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ALLELOPATHIC CORRESPONDENCE IN SOIL ECOSYSTEM BETWEEN MICROBES AND PLANTS

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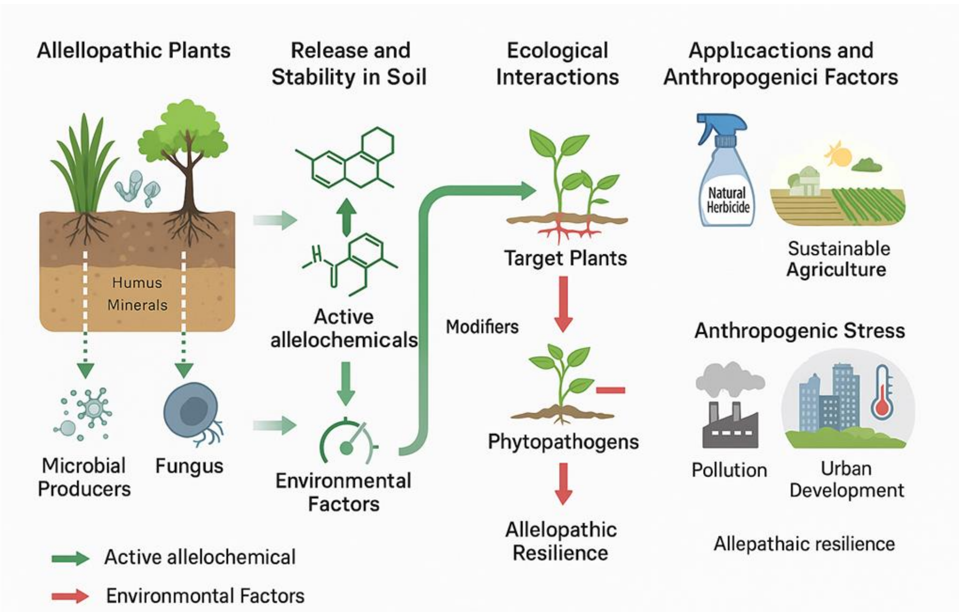
Abstract

Allelopathy is a form of ecological competition that takes place rather regularly in natural settings and has a significant influence on how biocenoses carry out the responsibilities that are essential to their continued existence. In the last few decades, numerous significant discoveries have been made about the isolation and identification of plant and microorganism metabolites with allelopathic activity, as well as their function in the ecosystems of soil. These findings have led to several critical breakthroughs. These findings were uncovered in connection with the allelopathic activity of the metabolites. As a further consequence of these findings, the relevance of these metabolites has also been brought to light. In this article, the allelopathic qualities of plants and microbes, as well as the primary applications and mechanisms of allelochemicals, as well as the stability of allelochemicals in soil ecosystems, are investigated in depth. In addition, the primary applications and mechanisms of allelochemicals are discussed. In addition to discussing the consequences of anthropogenic activity, this article also addresses the one-of-a-kind qualities that allelopathic activity possesses when it is present in an environment that is experiencing change. These characteristics are only seen when allelopathic activity is present in an environment where anthropogenic activity is also present. Allelopathic interactions between various species are essential to the process of biocenosis, which depends largely on these interactions. Allelopathy is something that must be taken into consideration for the future of research since it can regulate phytopathogens, which is imaginable. Because of this, allelopathy is something that needs to be taken into consideration.

Keywords: Allelochemicals, biocenosis, ecological, interaction, metabolites, microbes

Graphical abstract



INTRODUCTION

Allelopathy is a naturally occurring process that has been shown to have a major impact on the operation of biocenoses. It is performed through the production and release of metabolites that have allelopathic activity, and it involves a range of different chemical interactions that take place between organisms (Chaïb *et al*., 2021). The interactions that take place between plants are the most prevalent thing that people mean when they talk about allelopathy (Kong *et al*., 2024); However, it can also be used to refer to the interactions that take place between different types of microorganisms, as well as the interactions that take place between plants and different types of bacteria (Cipollini *et al*., 2012).

Hydrocarbons, terpenes, flavonoids, polyacetylenes, and fatty acids are only a few examples of the chemical classes represented by allelopathic compounds. The most prevalent phytotoxins are quinones and phenolic chemicals (Latif *et al*., 2017). Flavonoids provide defense for plants in several ways. Allelochemicals undergo microbiological change (Jilani *et al*., 2008), which yields new molecules with distinct biological characteristics (Aslam *et al*., 2017). Allelopathy is a resource-based conflict (Nazarov and Shirokov, 2014) and is greatly impacted by factors such as the structure of the soil, humidity, temperature, the availability of nutrients, the concentration of allelochemicals, as well as either plant's resistance or vulnerability to the effects of microorganisms (Inderjit *et al*., 2008; Perry *et al*., 2007). Because of this, it is sometimes more difficult to differentiate between the allelopathic influence and the effects of other environmental factors. Maintaining soil cover, increasing soil fertility, and restoring regions that have been anthropogenically disturbed all strongly rely on having a solid consideration of the dynamics of the organic condition of the soil and the biota that inhabit it. In the past, the research on allelopathy was intended to address issues with agrocenoses, specifically the interaction between weeds and crops (Tesio and Ferrero, 2010). Herbicides harm both the environment and people; therefore, this is primarily related to the quest for alternatives (Patni *et al*., 2018).

