μM causes an adverse reaction that inhibits the activity of substances secreted by sorghum roots. The growth and development of root hairs slowed down as jasmonic acid concentrations increased [87,93].

Aqueous extracts from sunflower, sorghum, and rice on weed plants showed excellent results in the case of *Parthenium hysterophorus* L. (Table 6). The extracts were obtained from roots and shoots, and several dilutions with different concentrations of the active substance were performed (5%, 10%, 15%, 20%, 25%). The active substance was applied to the aerial parts of the plants as well as to their seeds. Extracts were also prepared from plant buds, which had a much greater phytotoxic effect on the root growth of parthenium plants [76,94,95].

Table 6. Plants with allelopathic potential and their action.

Allelopathic Plant	Target Species	Application/ Method	Conc.	Observed Effect	Mode of Action	Involved Compounds	Observations	References
Basil (essential oil)	<i>Agropyron repens</i> (L.) P. Beauv., <i>Setaria viridis</i> (L.) P. Beauv., <i>Amaranthus retroflexus</i> L., and <i>Echinochloa crus-galli</i> (L.) P. Beauv.	Foliar application	0.8–12.8%	Biomass reduction up to 68% (10 days)	Contact phytotoxicity	Volatile essential oils	Concentration-dependent effect	[43,51]
Aromatic essential oils	Weed seeds (dicotyledonous species)	Substrate application	3–20%	Germination inhibition up to 88%	Inhibition of germination and early growth	Volatile, etheric compounds	Increased efficiency above 6%	[42,55]
Pelargonic acid + essential oils	<i>Agropyron repens</i> (L.) P. Beauv., <i>Lolium rigidum</i> Gaud., et <i>Avena sterilis</i> L.	Foliar application	-	Biomass reduction up to 96%	Contact and systemic action	Pelargonic acid, lemon essential oil, and manuka oil	~90% efficiency in combinations	[44,59]
<i>Sorghum</i> (sorgoleone)	Agricultural weeds	Root release	-	Radicular phytotoxic effect	Chemical inhibition at the soil level	Sorgoleone, p450 enzymes	JA > 1 μM inhibits development	[87,96]
<i>Helianthus</i> , <i>Sorghum</i> , <i>Rice</i> (aqueous extracts)	<i>Parthenium hysterophorus</i> L.	Application to leaves and seeds	5–25%	<i>Helianthus</i> : 69%, <i>sorghum</i> : 56%	Inhibition of germination and growth	Water-soluble compounds	Bud extracts showed the highest efficiency	[76]

JA—Jasmonic acid.

The study showed that root extracts were less toxic than shoot extracts, with results observed only at 25% concentration. Extracts from the vegetative parts showed better results at minimum concentrations and very good results at maximum concentrations. Rice extracts showed distinct results, with low allelopathic activity; only at concentrations of 20 and 25% were root extracts ineffective (Table 6). For the *Helianthus* species, the results were up to 69% inhibition of germination, and for the *Sorghum* species, up to 56%.

The reviewed studies highlight the potential of natural plant-derived compounds, such as essential oils, aqueous extracts, and plant-derived fatty acids, as sustainable alternatives for weed control. The observed allelopathic effects include germination inhibition, biomass reduction, and root development impairment, the intensity of which depends on concentration, application method, and the specific target's sensitivity.

The combined use of bioactive substances, especially pelargonic acid with essential oils, leads to synergistic effects and superior efficiency compared to individual application. The presented results support the use of allelopathy as a context and management mechanism, with potential applications in the development of bioherbicides and integrated weed control strategies; further studies under field conditions are necessary to validate and optimize these approaches.

6. Allelopathy in Sustainable and Organic Vegetable Production

In the context of sustainable and organic vegetable production, allelopathy represents a valuable ecological mechanism that can be strategically integrated into agroecosystem management to reduce weed pressure and reliance on synthetic chemical inputs. Sustainable agriculture emphasizes environmentally friendly practices that maintain soil health, preserve biodiversity, and minimize negative ecological impacts. At the same time, organic farming strictly limits the use of synthetic herbicides, thereby necessitating alternative weed control strategies (Figure 3).

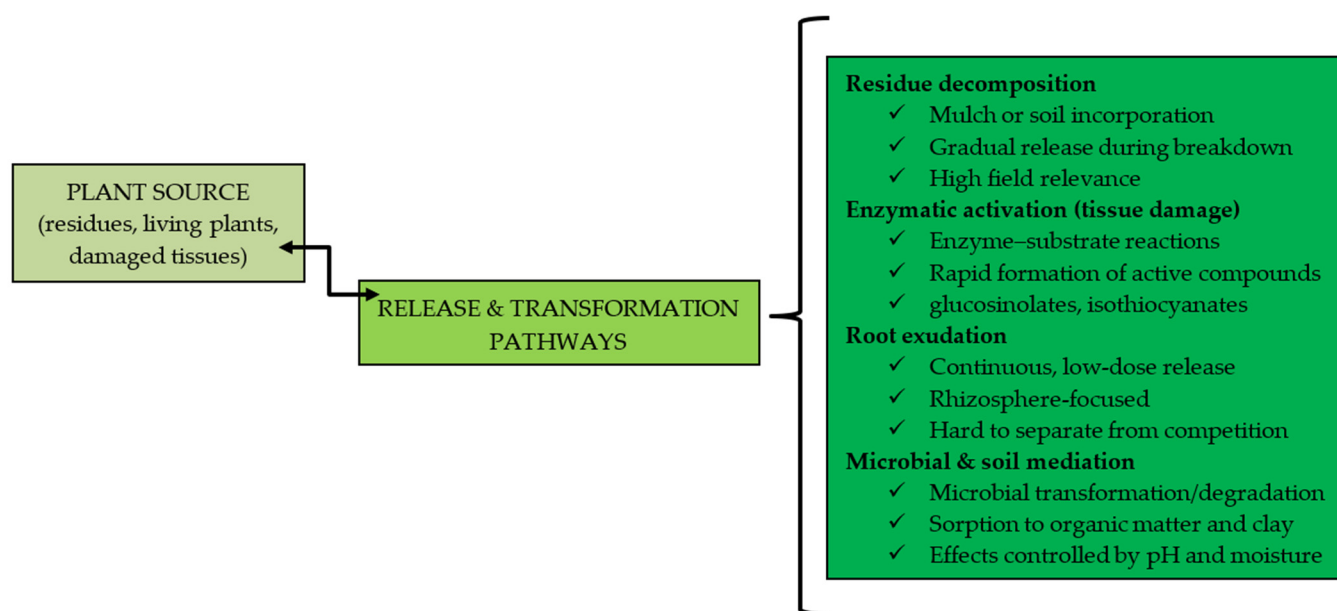


Figure 3. The conceptual framework of allelopathic mechanisms by the plant source.

Crop rotation is a fundamental agricultural practice that involves systematically alternating different crop species on the same land over time. This prevents the continuous cultivation of the same plant species, which would otherwise favour the growth of specific weed communities adapted to those conditions. Because cultivated plants have different nutritional requirements, root architectures, and growth dynamics, crop rotation alters

the ecological niches available to weeds, thereby reducing their abundance and diversity. Furthermore, crop rotation involves dividing agricultural land into plots that are sown with different crops each year, thereby disrupting weed life cycles and gradually reducing weed biomass (Figure 4). Consequently, the need for chemical herbicides is significantly reduced, contributing to more sustainable and environmentally sound cropping systems [97,98].

