

Mechanisms of allelopathic interactions for sustainable weed management

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ABSTRACT

Plant allelopathy is a response to external stimuli by releasing secondary metabolites. It can be an effective sustainable strategy for weed control. Roots are the main point of release of allelochemicals. This phenomenon has the potential to facilitate environmentally cleaner weed control and avoid the concerns associated with the misuse of agro-chemicals for pest and weed management. The review comprehensively elaborates the mechanisms involving the release of allelochemicals by plants and the factors affecting its transport from a donor plant to a receiver. Although allelochemicals are produced by the entire plant, root exudation is the primary source of release of these chemicals into the soil environment. The study attempts to lucidly explain the physiology behind phytotoxic effects imparted by allelochemicals on target plants. We have discussed the various direct and indirect effect of allelochemicals on plant physiology and morphology. The review sheds light on the phytotoxic variation caused due to variable residue decomposition rates under changing climatic conditions. The various crop-weed, weed-crop and weed-weed allelopathic interactions and their possible response mechanisms have been briefly elaborated with reference to earlier works. We have shown the potential of integrating allelopathy and agronomic management practices for sustainable and environmentally safe weed management. The mechanistic insight of interferences caused by environmental factors on the bioavailability of allelochemicals is essential to develop an environmentally sound method of curbing the weed menace in agro-ecosystems. The studies on transport processes involving the release of allelochemicals from plants need more attention so as to exploit this knowledge in regulating the output of these compounds at a cellular level.

1. Introduction

Weeds are one of the most important constraints to crop productivity worldwide, causing yield losses in the range of 45–95 percent by competing for light, water, and nutrients with the main crop (Oerke,

2006; Das, 2008; Kumar et al., 2022). Hand weeding, mechanical weeding, and herbicide treatments have been the most common conventional weed management methods for reducing weed saturation (Abbas et al., 2021). Despite their substantial contribution, these methods are accompanied by several challenges, including the

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development of herbicide resistance in weeds (Harker, 2013) and exorbitantly high expenses incurred during weed control practices (McErlich and Boydston, 2014), thus necessitating the development of a more convenient, environmentally friendly, and low-input driven efficient strategy for weed management (Das et al., 2021). Allelopathy is gaining widespread popularity as a sustainable weed management strategy for combating the challenge of environmental pollution and herbicide resistance (Jabran et al., 2015). It is the phenomenon in which an organism secretes biochemicals (otherwise known as allelochemicals) that causes interference either positively or negatively, affecting the growth and development of other organisms. Allelopathy exploits the application of plant-derived secondary metabolites in disease and pest management, thus acting as a defense mechanism. The growing concerns over the excess use of herbicides and its ramifications on ecological sustainability have resulted in a shift toward other bio-rational alternatives. Allelopathy can offer a potent bio-rational option for weed management in cropping systems. Allelopathic plants transfer allelochemicals into the environment through root exudates, volatilization from above-ground plant parts, and leaching or decomposition of plant detritus when cultivated in intercropping systems (Scavo et al., 2018).

The historical developments of allelopathy, as per the records, started with the keen observations of Theophrastus (300 BC) and Pliny II (1 AD), relating to the marring of farmland by growing crops like chickpea, barley, fenugreek and bitter vetch (Weston, 2005). They were well aware of the sickening of fertile farmlands, which was accredited to the biochemicals released by the plants. However, proper scientific evidence of the allelopathic effect from root exudates was put forward by De Candolle (Singh et al., 2001). This concept was later extrapolated to address the weed menace by exploring the possible allelopathic effect of crops (cover crop, crop rotation, intercrop, crop residue incorporation or retention) to suppress weed growth in agricultural fields (Putnam and Duke, 1974; Behera and Das, 2019; Behera et al., 2019). The allelochemicals are mostly secondary metabolites with diverse chemical structures and properties, mostly belonging to the group of phenolics, flavonoids, terpenoids, alkaloids, momilactone, jasmonates, salicylates, hydroxamic acids, brassinosteroids, polysaccharides, glucosinolates, and amino acids that are released as byproducts during various