Even though allelopathy has been actively studied in recent years, the data that have been collected are scarce or controversial, which is particularly true for soil processes (Blanco, 2007). Because allelopathy has primarily been investigated in the laboratory and under artificial conditions (Inderjit, 2002), several writers are dubious about its veracity (Jose *et al*., 2006). Because allelopathy is simultaneously influenced by many biotic and abiotic aspects in natural biocenoses, research on the phenomenon takes place in controlled laboratory settings. This makes it much easier to understand and analyze the findings (Ehlers, 2011).

Further study is necessary to find solutions to various issues relating to allelopathy as a natural occurrence with significant practical and scientific implications. This chapter discusses the primary roles of the allelochemicals and the function of allelopathic relations in the biocenoses, the distinctive characteristics of allelopathy due to anthropogenic activities and changing ecological conditions, and the potential for using allelopathy to regulate phytopathogens.

PLANTS' ALLELOPATHIC CHARACTERISTICS

Allelopathy and Its Role in Plant Interactions

One of the major factors in identifying the kind of plant connection is allopathy. Allelopathic plants secrete a variety of metabolites, which help to develop a certain environment around them (Kondrat'ev *et al*., 2014). According to some species, it may be harmful, beneficial, or neutral (Anaya *et al*., 2013) as shown in Fig. 1.

From a practical standpoint, considerable emphasis should be given to metabolites that prevent competitive plant species from reproducing, growing, or surviving either directly or indirectly (Hierro and Callaway, 2003). There are numerous articles that describe this allelopathic action for plants of various species. On the contrary, when the same invasive species was investigated in certain cases, completely different results were discovered (Blair *et al*., 2006). These discrepancies may stem from variations in research methods (Ehlers, 2011).

Root systems have a major role in how plants in phytocenoses interact (Khaleeq *et al*., 2024). Allelopathic plant metabolites have an effect not only on the growth and imitation of the plants but also on mycorrhizal activity and the progression of microbes (Blanco, 2007). Allelopathic compounds penetrate plants in a variety of complex and intricate ways. According to Putnam and Tang (1986), they typically enter acceptor plants through the root system, where water and nutrients are carried upward. In some plants, this process is followed by pathological alterations to the vascular bundle's xylem. According to Simagina and Lysyakova (2010), the acceptor plants *Salicornia europaea* exhibit intense lignification of conduction routes because of metabolites from plants with allelopathic qualities such as *Artemisia santonica* and *Limonium gmelinii*. Changes in membrane permeability, chloroplast photochemical activity, mitochondrial division rate, the concentration of chlorophyll, and the function of the ribosome, or the general cells' functioning, are all effects of metabolites with allelopathic activity at the cellular level (Einhellig, 2004). Allelochemicals alter the function of intracellular enzymes and membrane proteins, particularly antioxidant enzymes (Li *et al*., 2011).

For instance, 2-benzoxazolinone (BOA) brings oxidative stress in the *Phaseolus aureus* (which belongs to the family Leguminosae) that is conveyed through an escalation in the proline content, malondialdehyde, and the hydrogen peroxide, as well as an increase in the antioxidant enzymes' activity such as superoxide dismutase, ascorbate peroxidase, guaiacol peroxida (Batish *et al*., 2006). Allelochemicals can therefore have an impact on biochemical and physiological processes as well as on cellular, molecular, or ultrastructural alterations.

Plants' Allelopathic Substances

Only a few of the recognized metabolic products currently exhibit allelopathic action. In the roots and rhizosphere of plants, phenolic compounds, alkaloids, terpenoids, other metabolites, and steroids having allelopathic activity have been found.

Because they are the most pervasive higher plant poisons and generate significant allelopathic tension in phytocenoses, phenolic compounds are thought to play a special function. According to Latif *et al*. (2017), phenolic chemicals are currently associated with more than 8000 identified metabolic products. The hydroxycinnamic and hydroxybenzoic acids, coumarins, dihydrochalcones, flavonoids, and other biologically active chemicals of the same category that accumulate in the soil, assist in hindering the germination of the seeds as well as the growth of plants.