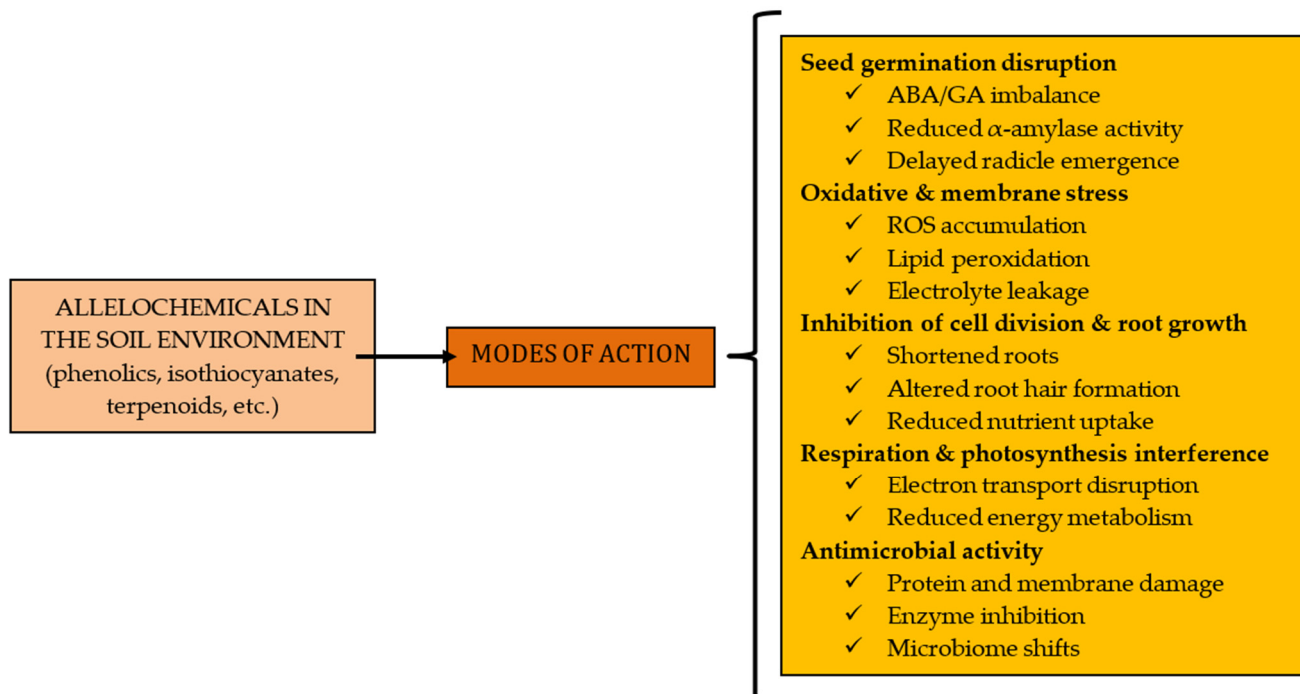


Figure 4. The conceptual framework of allelopathic mechanisms by the source of allelochemicals.

Intercropping is another important practice widely used in vegetable production and small-scale farming systems, though it can also be applied in larger agricultural operations. This method involves the simultaneous cultivation of two or more plant species or the use of cover crops [99] alongside the main crop. Intercropping systems primarily suppress weeds by reducing the amount of light reaching the soil surface, a critical factor for weed seed germination and early seedling development. In addition, intercrops compete with weeds for essential resources such as nutrients, water, and space, further limiting the establishment of invasive species in cultivated fields or gardens [12,100]. In some cases, the allelopathic potential of certain cover crops enhances this suppressive effect through the release of bioactive compounds into the soil (Figure 5) [23,96].

Traditionally, weed control in agricultural systems has relied on mechanical methods, including soil tillage, manual or mechanical weeding, and mulching. These approaches physically remove weeds without chemical inputs and remain widely accepted in organic farming. However, they are often labor-intensive and time-consuming, particularly in small-scale vegetable production systems. In response to these limitations, increasing attention has been directed toward the development and implementation of bioherbicides as innovative alternatives. Bioherbicides based on plant extracts, fatty acids, essential oils, or beneficial microorganisms offer a promising solution for sustainable weed management, aligning with the principles of organic farming and environmental protection [30].

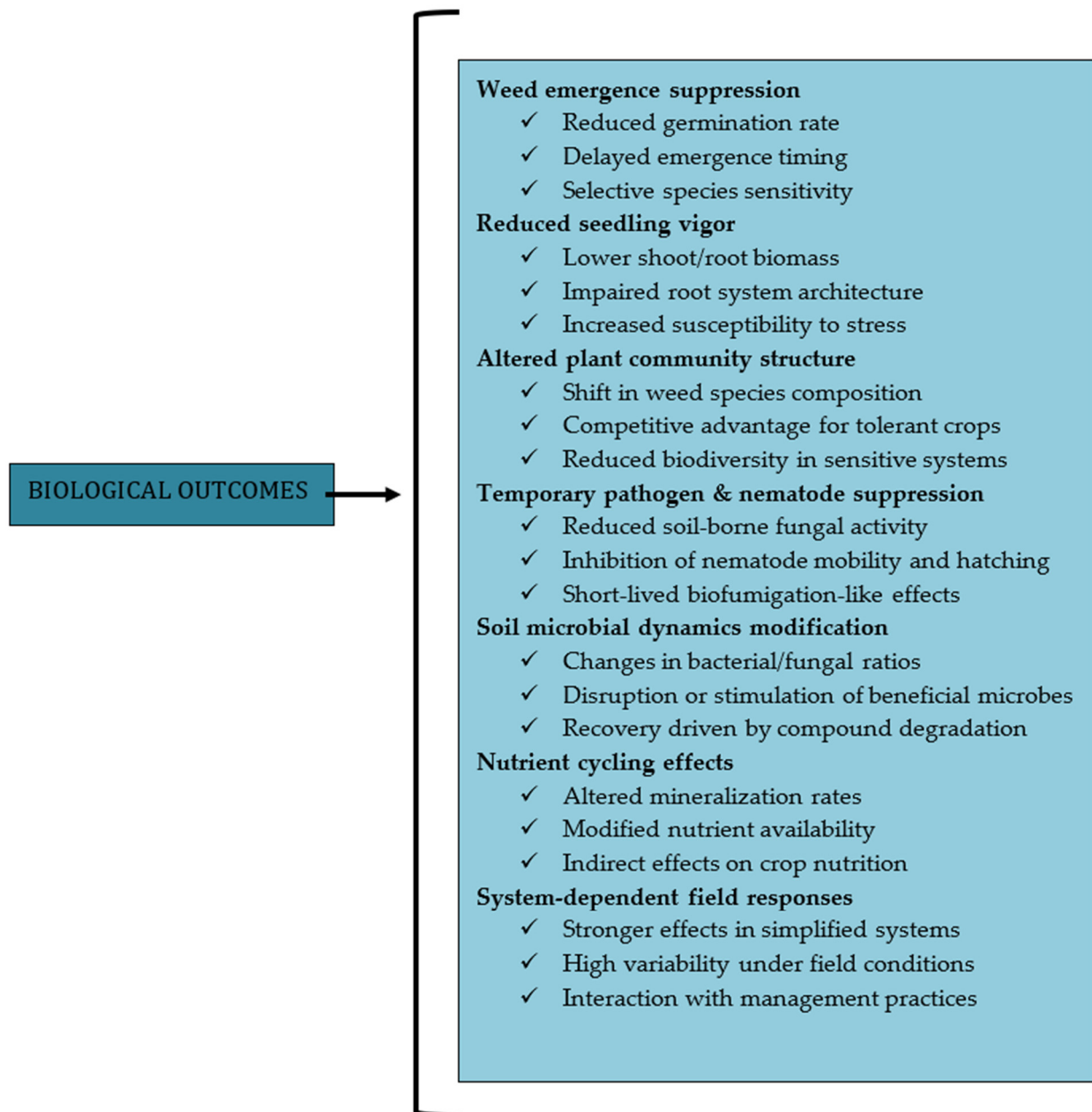


Figure 5. The conceptual framework of allelopathic mechanisms by the biological outcomes.