physiological processes in plants (Farooq et al., 2011). The inhibitory or stimulatory effects of allelochemicals depend on their concentration and the recipient species. For instance, the aqueous leaf extract of *Annona muricata* inhibited the seedling growth of *Vigna radiata* and *Eleusine coracana* at high concentrations, whereas it stimulated the germination, seedling length, pigments, starch, protein, amino acid, carbohydrate, peroxidase, and catalase contents of the *Vigna radiata* seedlings at low concentration (1%) (Kannan and Palayian, 2022). The stimulatory effect of allelochemicals on plants can be exploited for producing biofertilizers (Hussain et al., 2017; Behera et al., 2021), while those with inhibitory effects may be used as weed suppressants and disease control agents (Farooq et al., 2011; Latif et al., 2017). The different types of allelopathic interactions are illustrated in Fig. 1. The sensitivity of the plants towards these biochemicals is selective, the knowledge of which is critical for targeted weed management with higher efficiency. Present-day researchers share their concerns regarding the ecological and physiological significance of weed-crop/crop-weed interferences and extend major emphasis on the mechanisms involved in allelopathy phenomena and the mode of action. Therefore, this review work has been lucidly synthesized with a broad objective of exploring the mechanism of action of allelochemicals, the factors affecting the efficacy of allelochemicals in managing the weed problem, and understanding the various types of plant-plant (crop-weed) interactions for extending its application at farm level for sustainable weed management.

2. Mechanism of release of allelochemicals

Allelopathy is a form of communication between plants, and they communicate by synthesizing various compounds through secondary metabolites (Yoneya and Takabayashi, 2014). The secondary metabolites are mostly released through the leaf, stem and roots of plants (Iqbal et al., 2020). The synthesis of these compounds is associated with the activation of some specialized genes and the presence of precursor molecules inside the plants. These activation processes often depend on environmental stimuli (Croteau et al., 2000). It is evident that not all bioactive metabolic compounds possess the allelopathic effect on surrounding organisms (Neori et al., 2000). Among all the pathways, root exudates are the most prominent source of release of allelochemicals

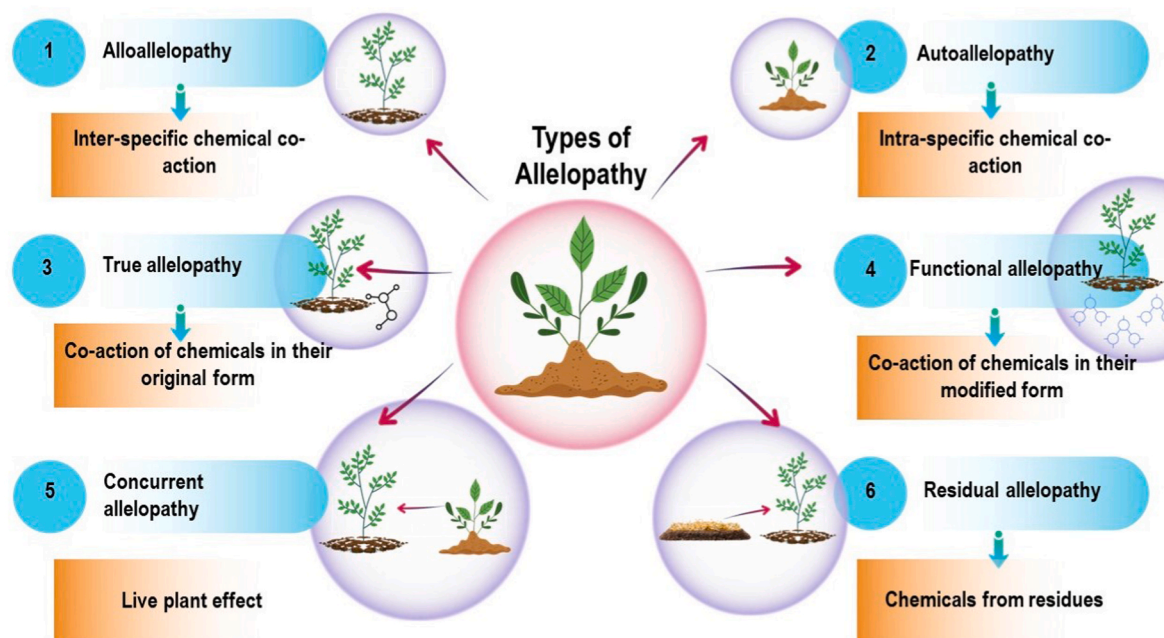


Fig. 1. A figurative illustration showing types of allelopathic interactions existing between donor and receiver plants. Allelopathic interactions have been classified on the basis of source (1 and 2), form (3 and 4) and action time of allelochemicals (5 and 6) (Das, 2008).