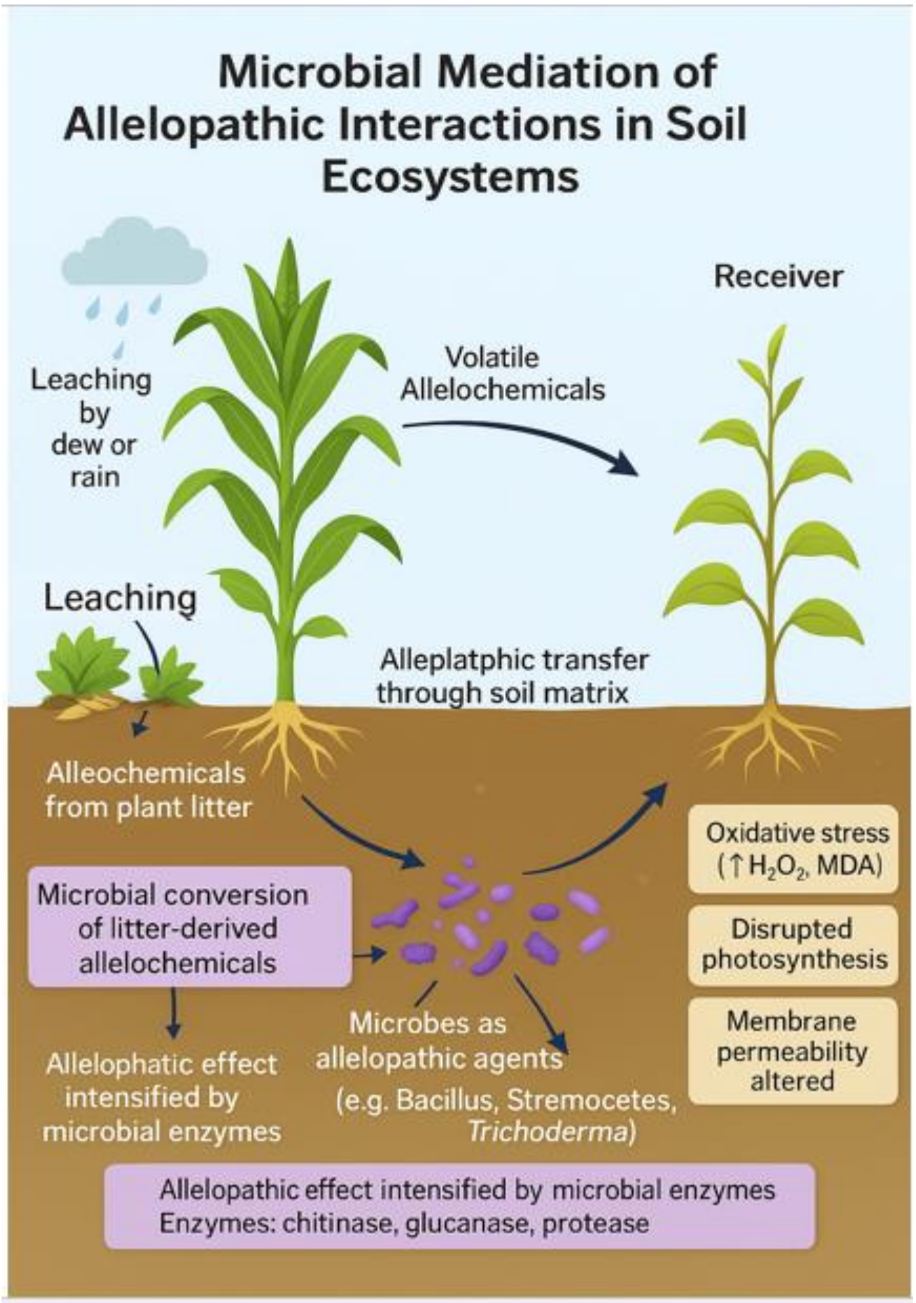


Figure 1: Allelopathic plant interactions

Terpenoids are a broad class of plant compounds (Table 1). Isoprene blocks make up the carbon skeleton of these organisms. Semi- and monoterpenes, respectively, have one or two blocks, whereas polyterpenes have more than eight. According to certain scientists, this group of chemical compounds has a substantial amount of structural variety, which facilitates the active management of environmental connections in biocenoses (Bardin *et al*., 2015). Over 24,000 terpenoids have been described thus far. Because they are the metabolic byproducts of a wide variety of plants, ranging from trees to herbs, many of them have the potential to have both inhibiting and stimulating impacts on the plants and microbes (Ehlers, 2011).

Table 1. Allelopathic Plant Substances

Substance	Mode of Action	Reference
Phenolic compounds 1. Cinnamic acid 2. Benzoic acid	Influence on the permeability of membranes, hormonal activity, photosynthetic activity, respiration, and the production of organic molecules	(Latif *et al*., 2017)
Terpenoids 1. 1,8-Cineol 2. Thymol	Influence on respiration, membrane permeability, and all mitosis stages	(Huang *et al*., 2023)
Alkaloids 1. Berberine 2. Papaverine	DNA structure affects protein synthesis, membrane permeability, and enzyme activity.	(Han and Li, 2023)
Cyclic hydroxamic acid 1. BOA 2. DIMBOA	Effect on covalent protein modification and ATPase activity	(Latif *et al*., 2017)