By definition, bioherbicides are products derived from natural sources, including microorganisms (such as bacteria, fungi, and viruses), plant-derived compounds, or other organic compounds, and are used for weed control. These products are considered ecological alternatives to conventional chemical herbicides and, in some cases, to treatments applied against plant diseases and pests. Their use is associated with a reduced environmental impact, lower toxicity to non-target organisms, and improved compatibility with biodiversity conservation strategies [11,43,73].

Bioherbicides can be classified into several main categories based on their origin and mode of action.

- (a) Microorganism-based bioherbicides contain bacteria or fungi capable of producing secondary metabolites that inhibit the germination and development of weed seeds or seedlings. Representative examples include *Phytophthora palmivora* Butler., which has been used to control weeds in perennial crops, and *Alternaria cassiae* Ness., which exhibits activity against specific weed species in legume crops [13,80,101,102]. These

biological agents act by infecting, producing toxins, or interfering with essential physiological processes in target weeds.

- (b) Plant extract-based bioherbicides rely on natural compounds produced by plants with allelopathic potential. Certain plant species can secrete volatile or water-soluble substances with herbicidal properties, which can be exploited for weed management. Extracts derived from pelargonium or citrus plants have demonstrated effectiveness against annual weeds. Pelargonic acid, a naturally occurring monocarboxylic acid found in *Pelargonium* species and several other plants, is widely used as a contact bioherbicide, causing rapid desiccation of weed tissues upon application [44,57–60,87,88,103,104].
- (c) Organic acids and essential oils constitute another important group of bioherbicides. These natural substances are predominantly obtained from aromatic and medicinal plants and exhibit strong allelochemical properties. Their herbicidal activity is often associated with damage to cellular membranes and disruption of metabolic processes in weed tissues. *Citrus* oil, for instance, is used as a contact bioherbicide, while fatty acids such as caprylic and capric acid exert phytotoxic effects by dissolving the protective waxy layer of leaves. Additionally, lipid benzoquinones such as sorgoleone are produced by *Sorghum* Moench. species, interfere with photosynthetic processes and membrane integrity, ultimately leading to plant death [54,59,60,96].

Overall, integrating allelopathy-based strategies and bioherbicides into sustainable, organic vegetable production systems offers significant potential for effective weed control while reducing dependence on synthetic chemical herbicides. These approaches support the development of resilient agroecosystems that balance productivity with environmental stewardship.

7. Challenges, Knowledge Gaps, and Future Research Directions

A recurring pattern in the literature on allelopathy is the significant discrepancy between the activities obtained under controlled conditions and those observed in field experiments. Studies conducted in the laboratory or greenhouse frequently report pronounced inhibitory effects on germination and plant growth due to the use of high concentrations of allelopathic compounds that often exceed naturally occurring levels in the soil. These effects are amplified by the reduced buffering capacity of the substrate used, the absence or limited activity of microbial communities, and uniform environmental conditions, which reduce degradation processes, adsorption, or chemical transformation of allelochemicals.

In contrast, studies conducted under field conditions reflect the complexity and heterogeneity of the natural environment, where the non-uniform distribution of allelopathic compounds, soil dynamics, and biotic interactions significantly influence the intensity and persistence of the observed effects (Table 7). In these systems, allelochemicals are subject to processes of dilution, leaching, adsorption onto soil particles, and microbial transformation, which can considerably reduce their bioavailability and biological activity. In addition, confounding physical effects, such as shading, changes in soil temperature, moisture retention, or structural changes induced by crop residues, can mask or amplify plant responses, making it difficult to attribute observed effects solely to chemistry.

Table 7. Comparative data between laboratory studies and field studies [105–107].

Aspect	Greenhouse/ Pot Experiments	Field Studies	Implications for Interpretation
Allelochemical concentration	Highly effective concentrations due to small soil volume and limited dilution	Strong dilution and uneven spatial distribution	Greenhouse results often overestimate field-level effects
Soil microbial complexity	Reduced microbial diversity and activity	High microbial diversity and functional redundancy	Rapid degradation or transformation of allelochemicals in field soils
Environmental conditions	Controlled moisture and temperature	Highly variable, weather-dependent	The activation and decay of compounds depend on rainfall and temperature
Residue–soil contact	Uniform mixing and contact	Variable incorporation depth and mulch distribution	Inconsistent exposure of target organisms in the field
Chemical persistence	Longer persistence of active compounds	Short-lived activity due to leaching, volatilization, and microbial breakdown	Narrow dose–time window under field conditions
Confounding mechanisms	Largely minimized or absent	Dominant (mulch shading, physical suppression, nutrient dynamics, competition)	Difficult to separate chemical effects from physical and ecological ones
Reproducibility	High experimental repeatability	Lower reproducibility across sites and seasons	Multi-site and multi-year trials are required
Predictive value for practice	Useful for mechanistic understanding	Essential for agronomic validation	Field studies are the ultimate test of practical relevance

This scale dependence emphasizes that allelopathy in crop systems must be understood as a process shaped by ecological context and agricultural management practices, rather than as a universal, predictable, and constant mechanism of chemical control. The efficiency of allelopathic interactions is influenced by factors such as soil type, moisture regime, microbial community structure, crop rotation, and crop residue management. Therefore, extrapolation of results obtained under controlled conditions to the field scale requires methodological caution.

In this sense, drawing relevant conclusions for the practical application of allelopathy requires prioritizing studies conducted across multiple locations and over multiannual periods that capture the spatial and temporal variability of agricultural ecosystems. It is also essential to explicitly separate the chemical effects of allelochemicals from physical and competitive interactions between plants by using appropriate experimental designs and complementary analytical methods. Only through such an integrated approach can the potential of allelopathy as a functional tool in sustainable crop management be realistically assessed.

Starting from the frequent observation in the literature of a consistent discrepancy between activities obtained under controlled conditions (in laboratories or greenhouses) and those observed in the field, this paper discusses the pedological, biotic, and experimental factors that determine this variability, as well as the analytical and experimental methods necessary to advance understanding of, and practical application of, allelopathy.

Many studies reported in the literature indicate the strong inhibitory effects of plant extracts or isolated compounds on germination and growth under controlled conditions. However, these effects are often not confirmed or are greatly reduced at the field scale. Possible explanations include concentrations used in laboratories that exceed natural soil levels; substrates with low buffering capacity; the absence or weak activity of microbial communities that degrade or transform allelochemicals; and uniform environmental conditions that minimise dispersion, adsorption, and degradation processes (Table 8).

Table 8. Synthesis of methodological challenges in allelopathy [105–109].