into the rhizosphere (Jilani et al., 2008). The mechanism of release of allelochemicals from the roots of the donor plant as exudate is described vividly in Fig. 2. However, other routes, such as washing out from the plant parts, volatilization from leaves, and residue decomposition, are also important alternative pathways for releasing these bioactive compounds (Singh et al., 2021). Apart from exudation, these may be released from roots by simple diffusion (low molecular weight metabolites) or by lysis of vesicles present at the surface of root caps (Latif et al., 2017). In the case of high molecular weight substances, membrane-bound proteins actively participate in inter- and intra-cellular transport by loading metabolites into vesicles and later removing the contents into the extracellular space (Weston et al., 2012). Some of the widely studied protein carriers include ATP binding cassette (ABC) family and the multidrug and toxic compound extrusion (MATE) family (Weston et al., 2012). The ABC protein family is one of the largest transporter families that are primary active transporters involving ATP hydrolysis to transport bioactive compounds (Dermauw and Van Leeuwen, 2014). Apart from nutrients, lipids, steroids, and xenobiotics, these transporters also transport a wide range of metabolites (Rees et al., 2009). They are localized in the plasma membrane, tonoplast, mitochondria, and chloroplasts, taking part in the plant defense mechanism and responding to abiotic stresses (Kang et al., 2011). For instance, a pleiotropic drug resistance (PDR)-type ABC protein (*NpABC1*) was involved in the defense response system in *Nicotiana plumbaginifolia* (Jasiński et al., 2001). In a study, a *Arabidopsis* gene *AtPDR12* (a member of the PDR subfamily) was found to be actively involved in the transfer of metabolites imparting resistance to the fungal pathogen, as shown by the pathogen signal metabolite treatment (Campbell et al., 2003). The MATE genes are also involved in transporting secondary metabolites along the electrochemical gradient of ions (Scavo et al., 2019). These were identified in the *Arabidopsis* family and carried *DTX* (from detoxification) initials, which are secondary active transporters (Li et al., 2002). An *Arabidopsis* gene named *AtDTX1* encodes a protein that facilitates the export of alkaloids and other toxic compounds from roots (Li et al., 2002). The role of these genes in root exudation of secondary metabolites has been tested in various crops, viz., maize (*ZmMATE2*) (Kidd et al., 2001), rice

(*OsPEZ1* and *OsPEZ2*) (Bashir et al., 2011), and sorghum (*SbMATE1*) (Zhang et al., 2019). A better understanding of biosynthetic pathways, enzymes, and genes responsible for the synthesis and release of allelochemicals could lead to selective weed management through allelopathy.

3. Factors affecting the release of allelochemicals

3.1. Environmental stress factors

Environmental factors may have a direct or indirect impact on a plant's ability to use allelopathy. The main environmental factors that regulate the net effect of allelopathy include temperature, radiation, availability of nutrients, and stressors (Meiners et al., 2012). For instance, stress imparted by UV radiation, nutritional deficiency, wounding, and plant pathogen invasion is known to cause an upswing in phenyl ammonia lyase (PAL) activity, which is the first step in the production of phenols (Dixon and Paiva, 1995; Croteau et al., 2000). Cinnamic acid, produced by cucumber, is ascertained to be the precursor of phenylpropanoids which is credited for peroxidation and decreased activity of H^+ -ATPase activity in the plasma membrane, ultimately reducing the root viability of target plants (Ding et al., 2007). Adverse environmental conditions also boost jasmonate synthesis and release. As a result, these hormones can up-regulate the expression of genes involved in secondary metabolism in plants (Wasternack and Parthier, 1997). The influence of environmental stressors on the generation of sorgoleone can be made worse by the presence of other plants around sorghum (Dayan, 2006). The generation of various allelochemicals is likewise influenced by environmental pressures brought on by plant interactions (Rivoal et al., 2011). The primary allelochemicals in rice have been identified as the diterpenes momilactone A and B, which were initially isolated from rice husks (Kato-Noguchi et al., 2010; Yazaki et al., 2017). Momilactone B concentration was approximately seven times higher in rice seedlings cultivated with barnyard grass (*Echinochloa crusgalli* L. Beauv.) than in rice seedlings raised alone (Kato-Noguchi, 2011). Low-land weed species such as *Echinochloa crusgalli*,