In allelopathic relationships, heterocyclic nitrogen-containing chemicals known as alkaloids play a significant role (Table 1). According to Yang and Stockigt (2010), more than 20,000 secondary metabolites have been found and allocated to this group. Alkaloids play a crucial part in protecting plants from herbivores, other plants, and microbes, which accounts for their widespread distribution. For instance, wild tobacco belonging to the genus *Nicotiana* is more likely to create nicotine when herbivorous animals consume and kill it, and nicotine has an allelopathic effect on other annual wildflowers (Quinn *et al*., 2014). Several members of the Gramineae family produce cyclic hydroxamic acid glycosides that have bactericidal, fungicidal, and phytotoxic effects. Plant enzymes convert the two chemicals that make up this group's primary representatives, (2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one) and (2,4-dihydroxy-1,4-benzoxazin-3-one), into aglycones where allelopathic activity is exhibited (Latif *et al*., 2017).

Aglycones break down to produce the compounds B(2-benzoxazolinone) and B(A) (6-methoxy-2-benzoxazolinone), both of which have allelopathic characteristics (Table 1). Benzoxazolinones protect plants from pests and phytopathogens. Plant metabolites having allelopathic activity may modify, strengthen, or weaken the functions of soil biota to regulate soil biota activity and promote plant development.

Allelopathic Substances' Formation: Contributing Factors

Numerous living and nonliving factors affect the development of allelopathic chemicals and their impacts. According to Tang *et al*. (1995), plants cultivated in nutrient-poor soil produce more physiologically active metabolites than those grown in nitrogen-rich soil. They first proposed this after it was revealed that plants with moisture and phosphate shortages demonstrated a great level of allelopathic activity (Sara *et al*., 2024).

In the absence of phosphorus, *Lupinus angustifolius* roots will produce the flavonoid genistein (Weisskopf *et al*., 2006), which serves as a precursor in the production of the antimicrobial phytoalexins and phytoanticipins (Zeng *et al*., 2008). Discharge of such compounds in the rhizosphere, which noticeably plays a dynamic character in phosphorus source to the plants that confine mobilization of unavailable phosphorus via microbial degradation of citrate (Sugiyama and Yazaki, 2012). UV light, water stress, and temperature are stressors that may activate the allelopathic features (Reigosa *et al*., 2002). High or low temperatures may be conducive to stimulation. Important characteristics are influenced by temperature, particularly the activity of enzymes and the cell membranes' viscosity (Samim *et al*., 2023).

In the creation of allelopathic chemicals, soil type is crucial. Soil that is more aerated and with a granular consistency, as opposed to compact soil, creates more allelochemicals. Pathogens, plant pests, parasites, and interactions with other plants are some examples of biotic stimulating factors (Rivoal *et al*., 2011). According to available research, plants produce chemicals with allelopathic action more frequently when the environment is adverse.

Forest Ecosystems Allelopathy

The phenomenon of allelopathy is pervasive in timberlands and has a significant impact on tree development and growth (Blanco, 2007; Rasheed, 2024). This is a common occurrence among numerous tree species native to Australia's northern and tropical forests, temperate zones, and eucalyptus groups. (Weidenhamer *et al.,* 1989) found that soil qualities and other environmental factors considerably influenced the intensity and efficiency with which trees formed biologically active chemicals. Forest management and quality enhancements benefit greatly from the study of allelopathy (Blanco, 2007). The occurrence of this process in the forest ecosystem is currently being considered in numerous nations due to its scientific and practical significance. Nevertheless, despite its prominence and widespread incidence, there is a chronic shortage of information on allelopathy in forests. According to several experts, this is due to difficulty in separating allelopathic effect from further factors such as the struggle for food (Kimmins, 2004).

MICROBIAL ALLELOPATHIC ACTIVITIES

Phytopathogens controlled by microbes

Recent decades have seen a surge in research into the allelopathic properties of soil microorganisms (Maksimov *et al*., 2011) because of the widespread adoption of allelopathic methods for protecting plants from pathogens (Aslam *et al*., 2017). In plants, microbes act both as mediators and targets of allelopathy, as shown in Fig. 2.

Phytopathogens can be controlled microbiologically as a substitute for chemical plant fortification (Javaid and Shoaib, 2013). While PPCs do a good job, pesticides kill off both harmful and helpful bacteria (Maksimov *et al*., 2011; Pervaiz *et al*., 2024). In addition, most of them accumulate in food, are highly carcinogenic, and are poorly used by soil microbiota (Patni *et al*., 2018). Microbiological preparations, conversely, achieve their effects by controlling the population density of harmful microorganisms, establishing competitive relationships with native microorganisms, and inducing system stability in the natural environment.

Numerous studies have demonstrated that microorganisms of diverse phylogenetic origins can be effective antagonists of phytopathogens (Podile and Kishore, 2006; Aleem, 2024). Although actinomycetes are the primary source of antibiotics in nature, most investigations on microbial allelopathy have been conducted on micromycetes and bacteria (Gerbore *et al*., 2014). *Agrobacterium*, *Pseudomonas*, *Bacillus,* and *Streptomyces* were used in the production of commercial biological products based on the fungi *Ampelomyces*, *Candida*, *Coniothyrium,* and *Trichoderma*.