Category	Key Aspect	Concise Description	Implications for Research and Practice
Methodological challenges	Unrealistic concentrations	Use of crude extracts or pure compounds at concentrations exceeding those naturally occurring in soils	Overestimation of allelopathic potential and limited field relevance
Methodological challenges	Inadequate experimental controls	Use of activated carbon may alter nutrient availability and microbial activity	Misinterpretation of strictly chemical allelopathic effects
Methodological challenges	Limited spatial and temporal replication	Field studies conducted at a single site or during a single growing season	Reduced the generalizability and reproducibility of results
Methodological challenges	Confounding mechanisms	Physical effects and resource competition are not clearly separated from chemical effects	Difficulty in attributing observed effects exclusively to allelopathy
Knowledge gaps	Actual soil concentrations	Lack of data on the real spatial and temporal levels of allelochemicals in soils	Uncertainty regarding ecological and agronomic relevance
Knowledge gaps	Molecular mechanisms	Limited understanding of the physiological and molecular responses of target plants under natural conditions	Restricted ability to predict crop and weed responses
Knowledge gaps	Multitrophic interactions	Insufficient investigation of effects on soil microorganisms and other trophic levels	Underestimation of indirect effects and ecological feedbacks
Knowledge gaps	Long-term effects	Scarcity of multi-annual and crop rotation studies	Poor understanding of cumulative impacts in agricultural systems
Future directions	Multi-site, multi-year studies	Replicated experiments across locations and years	Increased robustness and transferability of findings
Future directions	Advanced chemical analytics	Integration of lc–ms/ms, metabolomics, and isotopic tracing	Accurate quantification and tracking of allelochemicals
Future directions	Factorial experimental designs	Experimental separation of competition, physical, and chemical effects	Clear identification of dominant mechanisms

Table 8. *Cont.*

Category	Key Aspect	Concise Description	Implications for Research and Practice
Future directions	Microbial ecology focus	Studies on microbial degradation and adaptation to allelochemicals	Improved prediction of persistence and efficacy in soils
Future directions	Integrated modeling	Development of soil–plant–microbe mechanistic models	Predictive assessment of allelopathy under field conditions
Future directions	Agronomic evaluation	Assessment of benefits and risks in real cropping systems	Realistic implementation in sustainable agriculture

These factors lead to overestimation of allelopathic potential when extrapolating to real agroecosystem conditions. In soil, the ‘bioactive’ concentration of an allelochemical results from a dynamic balance between source (exudation and decomposition), sorption to soil particles, leaching, and abiotic and biotic degradation and chemical transformations (e.g., hydrolysis and oxidation). Soil characteristics such as texture, organic matter content, pH, and iron and aluminium content strongly influence the sorption and mobility of phenolic, coumarin, and quinone compounds.

Studies investigating sorption and persistence reveal significant variability among soils and demonstrate that many allelochemicals are rapidly adsorbed or metabolised, reducing their long-term effects and durability. These processes must be considered when interpreting allelopathic efficacy in the field.

Allelopathy is a biological phenomenon with real agronomic potential. However, its practical use in crop management requires a methodological reorientation, shifting the focus from “demonstration” studies conducted under controlled conditions to interdisciplinary, multi-site, and multi-annual projects that integrate environmental chemistry, microbial ecology, modelling, and agronomy. Only by taking a holistic, rigorous, and reproducible approach will we be able to accurately evaluate the role that allelopathy can play in sustainable agricultural systems.

8. Conclusions

Allelopathy can contribute to weed control in vegetable systems, particularly when integrated into practices involving plant residues, mulching, and high-biomass cover crops. In such systems, biochemical interactions operate alongside physical suppression mechanisms to limit weed development.

The widespread adoption of allelopathy remains limited by inconsistent performance under field conditions, which is primarily influenced by soil properties and climatic variability. This highlights the need for standardized management approaches specific to horticulture, rather than relying exclusively on laboratory bioassays.

Numerous allelopathic compounds with inhibitory effects on plant growth have been identified, particularly from aromatic and medicinal species. Evidence from both vegetable and cereal cropping systems suggests that these compounds can reduce weed pressure and decrease reliance on synthetic inputs.

The biological activity of allelochemicals largely depends on their chemical structure and mode of action, affecting processes such as seed germination, early seedling development, oxidative stress responses, and biomass accumulation.

Allelopathic substances represent a promising and environmentally sound tool for weed management in organic farming, with potential benefits for biodiversity conservation, soil quality improvement, and reduced herbicide use.

Future research should prioritize field-scale validation and the identification of novel allelopathic compounds and mechanisms of action, enabling the development of practical management protocols and supporting more sustainable vegetable production systems.

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References

1. Rice, E.L. *Allelopathy*; Academic Press: Cambridge, MA, USA, 1974; ISBN 0-12-587050-7.
2. Istrate, A.-M.-R.; Stoleru, V. Studies on the Behavior of Peri-Urban Iasi Inhabitants Toward Decorative Vegetable Gardens. In *ISHS Acta Horticulturae 1441: EHC2024: International Symposium on Urban Horticulture: From Vertical Farming to Planting Design*; ISHS: Leuven, Belgium, 2025; pp. 89–96. [\[CrossRef\]](#)
3. Istrate, A.-M.-R.; Cojocariu, M.; Teliban, G.-C.; Cojocaru, A.; Stoleru, V. Quality and Yield of Edible Vegetables from Landscape Design. *Horticulturae* **2023**, *9*, 615. [\[CrossRef\]](#)
4. Cheema, Z.A.; Farooq, M.; Wahid, A. *Allelopathy: Current Trends and Future Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; ISBN 978-3-642-30594-8.
5. Revillini, D.; David, A.S.; Reyes, A.L.; Knecht, L.D.; Vigo, C.; Allen, P.; Searcy, C.A.; Afkhami, M.E. Allelopathy-Selected Microbiomes Mitigate Chemical Inhibition of Plant Performance. *New Phytol.* **2023**, *240*, 2007–2019. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Al Harun, A.Y.; Johnson, J.; Uddin, N.; Robinson, R.W. The Effects of Temperature on Decomposition and Allelopathic Phytotoxicity of Boneseed Litter. *J. Environ. Sci.* **2015**, *33*, 1–11. [\[CrossRef\]](#)
7. Altman-Kurosaki, N.T.; Pratte, Z.A.; Stewart, F.J.; Hay, M.E. Coral–Algal Competition: Allelopathy, Temporal Variance, and Effects on Coral Microbiomes. *Coral Reefs* **2025**, *44*, 49–62. [\[CrossRef\]](#)
8. Calara, M.; Munteanu, N.; Brezeanu, C.; Brezeanu, P.M.; Balaita, C.; Antal Tremurici, A.; Muscalu, S.P.; Stoleru, V.; Stan, T.; Teliban, G.C.; et al. Weed Infestation Dynamics Influenced by Some Allelopathic Species in Climbing Bean (*Phaseolus vulgaris*) Crop. In *Lucrari Stiintifice, Seria Horticultura*; Editura “Ion Ionescu de la Brad”: Iași, Romania, 2024; Volume 67, p. 121.
9. Kumar, N.; Singh, H.; Giri, K.; Kumar, A.; Joshi, A.; Yadav, S.; Singh, R.; Bisht, S.; Kumari, R.; Jeena, N.; et al. Physiological and Molecular Insights into the Allelopathic Effects on Agroecosystems Under Changing Environmental Conditions. *Physiol. Mol. Biol. Plants* **2024**, *30*, 417–433. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Choudhary, C.S.; Behera, B.; Raza, M.B.; Mrunalini, K.; Bhoi, T.K.; Lal, M.K.; Nongmaithem, D.; Pradhan, S.; Song, B.; Das, T.K. Mechanisms of Allelopathic Interactions for Sustainable Weed Management. *Rhizosphere* **2023**, *25*, 100667. [\[CrossRef\]](#)
11. El Marsni, Z.; Casas, L.; Mantell, C.; Rodríguez, M.; Torres, A.; Macias, F.A.; Martínez de la Ossa, E.J. Allelopathic Properties of the Fractions Obtained from Sunflower Leaves Using Supercritical Carbon Dioxide: The Effect of Co-Solvent Addition. *J. Supercrit. Fluids* **2013**, *82*, 221–229. [\[CrossRef\]](#)
12. Meiners, S.J. Functional Correlates of Allelopathic Potential in a Successional Plant Community. *Plant Ecol.* **2014**, *215*, 661–672. [\[CrossRef\]](#)
13. Guo, X.; Liu, X.-Y.; Jiang, S.-Y.; Guo, S.-X.; Wang, J.-F.; Hu, Y.; Li, S.-M.; Li, H.-M.; Wang, T.; Sun, Y.-K.; et al. Allelopathy and Arbuscular Mycorrhizal Fungi Interactions Shape Plant Invasion Outcomes. *NeoBiota* **2023**, *89*, 187–207. [\[CrossRef\]](#)