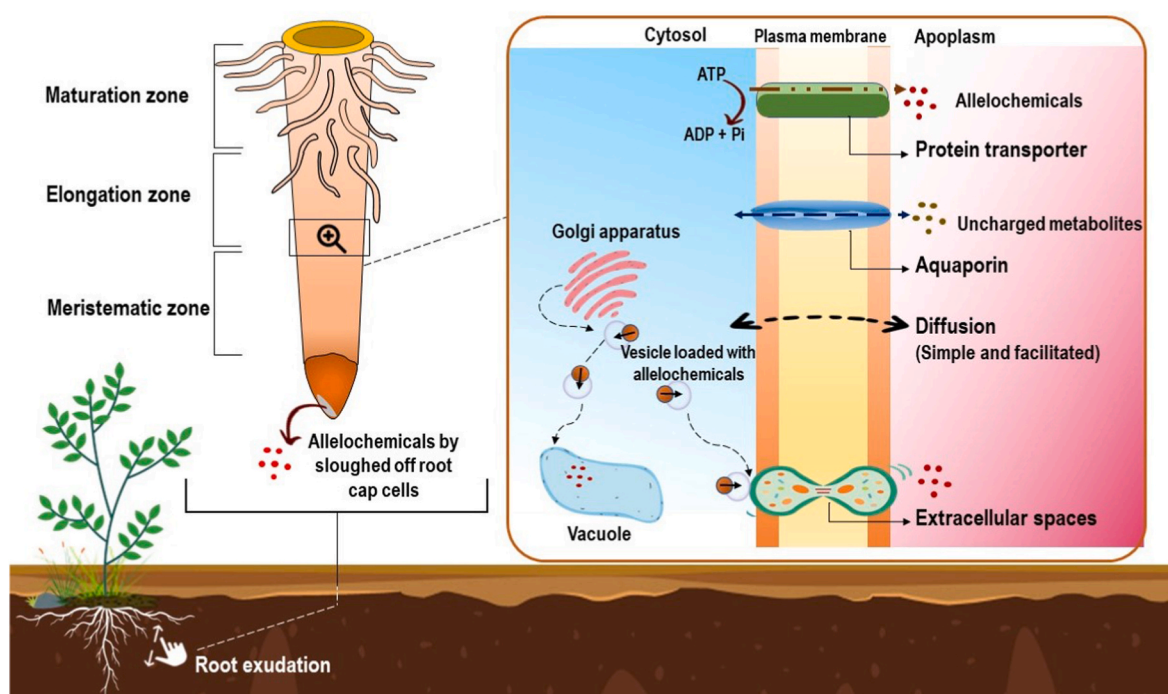


Fig. 2. A conceptual diagram depicting the possible mechanism of release of allelochemicals via root as exudates. The low molecular weight compounds are proposed to be transported by simple/facilitated diffusion, while those having high molecular weight mainly get released by protein transporters (ABC, MATE, etc.), or through vesicles. The aquaporins also take part in release of uncharged secondary metabolites.

Lactuca sativa, and others thrived more successfully next to rice plants lacking in momilactone production than they did next to wild-type rice plants (Toyomasu et al., 2014). At micromolar levels, momilactones also build up in the rice shoots, roots, and root exudates in addition to the husk (Hasegawa et al., 2010). Momilactone B is 17 times more effective than momilactone A at preventing growth in *Arabidopsis thaliana* (Kato-Noguchi et al., 2012). Momilactone B is therefore regarded as the rice allelochemical with highest potency (Murphy and Zerbe 2020). On the other hand, momilactone A has been primarily connected to rice resistance towards fungi pathogens (Hasegawa et al., 2010). Study shows that momilactone B is preferentially secreted from roots (Toyomasu et al., 2008). However, the increased production of momilactones by above-ground plant parts was also observed after the attack of pathogens like *Magnaporthe oryzae*, *M. grisea*, and *Rhizoctonia solani* (Lu et al., 2018). Allelochemical's effectiveness can be affected by environmental conditions that impact the ease of its degradation in the soil. In a study, 2, 4-dihydroxy-2H-1,4-benzoxazin-3(4H)-one (DIBOA) displayed a half-life of 43 h in non-sterilized soil. The final breakdown product of DIBOA and 2-aminophenoxazin-3-one (APO) had a low mineralization rate with more than 90 days half-life period (Macías et al., 2005). Additionally, soil bacteria accelerate the mineralization rate of flavonoid glycosides released by rice plants, resulting in aglycosylated compounds. The half-lives of flavonoid glycosides and aglycosides are 2 h and 30 h, respectively, suggesting that the second group has a stronger and sustained allelopathic activity (Kong et al., 2007). The synthesis of allelochemicals, their bioavailability and their impact on target species depend on the environmental conditions. Therefore, environmental variables and other processes that alter the fate of chemicals in the environment are crucial for the allelopathic relationship between plants in agroecosystems to aid weed management. Significant research findings support the hypothesis that environmental stress can boost the production of allelochemicals.