Bacterial activity

Plant-growth-promoting rhizobacteria, or PGPRs, are a common name for rhizobacteria that aid in plant growth. These are categorized as biopesticides in the US (Slininger *et al*., 2003). Plant roots provide a range of metabolites that provide food for microbes that coexist with plants in tissues of the root system in the surrounding soil and on the root surfaces. Gram-negative bacteria dominate the rhizosphere, such as *P. fluorescens*, *P. pulida*, *P. corrugate*, *P. aureofaciens*, and others. These microorganisms are also targeted by agrobiotechnology. They act as a cornerstone for organic plant defense against phytopathogens and as biostimulators for plant development and production (Podile and Kishore, 2006). When treated to roots, seeds, and seedlings, pseudomonads PGPR's several strains can considerably lower the occurrence of plant disease and enhance plant production (Saeed *et al*., 2021).

Rhizobacteria, which inhabit the roots of plants, can be beneficial, detrimental, or neutral depending on how they affect the plant (Dobbelaere *et al*., 2003). Production of the hydrolytic enzymes (lipase, chitinase, gluconase, and protease) that can break down other bacterial or fungal cells, the antagonism for the food on the surface of plant roots with the involvement of enzyme aminocyclopropane-1-carboxylate-deaminase deaminase are all examples of microbial interactions (Kanwal *et al*., 2024).

Antibiotics, siderophores, and bacteriocins are the three types of physiologically active metabolites that have proven to be the most effective in inhibiting or completely stopping the phytopathogen's growth (Beneduzi *et al*., 2012). The fact that iron ions' poor bioavailability is a restrictive factor for the growth of phytopathogenic microbes explains why siderophores (iron complexions) are of interest to researchers.

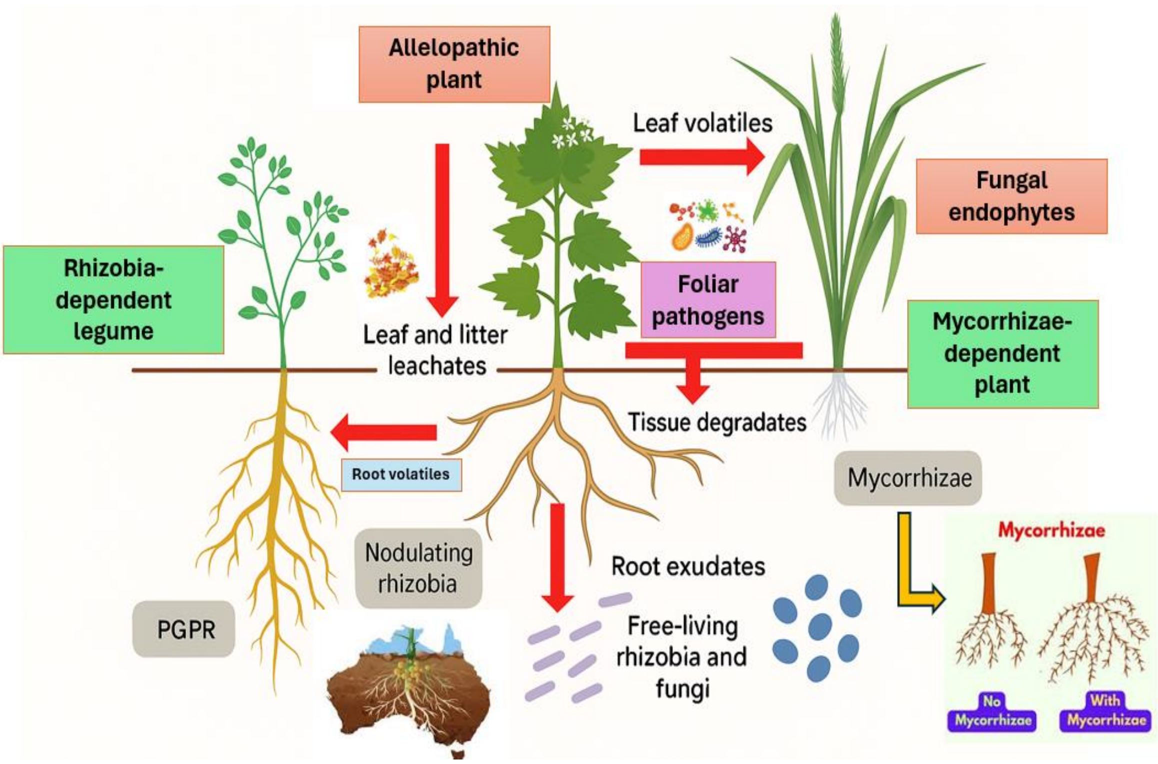


Figure 2: Microorganisms as mediators and targets of allelopathy (Cipollini *et al*., 2012)