14. Shadab, M.; Bhatti, N.; Ain, Q.; Akhtar, N.; Parveen, U.; Alharby, H.F.; Hakeem, K.R.; Siddiqui, M.B. Allelopathy for the Sustainable Management of Agricultural Pests: Appraisal of Major Allelochemicals and Mechanisms Underlying Their Actions. *S. Afr. J. Bot.* **2024**, *175*, 496–513. [\[CrossRef\]](#)
15. Callaway, R.M.; Vivanco, J.M. Invasion of Plants into Native Communities Using the Underground Information Superhighway. *Allelopath. J.* **2007**, *19*, 143–152.
16. Molisch, H. *Der Einfluß Einer Pflanze Auf Die Andere Allelopathie*; Gustav Fischer: Jena, Germany, 1937.
17. Rice, E.L. Allelopathy—An Overview. In *Chemically Mediated Interactions Between Plants and Other Organisms*; Cooper-Driver, G.A., Swain, T., Conn, E.E., Eds.; Springer: Boston, MA, USA, 1985; pp. 81–105, ISBN 978-1-4757-9658-2.
18. Inderjit; Duke, S.O. Ecophysiological Aspects of Allelopathy. *Planta* **2003**, *217*, 529–539. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Jabran, K.; Mahajan, G.; Sardana, V.; Chauhan, B.S. Allelopathy for Weed Control in Agricultural Systems. *Crop Prot.* **2015**, *72*, 57–65. [\[CrossRef\]](#)
20. Price, A.; Kelton, J. Allelopathic Weed Suppression Through the Use of Cover Crops. In *Weed Control*; BoD—Books on Demand: Norderstedt, Germany, 2012; pp. 12–30, ISBN 978-953-51-0159-8.
21. Tabaglio, V.; Marocco, A.; Schulz, M. Allelopathic Cover Crop of Rye for Integrated Weed Control in Sustainable Agroecosystems. *Ital. J. Agron.* **2013**, *8*, e5. [\[CrossRef\]](#)
22. Ullah, R.; Aslam, Z.; Attia, H.; Sultan, K.; Alamer, K.H.; Mansha, M.Z.; Althobaiti, A.T.; Kashgry, N.A.T.A.; Algethami, B.; Zaman, Q.u.; et al. Sorghum Allelopathy: Alternative Weed Management Strategy and Its Impact on Mung Bean Productivity and Soil Rhizosphere Properties. *Life* **2022**, *12*, 1359. [\[CrossRef\]](#)
23. Hoffman, M.L.; Weston, L.A.; Snyder, J.C.; Regnier, E.E. Allelopathic Influence of Germinating Seeds and Seedlings of Cover Crops on Weed Species. *Weed Sci.* **1996**, *44*, 579–584. [\[CrossRef\]](#)
24. Bangarwa, S.K.; Norsworthy, J.K.; Mattice, J.D.; Gbur, E.E. Glucosinolate and Isothiocyanate Production from Brassicaceae Cover Crops in a Plasticulture Production System. *Weed Sci.* **2011**, *59*, 247–254. [\[CrossRef\]](#)
25. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental Impact of Different Agricultural Management Practices: Conventional Vs. Organic Agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124. [\[CrossRef\]](#)
26. Morra, M.J.; Kirkegaard, J.A. Isothiocyanate Release from Soil-Incorporated Brassica Tissues. *Soil. Biol. Biochem.* **2002**, *34*, 1683–1690. [\[CrossRef\]](#)
27. Ko, D.-Y.; Seo, S.-M.; Lee, Y.-H.; Gil, C.S.; Lee, H.; Ku, K.-M. Turning Glucosinolate into Allelopathic Fate: Investigating Allyl Isothiocyanate Variability and Nitrile Formation in Eco-Friendly Brassica Juncea from South Korea. *Sci. Rep.* **2024**, *14*, 15423. [\[CrossRef\]](#)
28. Hanschen, F.S.; Winkelmann, T. Biofumigation for Fighting Replant Disease—A Review. *Agronomy* **2020**, *10*, 425. [\[CrossRef\]](#)
29. Ji, Y.; Zhang, Y.; Fang, W.; Li, Y.; Yan, D.; Cao, A.; Wang, Q. A Review of Biofumigation Effects with Plant Materials. *New Plant Prot.* **2024**, *1*, e21. [\[CrossRef\]](#)
30. Singh, H.P.; Batish, D.R.; Kohli, R.K. Allelopathic Interactions and Allelochemicals: New Possibilities for Sustainable Weed Management. *Crit. Rev. Plant Sci.* **2003**, *22*, 239–311. [\[CrossRef\]](#)
31. Khamare, Y.; Chen, J.; Marble, S.C. Allelopathy and Its Application as a Weed Management Tool: A Review. *Front. Plant Sci.* **2022**, *13*, 1034649. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Hickman, D.T. Cropping System Redesign for Allelopathy: A Vision for the ‘Post-Herbicide Era’. *Weed Res.* **2025**, *65*, e70022. [\[CrossRef\]](#)
33. Stoleru, V.; Munteanu, N.; Stoleru, C.M.; Rotaru, L. Cultivar Selection and Pest Control Techniques on Organic White Cabbage Yield. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2012**, *40*, 190–196. [\[CrossRef\]](#)
34. Calara, M.; Munteanu, N.; Brezeanu, C.; Brezeanu, P.M.; Avasiloeaiei, D.I. Allelopathic Potential Assessment of Different Vegetal Extracts on Lettuce Seed Germination. In *Lucrări Stiintifice, Seria Horticultura*; Editura “Ion Ionescu de la Brad”: Iași, Romania, 2023; Volume LXVII.
35. Calara, M.; Munteanu, N.; Avasiloeaiei, D.I.; Brezeanu, C.; Brezeanu, P.M.; Hlihor, M. Assessing the Allelopathic Potential of Various Species for Weed Control in Organic Farming on a Climbing Bean Crop. In *Lucrări Stiintifice, Seria Horticultura*; Editura “Ion Ionescu de la Brad”: Iași, Romania, 2023; Volume LXVIII.
36. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Is There a Need for a More Sustainable Agriculture? *Crit. Rev. Plant Sci.* **2011**, *30*, 6–23. [\[CrossRef\]](#)
37. Islam, A.K.M.M. Allelopathy of Five Lamiaceae Medicinal Plant Species, Extended Summary in Lieu of Dissertation. Ph.D. Thesis, Ehime University, Matsuyama, Japan, 2014.
38. Allelopathy. Available online: <https://en.wikipedia.org/w/index.php?title=Allelopathy&oldid=1318939567> (accessed on 20 January 2026).
39. Bezuidenhout, S.R. KZN Agriculture & Rural Development—Allelopathy. Available online: <https://www.kzndard.gov.za/allelopathy> (accessed on 20 January 2026).
40. McCoy, R.M.; Widhalm, J.R.; McNickle, G.G. Allelopathy as an Evolutionary Game. *Plant Direct* **2022**, *6*, e382. [\[CrossRef\]](#)