3.2. Plant factors

A plant root system serves various purposes, including anchoring the plant and absorbing nutrients and water. According to an estimate, higher plants create approximately 10,000 allelochemicals, with a wide variety of action mechanisms in the target plants (Weston et al., 2012). In response to biotic and abiotic stressors, the roots of several weed and crop species continuously secrete bioactive substances (low- and high-molecular-weight) into the rhizosphere (Bertin et al., 2003). The term "root exudate" refers to the substances that plant roots exude into the soil (Walker et al., 2003). Their amount and quality depend on the cultivar type, growth stage, plant and environmental stressors (Badri and Vivanco, 2009). For instance, it has been found that rice exudation rates were maximum during the flowering period while being very low in the seedling and maturity stage (Aulakh et al., 2001). Root exudations from sorghum and wheat were higher upon increasing soil compaction, drying and decrease in the available pool of nutrients, while it increased with the ageing of plants (Weil and Brady, 2017). Growing root systems typically exude more metabolites, which indicates its positive correlation with root growth (Lucas García et al., 2001). Additionally, the root system architecture and the type of root surface morphology are all factors that affect the determination of the qualitative and quantitative composition of exudates (Badri and Vivanco, 2009).

Higher plants with strong allelopathic properties are commonly incorporated into the soil for weed-control purposes. A study showed the phytotoxic variation with residue decomposition rate in the soil by using allelopathic plants, viz. alfalfa and kava as soil amendment (Xuan et al., 2005). Both alfalfa and kava strongly inhibited the growth of barnyard grass and *Monochoria* for up to 10 days (80–100% weed control). However, after 20–25 days, the magnitude of inhibition was drastically reduced, but it was still effective (50% weed control). Similarly, the allelopathic and decomposition patterns of *Jasminum officinale* L. f. var. *grandiflorum* were assessed by Teerarak et al. (2010). A decline in

allelopathic potency of the plant residues became apparent as the decomposition time lengthened. A crucial step in the ecosystem functioning, nutrient and carbon cycling, and ultimately climate change is the decomposition of plant litter. The effect of temperature on phytotoxic dynamics of *Chrysanthemoides monilifera* subsp. *monilifera* (bone-seed) litter was studied by Al Harun et al. (2014). The results showed an increased concentration of water-soluble phenolics and dissolved organic carbon (DOC), with a decreased concentration of sulphate and nitrates in the soil under elevated temperatures. There was a considerable reduction in the germination rate, length and weight of hypocotyl and radicle of *Lactuca sativa* due to the higher release rate of allelochemicals from the litter at high temperatures. Therefore, identifying the suitable cultivar and growth stages of plant species with potential allelochemicals and evaluating them under the different plant and environmental stressors could open up new prospects for natural herbicides application.

3.3. Genetic factors

The proper genetic factors are required for plants to produce substances through secondary metabolism, including allelochemicals. For instance, understanding the enzymes and genes involved in momilactone B synthesis has aided the rice breeding program that sought to generate cultivars with a higher capacity to release allelochemical compounds (Toyomasu et al., 2008). Momilactone B, a diterpene molecule, is very effective against weeds. It is produced by the methylerythritol phosphate (MEP) pathway in the presence of the diterpene synthase enzyme (Dudareva et al., 2013). By employing reverse genetics, two genes were identified that were involved in the synthesis of diterpene synthase enzyme: 4-copalyl-diphosphate synthetase and kaurene synthase-like 4 (KSL4) (Xu et al., 2012). Momilactones are synthesized from the precursor geranylgeranyl diphosphate (GGPP) as diterpenes through a series of processes that occur in various cellular organelles and result in several intermediate products. On chromosome 4, a group of four genes have been identified that are involved in momilactone biosynthesis viz., Syncopalyl Diphosphate Synthase 4 (CPS4), Kaurene Synthase-Like 4 (KSL4), 9- β -Pimarane 7, 15-Diene Oxidase (CYP99A3), and Momilactone A Synthase (MAS) (Shimura et al., 2007). Two more, CYP701A8 and CYP76M14, are located on chromosomes 6 and 1, respectively (De La Peña and Sattely, 2021). A single gene, CYP76M8, is located on chromosome 2, in another biosynthetic gene cluster required for oryzalexin production (Wu et al., 2013). Together, the products of these seven genes on chromosomes 1, 2, 4, and 6, synthesize momilactone B from GGPP. Thus, identifying and manipulating factors controlling gene expression involved in allelochemical synthesis could augment the allelopathic potential of plant species.