Table 2. Bacterial activity related to sensitive plants

Bacteria	Substances	Sensitive Plants	Concentration	Effect* (%)	Reference
Pseudomonas sp.	HCN	Potato *Solanum tuberosum*	0.13 mg L^{-1}	40	(Helmi *et al*., 2024)
Bradyrhizobium japonicum	Rhizobiotoxin, indole-3-acetic acid	Not determined	Not determined	NT	(Torres *et al*., 2021)
Thermoactinomycete sp.	5'-Deoxyguanosine	Algae *Lemna minor*	100 mg L^{-1}	NT	(Torres *et al*., 2021)
Streptomyces hygroscopicus	Geldamicin, nigericin	*Lepidium sativum*	1–2 mg L^{-1}	50	(Díaz-Cruz *et al*., 2022)
Streptomyces hygroscopicus	Hydantocidin	Weed *Digitara ischaemum,* field mustard *Sinapis arvensis*, and others	500 mg L^{-1}	100	(Sin and Kadıoglu, 2021)
Streptomyces sp.	Blasticidin, 5-hydroxylmethyl-blasticidin	China bean *Vigna sinensis*, Winter weed *Stellaria media* and veronica *Veronica persica*	100 mg m^{-2}	64-98	(Li *et al*., 2013)
Streptomyces sp.	Phthoxazolins B, C, and D	Radish *Raphanus sativus* and sorghum *Sorghum bicolor*	63–250 mg per test tube	40-90	(Li *et al*., 2013)
Streptomyces chromofuscus	Herboxidien	Maize *Zea mays*, colza *Brassica napus*, and buckwheat *Fagopyrum sagittatum*	6.9 mg m^{-2}	100	(Cinkocki *et al*., 2021)

***Effect% % is growth inhibition, and NT stands for not determined.**

Table 3: Spectrum of biological effects of the Fungal toxins

Mycotoxins	Producers	Biological effect	References
Rubratoxin	*Penicillium rubrum, P. funiculosum*	Fungicidal, phytotoxic, and zootoxic	Masi *et al*., 2018
Sterigmatocystin	*Aspergillus ustus, A. nidulans, A. versicolor*	Bactericidal, phytotoxic, and zootoxic	Mahata *et al*., 2022
Patulin	*P. daleae, P. expansum A. clavatus*	Fungicidal, bactericidal, phytotoxic, and zootoxic	Tannous *et al*., 2020
Citrinin	*P. citrinum, A. pseudoterreus*	Fungicidal, bactericidal, phytotoxic, and zootoxic	Kamle *et al*., 2022
Ochratoxin	*A. ochraceus, A. clavatus, P. veridicatum*	Fungicidal, bactericidal, phytotoxic, and zootoxic	Svistova *et al*., 2004
Fumigatin	*A. fumigatus, A. flavus*	Fungicidal, phytotoxic, and amoebicidal	Rudramurthy *et al*., 2019
Trichodermin	*Trichoderma* spp.	Fungicidal and zootoxic	Yao *et al*., 2023
Fusarium acid	*Fusarium solani, F. oxysporum*	Fungicidal, bactericidal, and phytotoxic	Xu *et al*., 2023

Antifungal antibiotics play a significant role in antagonistic relationships, according to many writers (Haas and Keel, 2003; Akhter *et al*., 2017). The most widely used method of controlling phytopathogens is the synthesis of one or more antibiotics (Glick *et al*., 2007; Abbas *et al*., 2021a). Like geldanamycin, nigericin, and hydantocidin, which *Streptomyces hygroscopicus* produces and is an active producer of three anti-phytopathogen antibiotics. Phloroglucin byproducts of the phenazine, pyrrolnitrin, and pyoluteori generated through *pseudomonads, surfactin, iturin A, zwittermicin* A, through the members of genus Bacillus, and agrosin 84 and other antibiotics manufactured via agrobacteria, are among the antibiotics (Ulloa-Ogaz *et al*., 2015; Arshad *et al*., 2024b). Every antibiotic has a unique mechanism that determines how it affects cells. For instance, the functioning of ribosomes can be inhibited by certain antibiotics, while other antibiotics can regulate the cell membrane or other cellular components (Reid *et al*., 2002).

According to Dilantha *et al*. (2005), microbial antibiotics typically have antibacterial, antiviral, antihelmintic, insecticidal, and antioxidant properties that support plant growth. With respect to higher plants, several nonpathogenic bacteria are allelopathically active (Table 2). To date, only a small fraction of the numerous bacterial allelochemicals discovered have proven effective as herbicides. To be more precise, they include phosphinotricin, which is a result of the metabolism of *S. viridochromogenes*, and bialaphos, which is the byproduct of the *S. hygroscopicus* metabolism (Schwartz *et al*., 2004). This is because most provisions in the field have much lesser allelopathic activity than they do in lab settings (Rafeeq *et al*., 2020).