41. Indrea, D.; Apahidean, A.S.; Sima, R. *Legumicultură*; Academic Press: Cluj-Napoca, Romania, 2012.
42. Azirak, S.; Karaman, S. Allelopathic Effect of Some Essential Oils and Components on Germination of Weed Species. *Acta Agric. Scand. Sect. B Soil. Plant Sci.* **2008**, *58*, 88–92. [\[CrossRef\]](#)
43. Khare, P.; Srivastava, S.; Nigam, N.; Singh, A.K.; Singh, S. Impact of Essential Oils of *E. Citriodora*, *O. Basilicum* and *M. Arvensis* on Three Different Weeds and Soil Microbial Activities. *Environ. Technol. Innov.* **2019**, *14*, 100343. [\[CrossRef\]](#)
44. Travlos, I.; Rapti, E.; Gazoulis, I.; Kanatas, P.; Tataridas, A.; Kakabouki, I.; Papastylianou, P. The Herbicidal Potential of Different Pelargonic Acid Products and Essential Oils Against Several Important Weed Species. *Agronomy* **2020**, *10*, 1687. [\[CrossRef\]](#)
45. Bozari, S. Satureja Hortensis Bitkisinin Uçucu Yağlarının *Hordeum vulgare* L. Tohumları Üzerine Genotoksik Etkileri. *Kahramanmaraş Sütçü İmam Üniversitesi Doğa Bilim. Derg.* **2017**, *20*, 185. [\[CrossRef\]](#)
46. Veraplakorn, V. In Vitro Micropropagation and Allelopathic Effect of Lantana (*Lantana camara* L.). *Agric. Nat. Resour.* **2017**, *51*, 478–484. [\[CrossRef\]](#)
47. Xu, Y.; Chen, X.; Ding, L.; Kong, C.-H. Allelopathy and Allelochemicals in Grasslands and Forests. *Forests* **2023**, *14*, 562. [\[CrossRef\]](#)
48. Cheng, F.; Cheng, Z. Research Progress on the Use of Plant Allelopathy in Agriculture and the Physiological and Ecological Mechanisms of Allelopathy. *Front. Plant Sci.* **2015**, *6*, 1020. [\[CrossRef\]](#)
49. Fadiji, A.E.; Adeniji, A.; Lanrewaju, A.A.; Babalola, O.O. Dynamics of Soil Microbiome and Allelochemical Interactions: An Overview of Current Knowledge and Prospects. *Ann. Microbiol.* **2025**, *75*, 21. [\[CrossRef\]](#)
50. Alemayehu, Y.; Chimdesa, M.; Yusuf, Z. Allelopathic Effects of *Lantana camara* L. Leaf Aqueous Extracts on Germination and Seedling Growth of *Capsicum annuum* L. and *Daucus carota* L. *Scientifica* **2024**, *2024*, 9557081. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Mekky, M.S.; Hassanien, A.M.A.; Kamel, E.M.; Ismail, A.E.A. Allelopathic Effect of *Ocimum basilicum* L. Extracts on Weeds and Some Crops and Its Possible Use as New Crude Bio-Herbicide. *Ann. Agric. Sci.* **2019**, *64*, 211–221. [\[CrossRef\]](#)
52. Naila, S.; Haq, Z.U.; Abdullah, A.; Salam, A. Allelopathic Effect of *Taraxacum officinale* L. on Germination and Physiology of Wheat. In *Sustainable Intensification for Agroecosystem Services and Management*; Jhariya, M.K., Banerjee, A., Meena, R.S., Kumar, S., Raj, A., Eds.; Springer: Singapore, 2021; pp. 711–741, ISBN 978-981-16-3207-5.
53. Semerdjieva, I.; Atanasova, D.; Maneva, V.; Zheljazkov, V.; Radoukova, T.; Astatie, T.; Dincheva, I. Allelopathic Effects of Juniper Essential Oils on Seed Germination and Seedling Growth of Some Weed Seeds. *Ind. Crops Prod.* **2022**, *180*, 114768. [\[CrossRef\]](#)
54. Scognamiglio, M.; Esposito, A.; D'Abrosca, B.; Pacifico, S.; Fiumano, V.; Tsafantakis, N.; Monaco, P.; Fiorentino, A. Isolation, Distribution and Allelopathic Effect of Caffeic Acid Derivatives from *Bellis perennis* L. *Biochem. Syst. Ecol.* **2012**, *43*, 108–113. [\[CrossRef\]](#)
55. Pacheco, A.; Pohlen, J.; Schulz, M. Allelopathic Effects of Aromatic Species Intercropped with Coffee: Investigation of Their Growth Stimulation Capacity and Potential of Caffeine Uptake in Puebla, Mexico. *Allelopath. J.* **2008**, *21*, 39–56.
56. Zhao, H.-H.; Kong, C.-H.; Xu, X.-H. Herbicidal Efficacy and Ecological Safety of an Allelochemical-Based Benzothiazine Derivative. *Pest Manag. Sci.* **2019**, *75*, 2690–2697. [\[CrossRef\]](#)
57. Liang, G.; Niu, Y. The Allelopathic Effect of Para-Hydroxybenzoic Acid on the Gene Expression of Photosynthesis and Respiration in *Solanum lycopersicum*. *Curr. Plant Biol.* **2022**, *32*, 100261. [\[CrossRef\]](#)
58. Chadeganipour, M.; Haims, A. Antifungal Activities of Pelargonic and Capric Acid on *Microsporum Gypseum*. *Mycoses* **2001**, *44*, 109–112. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Loddó, D.; Jagarapu, K.K.; Strati, E.; Trespidi, G.; Nikolić, N.; Masin, R.; Berti, A.; Otto, S. Assessing Herbicide Efficacy of Pelargonic Acid on Several Weed Species. *Agronomy* **2023**, *13*, 1511. [\[CrossRef\]](#)
60. Coleman, R.; Penner, D. Organic Acid Enhancement of Pelargonic Acid. *Weed Technol.* **2008**, *22*, 38–41. [\[CrossRef\]](#)
61. Amali Jesudas, P. Sorgoleone from Sorghum Bicolor as a Potent Bioherbicide. *Res. J. Recent Sci.* **2014**, *3*, 32–36.
62. Dayan, F.E.; Rimando, A.M.; Pan, Z.; Baerson, S.R.; Gimsing, A.L.; Duke, S.O. Sorgoleone. *Phytochemistry* **2010**, *71*, 1032–1039. [\[CrossRef\]](#)
63. Einhellig, F.A.; Souza, I.F. Phytotoxicity of Sorgoleone Found in Grain Sorghum Root Exudates. *J. Chem. Ecol.* **1992**, *18*, 1–11. [\[CrossRef\]](#)
64. Gimsing, A.L.; Bælum, J.; Dayan, F.E.; Locke, M.A.; Sejerø, L.H.; Jacobsen, C.S. Mineralization of the Allelochemical Sorgoleone in Soil. *Chemosphere* **2009**, *76*, 1041–1047. [\[CrossRef\]](#)
65. Latif, S.; Chiapusio, G.; Weston, L.A. Allelopathy and the Role of Allelochemicals in Plant Defence. In *Advances in Botanical Research*; Elsevier: Amsterdam, The Netherlands, 2017; Volume 82, pp. 19–54, ISBN 978-0-12-801431-8.
66. Weir, T.L.; Vivanco, J.M. Allelopathy: Full Circle from Phytotoxicity to Mechanisms of Resistance. In *Allelopathy in Sustainable Agriculture and Forestry*; Zeng, R.S., Mallik, A.U., Luo, S.M., Eds.; Springer: New York, NY, USA, 2008; pp. 105–117, ISBN 978-0-387-77336-0.
67. Xu, G.; Shan, S.; Yun, Z.; Clements, D.R.; Yang, Y.-H.; Yang, S.-S.; Zhen, F.-P.; Jin, G.-M.; Zhang, F.; Feng, Z.; et al. Allelopathic Effects of Rapeseed (*Brassica juncea*) on Invasive Weed Phalaris Minor Retz. *Res. Sq.* **2024**. [\[CrossRef\]](#)