4. Interaction with soil environment

When an allelochemical is released into the environment, it undergoes a number of interacting processes (Fig. 3). These processes are broadly divided into three categories: transport, retention and transformation (Cheng, 1992; Weidenhamer, 1996; Cheng and Koskinen, 2002). Retention mechanisms impede the movement of chemicals from one point to another due to physical hindrances imparted by various soil constituents. The transformation processes will change the shape or structure of the allelochemicals, resulting in partial or complete molecular disintegration. The resulting transition product could be more potent, less potent or completely inactive than the parent compound. Transport processes control the movement of substances in the environment. The type of microorganisms present, the characteristics of the soil, and the soil environmental conditions are all important elements that can impact each step (Scavo et al., 2019). As a result, the fate of an allelochemical in the environment is determined by the kinetics and interaction of separate processes at a given site over time under a set of conditions. Although volatile allelochemical compounds play a

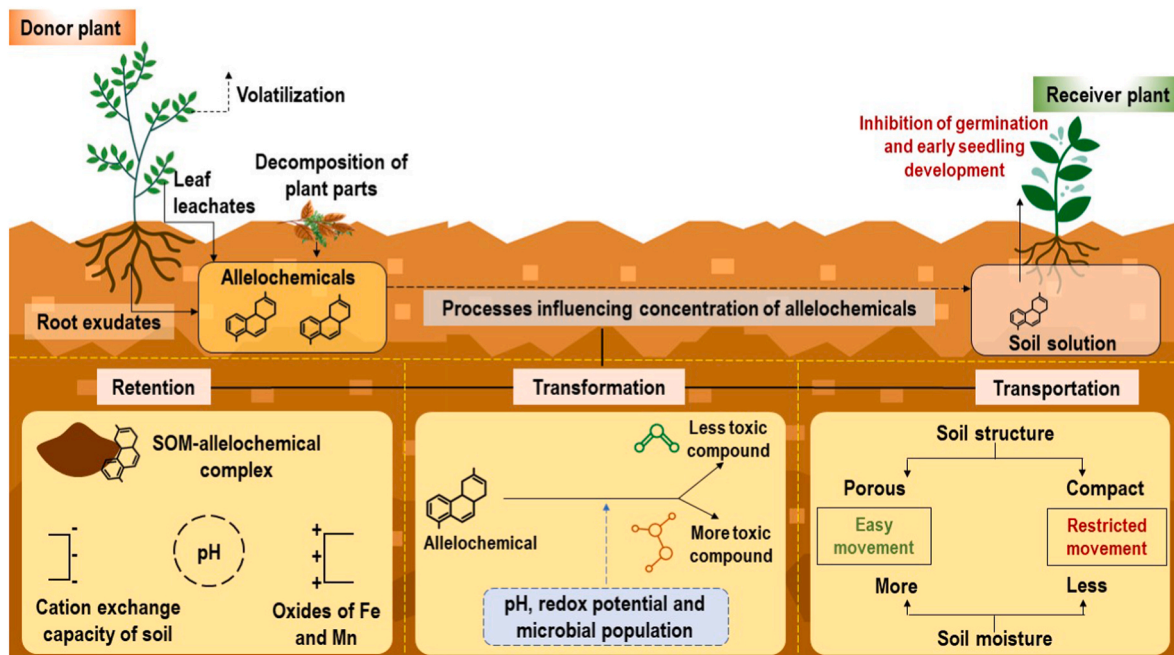


Fig. 3. An illustrative depiction of the various routes of release of phyto-allelochemical compounds and their interaction with various soil constituents. The bioavailability of these bioactive compounds is in direct correlation with the extent of retention and transformation it undergoes in soil before coming into the rhizospheric zone of the receiver plants for uptake.