Fungal activity

The most crucial element of the soil microbial community is fungi. According to Zvyagintsev (1999), their biomass reaches 50% of all soil microbial biomass. Fungi produce an extensive range of biologically active compounds during metabolism, comprising enzymes, antibiotics, and different toxins (Shaheen *et al*., 2024).

The toxins produced by fungi that have bactericidal and fungicidal properties are given special consideration. Fungal toxins are viewed as antibiotics from a biological perspective (Egorov, 2004). Representatives of a variety of systematic groups, such as imperfect fungi, zygomycetes, ascomycetes, entomopathogenic fungi, oomycetes etc., might create them.

Vegetation, mammals, bacteria, and fungi are just a few of the creatures that can be impacted by fungus toxins (Battilani *et al*., 2016; Arshad *et al*., 2021). Several mycotoxins are poisonous to humans, plants, and microbes. Toxins produced by deuteromycetes belonging to the genera *Penicillium, Aspergillus*, and *Fusarium* typically have a wide range of biological impacts; several of them are listed below in Table 3.

According to Daguerre *et al*. (2014), cyclic terpenoids, polypeptides, and polyketides make up most fungal poisons. Alternariol (*Alternaria tenuissima*), zearalenone (*Fusarium* spp.), citrinin (*Penicillium* spp.), patulin, aflatoxin (*Aspergillus fumigatus*), and other powerful mycotoxins with both zootoxic and phytotoxic qualities are examples of polyketides (Berestetskiy, 2008; Abbas *et al*., 2021b).

Toxins have diverse effects through various pathways. Mycotoxins' damaging effects primarily target the proteins and enzymes that make up cell membranes, including their structural and transport components (Duke and Dayan, 2011).

While certain toxins raise plant respiration rate and activity of oxidative enzymes, others block the conductive system, prevent respiration and photosynthesis, and disturb water balance in plants. Prokaryotes' ability to respire and phosphorylate can be inhibited by fungal toxins. In the soil microbial community and plant systems, toxin-producing micromycetes have extra benefits and outcompete their competitors (Davidova *et al*., 2024).

The stability of fungi's phytotoxins varies greatly (Vanhoutte *et al*., 2016). *Trichoderma harzianum*, *Aspergillus ustus*, and *Penicillium daleae* phytotoxins retain their action for a longer period, whereas *T. flavus* and especially *A. clavatus* phytotoxins retain their high level of activity for a very long period (Svistova *et al*., 2003). *Rhizopus stolonifer* phytotoxins, for instance, are quickly inactivated in soil.

ENZYMATIC FUNCTIONS

Microorganisms' lytic enzymes provide a crucial allelopathic purpose. The primary lytic enzymes of fungi are chitinase and β-glucanase since the key components of their cell walls include chitin and β-glucan. Lytic enzymes are required for mycoparasitism together with proteases (Daguerre *et al*., 2014; Arshad *et al*., 2024a). Mycoparasitism, commonly referred to as hyperparasitism, is the parasitic use of another fungus's resources. The production of the enzymes chitinase, protease, and glucanase allows parasitic fungi to dissolute the cell wall and enter phytopathogenic fungal hyphae.

Such as the enzyme-1,3-glucanase produced through *Clonostachys rosea*, and further fungi break down cell walls of the pathogens that cause *fusarium rot*, *Fusarium oxysporum*, and *Pythium aphanidermatum* root rot (Chatterton and Punja, 2009). Because it breaks down the cell wall and hinders the formation of *Botrytis cinerea* spores, the chitinase produced by *Serratia plymuthica* is responsible for the spread of a wide variety of plant diseases. The synergistic effect is significant when both chitinolytic and glucanolytic enzymes are acting on the same substrate at the same time, particularly when both *endochitinases* and -1,3-glucanases are engaged at the same time (Steyaert *et al*., 2004).

In addition to destroying the host organism's cell walls, fungi-derived proteases also work to inactivate the pathogens' infection-causing enzymes (Daguerre *et al*., 2014). Other enzymes that are crucial for controlling mycoparasitism can be degraded because of high protease production levels. In the parasite-pathogen system, the products of the breakdown of the cell wall that occur during mycoparasitism function as lytic enzyme stimulators. It is important to highlight that, in addition to higher plants, bacteria and fungi can produce these enzymes too (Kolombet, 2007).

Allelopathic interfaces, antibiosis, mycoparasitism, and their mutual influence may be the basis for antagonist microorganisms' effects on phytopathogenic fungi. This reflects the complex microbial interactions in soil. When *Trichoderma harzianum* and *Botritis cinerea* compete against one another, for example, there is a synergism between 1,3-glucanases and peptide antibiotics (peptaibols) and as well as between proteases and the chitinases involved in cell-wall disintegration. This synergism occurs even though both organisms are antagonistic to one another. Synergistic effect and enhanced fungicidal action are produced by peptide antibiotics, which prevent membrane-bound synthetase to host's -1,3 -1,3-glucan and resynthesize the -glucan of the cell wall (Sharma *et al*., 2022).