68. Cook, D.; Rimando, A.M.; Clemente, T.E.; Schröder, J.; Dayan, F.E.; Nanayakkara, N.P.D.; Pan, Z.; Noonan, B.P.; Fishbein, M.; Abe, I.; et al. Alkylresorcinol Synthases Expressed in Sorghum Bicolor Root Hairs Play an Essential Role in the Biosynthesis of the Allelopathic Benzoquinone Sorgoleone. *Plant Cell* **2010**, *22*, 867–887. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Al-Sherif, E.; Hegazy, A.K.; Gomaa, N.H.; Hassan, M.O. Allelopathic Effect of Black Mustard Tissues and Root Exudates on Some Crops and Weeds. *Planta Daninha* **2013**, *31*, 11–19. [\[CrossRef\]](#)
70. Cartea, M.E.; Francisco, M.; Soengas, P.; Velasco, P. Phenolic Compounds in Brassica Vegetables. *Molecules* **2010**, *16*, 251–280. [\[CrossRef\]](#)
71. Shen, S.; Xu, G.; Li, D.; Clements, D.R.; Jin, G.; Liu, S.; Yang, Y.; Chen, A.; Zhang, F.; Kato-Noguchi, H. Allelopathic Potential of Sweet Potato (*Ipomoea batatas*) Germplasm Resources of Yunnan Province in Southwest China. *Acta Ecol. Sin.* **2018**, *38*, 444–449. [\[CrossRef\]](#)
72. Valcheva, E.; Popov, V. Role of the Allelopathy in Mixed Vegetable Crops in the Organic Farming. *Sci. Papers Ser. A. Agron.* **2013**, *LVI*, 422–425.
73. Li, J.; Liu, Y.; Zhang, P.; Zeng, G.; Cai, X.; Liu, S.; Yin, Y.; Hu, X.; Hu, X.; Tan, X. Growth Inhibition and Oxidative Damage of Microcystis Aeruginosa Induced by Crude Extract of *Sagittaria trifolia* Tubers. *J. Environ. Sci.* **2016**, *43*, 40–47. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Lim, C.J.; Lim, C.K.; Arumugam, M.; Ee, G.C.L.; Omar, D.; Basri, M. Green Water-Dispersible Coarse Powder Nano-Formulation for Allelopathic Leaf Extract of *Mikania micrantha* Kunth Ex H.B.K. in Controlling the Rice Weed *Echinochloa colona* (L.) Link. *Ind. Crops Prod.* **2022**, *187*, 115468. [\[CrossRef\]](#)
75. Wang, F.; Zhao, W.; Chen, J.; Zhou, Y. Allelopathic Inhibitory Effect on the Growth of Microcystis Aeruginosa by Improved Ultrasonic-Cellulase Extract of Vallisneria. *Chemosphere* **2022**, *298*, 134245. [\[CrossRef\]](#)
76. Javaid, A.; Shafique, S.; Bajwa, R.; Shafique, S. Effect of Aqueous Extracts of Allelopathic Crops on Germination and Growth of *Parthenium Hysterophorus* L. *S. Afr. J. Bot.* **2006**, *72*, 609–612. [\[CrossRef\]](#)
77. Inderjit; Wardle, D.A.; Karban, R.; Callaway, R.M. The Ecosystem and Evolutionary Contexts of Allelopathy. *Trends Ecol. Evol.* **2011**, *26*, 655–662. [\[CrossRef\]](#)
78. Bakacsy, L.; Kardos, L.V.; Szepesi, Á.; Nagy, K.N.; Vasas, A.; Feigl, G. Investigation of the Allelopathic Effect of Two Invasive Plant Species in Rhizotron System. *Life* **2024**, *14*, 475. [\[CrossRef\]](#)
79. Li, Z.-H.; Wang, Q.; Ruan, X.; Pan, C.-D.; Jiang, D.-A. Phenolics and Plant Allelopathy. *Molecules* **2010**, *15*, 8933–8952. [\[CrossRef\]](#)
80. Inderjit. Soil Microorganisms: An Important Determinant of Allelopathic Activity. *Plant Soil.* **2005**, *274*, 227–236. [\[CrossRef\]](#)
81. Swathika, N.; Subramanian, K.S.; Marimuthu, S.; Chandrakumar, K. Green Herbicide Revolution: Development and Characterization of Eucalyptus Globulus Essential Oil-Loaded Nanoemulsion for Sustainable Weed Control. *BioNanoScience* **2025**, *15*, 480. [\[CrossRef\]](#)
82. De Miranda, C.A.S.F.; Cardoso, M.d.G.; Carvalho, M.L.M.d.; Machado, S.M.F.; Gomes, M.d.S.; de Andrade, J.; Teixeira, M.L. Atividade Alelopática de Óleos Essenciais de Plantas Medicinais Na Germinação E Vigor de Aquênios de Alfaca. *Semin. Ciências Agrárias* **2015**, *36*, 1783–1798. [\[CrossRef\]](#)
83. Bradley, M. *Petition for the Listing of Pelargonic Acid and Related C6—C12 Fatty Acids on the USDA National List of Allowed and Prohibited Substances*; DOW Agro Sciences LLC: Indianapolis, IN, USA, 2005.
84. Pan, Z.; Baerson, S.R.; Wang, M.; Bajsa-Hirschel, J.; Rimando, A.M.; Wang, X.; Nanayakkara, N.P.D.; Noonan, B.P.; Fromm, M.E.; Dayan, F.E.; et al. A Cytochrome P450 CYP71 Enzyme Expressed in Sorghum Bicolor Root Hair Cells Participates in the Biosynthesis of the Benzoquinone Allelochemical Sorgoleone. *New Phytol.* **2018**, *218*, 616–629. [\[CrossRef\]](#)
85. Sarr, P.S.; Nakamura, S.; Ando, Y.; Iwasaki, S.; Subbarao, G.V. Sorgoleone Production Enhances Mycorrhizal Association and Reduces Soil Nitrification in Sorghum. *Rhizosphere* **2021**, *17*, 100283. [\[CrossRef\]](#)
86. Zhong, S.; Xu, Z.; Li, Y.; Li, C.; Yu, Y.; Wang, C.; Du, D. What Modulates the Impacts of Acid Rain on the Allelopathy of the Two Asteraceae Invasives? *Ecotoxicology* **2023**, *32*, 114–126. [\[CrossRef\]](#) [\[PubMed\]](#)
87. Uddin, M.R.; Thwe, A.A.; Kim, Y.B.; Park, W.T.; Chae, S.C.; Park, S.U. Effects of Jasmonates on Sorgoleone Accumulation and Expression of Genes for Sorgoleone Biosynthesis in Sorghum Roots. *J. Chem. Ecol.* **2013**, *39*, 712–722. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Waligóra, H.; Nowicka, S.; Idziak, R.; Ochodzki, P.; Szulc, P.; Majchrzak, L. The Total Phenolic Compound and Sorgoleone Content as Possible Indirect Indicators of the Allelopathic Potential of Sorghum Varieties (*Sorghum bicolor* (L.) Moench). *J. Plant Prot. Res.* **2023**, *63*, 450–458. [\[CrossRef\]](#)
89. Uddin, M.R.; Park, S.U.; Dayan, F.E.; Pyon, J.Y. Herbicidal Activity of Formulated Sorgoleone, a Natural Product of Sorghum Root Exudate. *Pest Manag. Sci.* **2014**, *70*, 252–257. [\[CrossRef\]](#) [\[PubMed\]](#)
90. Rubatzky, V.E.; Yamaguchi, M. *World Vegetables: Principles, Production, and Nutritive Values*; Springer: New York, NY, USA, 2012; ISBN 978-1-4615-6015-9.
91. Hangan, A.-M.-R.; Cojocaru, A.; Teliban, G.-C.; Vintu, V.; Stoleru, V. Urban and Peri-Urban Vegetable Gardens Composition. *Sci. Papers. Ser. B. Hort.* **2021**, *LXV*, 457–464.
92. PubChem Sorgoleone. Available online: <https://pubchem.ncbi.nlm.nih.gov/compound/6475682> (accessed on 13 January 2026).