significant role in plant-to-plant allelopathy interactions, allelochemicals released into the soil as root exudates or as secondary products of residue disintegration in soil remain the most important source of allelopathic interaction (Tharayil et al., 2008). Thus, the soil is the primary medium of transport of allelochemicals from the donor plant to the receiver. However, the current understanding of the mechanism of interactions between these chemical compounds and soil constituents is inadequate and remains ambiguous (Tharayil et al., 2008).

The quantity of allelochemical present in soil solution in a solubilized condition ultimately determines the degree of its bioavailability. Batch equilibration study is generally employed for studying the sorption-desorption pathway of organic allelochemicals in soils which gives an idea of the extent of the effect the soil components (organic and inorganic) have on the release and bioavailability of these chemicals (Cheng and Koskinen, 2002). Studies show that the adsorption of phenolic acids is greatly influenced by soil properties, viz., oxides of Fe and Mn, organic matter content and pH (Inderjit and Bhowmik, 2004; Kobayashi, 2004). Upon comparing the retention behavior of phenolic acids released by poplar plantations in soil, Wang et al. (2011) inferred that p-HBA can exist in soil for a longer time compared to cinnamic acid and benzoic acid. The influence of pH on anion adsorption by soil components is particularly significant for organic biochemical, which particularly occurs by the electrostatic force of attraction with a positively charged surface of metal oxides (Gámiz et al., 2019). Salicylic acid, a phenolic compound type of allelochemical, is reported to show strong pH-dependent sorption in soils, particularly due to bidentate complex formation as attributed to its low pKa value ($pK_a = 2.9$) (Calvet et al., 2007; Gámiz et al., 2019). Interestingly, the phytotoxicity of allelochemicals varies with pH and texture of the soil as evident from the study of Galán-Pérez et al. (2021). It was observed that scopoletin sorption in soil was strongly correlated with pH and fine texture of soils, thus expressing its phytotoxic effect in acid soil in contrast to alkaline soil. Gámiz et al. (2018) conducted a study to deduce the factor contributing most to the sorption and desorption of monoterpenes in agricultural soils. They found strong sorption by organic sorbents, viz., humic acid, as opposed to pH and mineral sorbents, viz. clay, silt, and carbonate content, as evident from the distribution coefficient values.

Numerous reports of the impact of soil pH on allelochemicals have been described in the literature (Batish et al., 2007; Norouzi et al., 2015). Norouzi et al. (2015) noted that decreased soil pH levels increased the allelopathic effects of powdered below- and aboveground parts of alfalfa (*Medicago sativa*), sorghum (*Sorghum bicolor*), and tobacco (*Nicotiana tabacum* L.) on several weeds. Leaching of allelochemicals and, consequently, their phytotoxic effects are strongly influenced by soil texture (Albuquerque et al., 2011). Additionally, because clay minerals vary widely from one another, clay typology affects the availability of allelochemicals. The highest specific surface area, ion exchange capacity, water retention capacity, and consequently, the strongest retention power towards allelochemicals are found in smectite-dominated soils like Vertisols, which are highly rich in montmorillonites (expanding 2:1 silicate clays). The preservation of allelochemicals, however, is relatively poor in soils predominately composed of non-expanding 1:1 silicate clays, such as kaolinites. In coarse substrate (sand), the allelochemicals released by roots of *Hordeum vulgare* L. ssp. *vulgare* showed higher toxicity (Bouhaouel et al., 2018). In another study by Shaukat et al. (2003), sandy soils showed higher levels of phytotoxic effects from aqueous shoot extracts of *Coryza canadensis* L., followed by loamy sand and sandy loam soils. This is likely because of the minimal adsorption of allelochemicals on coarse soil texture soils as well as the low levels of microbial and chemical degradation. In an early study by Ohno and First (1998), organic matter and manganese oxide content strongly affected the sorption of phenolic acids in soils, increasing their residual life in the soil. Arguably, the external addition of organic matter acts as a food source for microbes resulting in enhanced microbial activity, which may prevent the build-up of allelochemicals to below-toxic levels (Inderjit and Weiner, 2001). Numerous studies have shown that soil organic matter (SOM) affects the availability of allelochemicals in soil (Fageria, 2012). Allelochemicals adsorption is low in hot-semi arid soils, which typically have low SOM, facilitating the spread and dispersion of allelopathic plants like *Rhaponticum repens* (L.) Hidalgo and *Centaurea maculosa* Lam (Grossi, 2008). Redox condition of soil also has a significant role to play in determining the phytoavailability of allelochemicals in soil. Reduced conditions (<400 mV) present in the soils under *Actinidia arguta* plantation showed a 20–70% increase in