Effects of conservation factors on microbial allelopathic activity

The number of soil-dwelling microbes has a substantial influence on the allelopathic action of microbes, in a manner that is analogous to how plants interact with one another. The amount of biologically dynamic metabolites in the soil and, consequently, the quantity of biologically active microbes, govern how higher plants are affected (Nadarajah and Abdul Rahman, 2021). When phytopathogens and their antagonists interact, soil type, temperature, acidity, and plant variety all matter (Kolombet, 2007; Tahir *et al*., 2024).

Allelopathic action may also be escalated because of the anthropogenic impacts, such as the contamination of soil by pesticides, oil products, and heavy metals (Polyak *et al*., 2017). According to Svistova *et al*. (2004), polluted ecosystems are categorized by a considerable buildup of fungus with a broad spectrum of antibiotic, fungicidal, and phytotoxic activity. The enhanced role of the metabolic regulation of the structure of the soil microbial community is responsible for this phenomenon.

Transformation of allelochemicals

The microbial community in the soil actively contributes to the degradation of materials, which has a substantial influence on the allelopathic interrelations in the soil. In soil, there are bacteria and fungi, and other microorganisms that degrade allelopathically active chemicals. Lower allelopathic activity is typically the outcome of the conversion of physiologically active chemicals into less harmful molecules (or their total consumption). However, the reverse result is also conceivable (Cipollini *et al*., 2012; Arshad *et al*., 2024a).

By converting allelopathic chemicals into more harmful byproducts (Inderjit, 2005), microorganisms can increase the effectiveness of these substances. Like, the Acinetobacter calcoaceticus can convert 2-benzoxazolinone into the more hazardous plant 2,2-oxo-1,1'-azobenzene and its methoxy byproducts (Macias *et al*., 2008). Simultaneously, soil phytotoxicity declines because of microbes using physiologically active phenolic chemicals (Jilani *et al*., 2008). The concentration of 8-hydroxyquinoline and catechin, which are excreted by roots of *Centaurea maculosa* and *C. diffusa*, is decreased by soil microbes (Inderjit *et al*., 2008; Perry *et al*., 2007). According to research on the antibacterial and antifungal properties of Lamiaceae plants (Vokou *et al*., 2002), some bacteria break down the monoterpenes that plants make and utilize them for their metabolism (Kalemba and Kunicka, 2003; Latif *et al*., 2017).

Pathogenic poisons can be broken down by some bacteria (Vanhoutte *et al*., 2016; McCormick, 2013). *Trichoderma* fungus breaks down the poisons that induce wood necrosis in vine infections such as eutypine, 4-hydroxybenzaldehyde, and D-3-phenylacetic acid. This is a trait that is unique to that species (Kolumbet, 2007; Aslam *et al*., 2017). Like, strain *T. album* Preuss breaks down eutypine to produce harmless alcohol eutypinol. Eutypine and 4-hydroxybenzaldehyde are two toxins that are capable of being broken down by a different strain of Trichoderma, and the strain *T. atroviride* can break down all three toxins.

These and numerous other facts demonstrate the significant and varied functions of soil microorganisms, which undoubtedly explain concentration in studies on their allelopathic activity (Blanco, 2007; Gray and Smith, 2005; Beneduzi *et al*., 2012). Plant diseases can be managed using microorganisms' capacity to break down the poisons produced by phytopathogens.

CONCLUSION

Allelopathy is a normal development in the ecosystem of soil. Recent research has yielded important information on the definition, identification, and function of plant metabolites and microorganisms with allelopathic activities in natural biocenoses. These studies' primary issues stem from the outcome of numerous biotic and abiotic environmental elements on allelopathic action, which causes some fragmentation and inconsistency in the findings. It is important to highlight how herbicides, nematocides, and fungicides affect the allelopathic interactions between plants and microbes. They generate microbial imbalances in the soil and alter the physicochemical properties of the soil. This establishes a level of interest in using allelopathy in a practical setting to lessen the use of agrochemicals on the soil.

An interesting area for more research could be the application of allelopathy to boost crop productivity, develop resistant crops, and manage weeds. Crops including maize, barley, wheat, peas, oats, tomatoes, soybeans, and others have already seen some advancement in agricultural farming. The fungi and bacteria that live in soil play a major role in finding solutions to these issues. The most significant areas for future study are (i) categorization of allelochemical characteristics and identification of the mechanisms underlying the effects at physiological and molecular levels (ii) rise in allelopathic action of the crops and (iii) investigation of the impact of natural and the anthropogenic factors on the study of interactions in complex biological systems may benefit greatly from modern molecular research techniques, particularly metabolome analysis.

Findings will help us better understand how microbes and plants interact and what functions they play in host-parasite and microbial-plant interactions in the natural world. There is a need for extensive research in this field by experts from various countries, as evidenced by the challenges in researching allelopathy generally and finding solutions to its specific concerns.

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AF, HMBA, AA, and BK conceived and designed the review. MAA, MAA, and MZM wrote the manuscript. TR and MA critically revised it.

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