93. Uddin, M.R.; Park, K.W.; Han, S.M.; Pyon, J.Y.; Park, S.U. Effects of Sorgoleone Allelochemical on Chlorophyll Fluorescence and Growth Inhibition in Weeds. *Allelopath. J.* **2012**, *30*, 61–70.
94. Ranjan Satapathy, S.; Prasad Khanduri, V.; Singh, B.; Riyal, M.K.; Kumar, S.; Kumar, P.; Rawat, D. Allelopathic Potential of *Ficus auriculata* and *Ficus semicordata* on Growth of Four Traditional Food Crops of Garhwal Himalaya. *J. Agric. Food Res.* **2022**, *9*, 100352. [\[CrossRef\]](#)
95. Tănase, B.E.; Zaharia Rogojină, M.; Stoleru, V. Preliminary Studies on the Allelopathic Effect of Some Endemic Species of Aromatic Plants and Their Possible Use as Bio-Herbicides. In *Lucrări Stiintifice, Universitatea de Stiințe Agricole și Medicină Veterinară Ion Ionescu de la Brad Iași, Seria Horticultura*; Editura “Ion Ionescu de la Brad”: Iași, Romania, 2024.
96. Santos, I.L.V.L.; da Silva, C.R.C.; dos Santos, S.L.; Maia, M.M.D. Sorgoleone: Benzoquinona Lipídica De Sorgo Com Efeitos Alelopáticos Na Agricultura Como Herbicida. *Arq. Inst. Biol.* **2012**, *79*, 135–144. [\[CrossRef\]](#)
97. Houben, S.; Brinks, H.; Salomons, J.; de Cara, M.; Thorsted, M.D.; Miche, V.; Molendijk, L.; Schlathoelter, M. Crop Rotation: Practical Information. Best 4 Soil. 2020. Available online: <https://www.best4soil.eu/assets/factsheets/12.pdf> (accessed on 17 November 2025).
98. Botanista, E. Crop Rotation—Characteristics, Advantages, Methods. Available online: <https://www.botanistii.ro/blog/rotatia-culturilor/> (accessed on 17 November 2025).
99. Hayyat, M.S.; Safdar, M.E.; Asif, M.; Tanveer, A.; Ali, L.; Qamar, R.; Ali, H.H.; Farooq, N.; Javeed, H.M.A.; Tarar, Z.H. Allelopathic Effect of Waste-Land Weeds on Germination and Growth of Winter Crops. *Planta Daninha* **2020**, *38*, e020173626. [\[CrossRef\]](#)
100. Kalisz, S.; Kivlin, S.N.; Bialic-Murphy, L. Allelopathy Is Pervasive in Invasive Plants. *Biol. Invasions* **2021**, *23*, 367–371. [\[CrossRef\]](#)
101. Wang, P.; Chai, Y.N.; Roston, R.; Dayan, F.E.; Schachtman, D.P. The Sorghum Bicolor Root Exudate Sorgoleone Shapes Bacterial Communities and Delays Network Formation. *mSystems* **2021**, *6*, 10–128. [\[CrossRef\]](#)
102. Kang, Y.; Gobler, C.J. Nitrogen Liberated Via Allelopathy Can Promote Harmful Algal Blooms. *Harmful Algae* **2023**, *129*, 102490. [\[CrossRef\]](#)
103. Hussain, M.I.; Araniti, F.; Schulz, M.; Baerson, S.; Vieites-Álvarez, Y.; Rempelos, L.; Bilsborrow, P.; Chinchilla, N.; Macías, F.A.; Weston, L.A.; et al. Benzoxazinoids in Wheat Allelopathy—From Discovery to Application for Sustainable Weed Management. *Environ. Exp. Bot.* **2022**, *202*, 104997. [\[CrossRef\]](#)
104. Carvalho, M.S.S.; Andrade-Vieira, L.F.; dos Santos, F.E.; Correa, F.F.; das Graças Cardoso, M.; Vilela, L.R. Allelopathic Potential and Phytochemical Screening of Ethanolic Extracts from Five Species of *Amaranthus* spp. in the Plant Model *Lactuca Sativa*. *Sci. Hortic.* **2019**, *245*, 90–98. [\[CrossRef\]](#)
105. Jilani, G.; Mahmood, S.; Chaudhry, A.N.; Hassan, I.; Akram, M. Allelochemicals: Sources, Toxicity and Microbial Transformation in Soil—A Review. *Ann. Microbiol.* **2008**, *58*, 351–357. [\[CrossRef\]](#)
106. Real, M.; Gámiz, B.; López-Cabeza, R.; Celis, R. Sorption, Persistence, and Leaching of the Allelochemical Umbelliferone in Soils Treated with Nanoengineered Sorbents. *Sci. Rep.* **2019**, *9*, 9764. [\[CrossRef\]](#)
107. Lau, J.A.; Puliafico, K.P.; Kopshever, J.A.; Steltzer, H.; Jarvis, E.P.; Schwarzländer, M.; Strauss, S.Y.; Hufbauer, R.A. Inference of Allelopathy Is Complicated by Effects of Activated Carbon on Plant Growth. *New Phytol.* **2008**, *178*, 412–423. [\[CrossRef\]](#) [\[PubMed\]](#)
108. Zhang, Z.; Liu, Y.; Yuan, L.; Weber, E.; van Kleunen, M. Effect of Allelopathy on Plant Performance: A Meta-Analysis. *Ecol. Lett.* **2021**, *24*, 348–362. [\[CrossRef\]](#) [\[PubMed\]](#)
109. Bonanomi, G.; Zotti, M.; Idbella, M.; Mazzoleni, S.; Abd-ElGawad, A.M. Microbiota Modulation of Allelopathy Depends on Litter Chemistry: Mitigation or Exacerbation? *Sci. Total Environ.* **2021**, *776*, 145942. [\[CrossRef\]](#) [\[PubMed\]](#)

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