allelopathic phytotoxicity attributed to the slow pace of the humification process resulting in a more mobile form of organic allelochemical compounds in the soil matrix (Zaimenko et al., 2020). The ion exchange capacity of the soil also plays a crucial role in the retention and transport processes of allelochemicals (Scavo et al., 2019). Belz et al. (2009) revealed that clay soils with high cation exchange capacity favour parthenin breakdown, which is the allelochemical responsible for the invasive success of *Parthenium hysterophorus* L.

Soil microorganisms can have both positive and negative impacts on plants as pathogens, mutualists, and nutrient cycling drivers can alter the microbial ecology in the soil beneath the canopy and around the roots (Bever, 2003; Van der Putten et al., 2001). When allelochemicals reach the soil, the microorganisms are known to detoxify or increase the toxicity of allelochemicals, influencing the allelopathic effect (Inderjit, 2005). The low concentration of extremely phytotoxic compounds such as catechin and 8-hydroxyquinoline in soil has been related to soil microbial activity (Kaur et al., 2009). Microflora determines the microbial decomposition of allelochemicals. In a study, the chemical interaction between a grass, *Agrostis capillaris* and the monoterpene “carvacrol” produced by its thyme neighbour plant was investigated (Ehlers, 2011). The presence of carvacrol in the soil significantly reduced *Agrostis* plant survival, with mortality being higher when soil microorganisms were absent. Plants showed a minimal survival rate with monoterpene treatment when the soil was sterile, compared to higher survival rates ranging from 20% to 40% when the soil was not sterilized (Ehlers, 2011). The habitat type could also seriously impact the release of allelochemicals by plants. Plants cultivated in natural fields have substantially higher levels of cis-dehydromatricaria ester (DME), an allelochemical isolated from *Solidago altissima*, than those grown as hydroponic cultures (Nakamura and Nemoto, 1996). The interaction of allelochemicals with the soil environment affects the efficacy of allelochemicals released from the plants into the soil ecosystem. Knowledge of such interaction could be used in modulating the persistence of an allelochemical in such a way that allelopathic-based weed management

could be availed for a longer time in crop fields.

5. Mechanism of phytotoxicity

Several researchers classified allelochemicals’ mode of action as direct or indirect, which are referred to as true or functional allelopathy, respectively, by Aldrich (1984). Allelochemicals can either directly affect the target (direct allelopathy) or, when released into the soil, degrade to secondary degradation products, which can either harm plant development or modify the microenvironment, indirectly affecting the growth. Considering that there could be innumerable types of biotic and abiotic factors affecting the fate of allelochemicals released into the soil environment, it is impossible to ascertain the dominance of direct allelopathy over indirect allelopathic effects in field conditions (Scavo et al., 2019). Hence, indirect allelopathy is considered to be more important from an ecological point of view (Inderjit and Weiner, 2001). Different modes of action of allelochemicals (Fig. 4) are discussed hereunder, and some recent works are outlined in Table 1.

5.1. Cell morphology and multiplication

It is envisaged that the reduction in plant growth caused by the secretion of allelochemicals is the result of the suppression of mitosis and disorganization of the structure of cell organelles (Gniazdowska and Bogatek, 2005; Sánchez-Moreiras et al., 2008; Mushtaq et al., 2019). Several researchers have quantified this by estimating mitotic index (MI), which is an important prognostic factor for deciding a cell’s ability to multiply at a particular time. Stem extracts of *Nicotiana plumbaginifolia* at higher concentrations decreased MI in root tip cells of *Allium cepa*, which resulted in disruption of cell polarity, sticky metaphase, and telophase with abnormalities in chromosome arrangement (Mushtaq et al., 2019). Apart from cytological aberrations, they also found severe modifications in the ultrastructure of the leaf of *Cassia tora* leaves, as evident from the scanning electron microscopy (SEM) images of

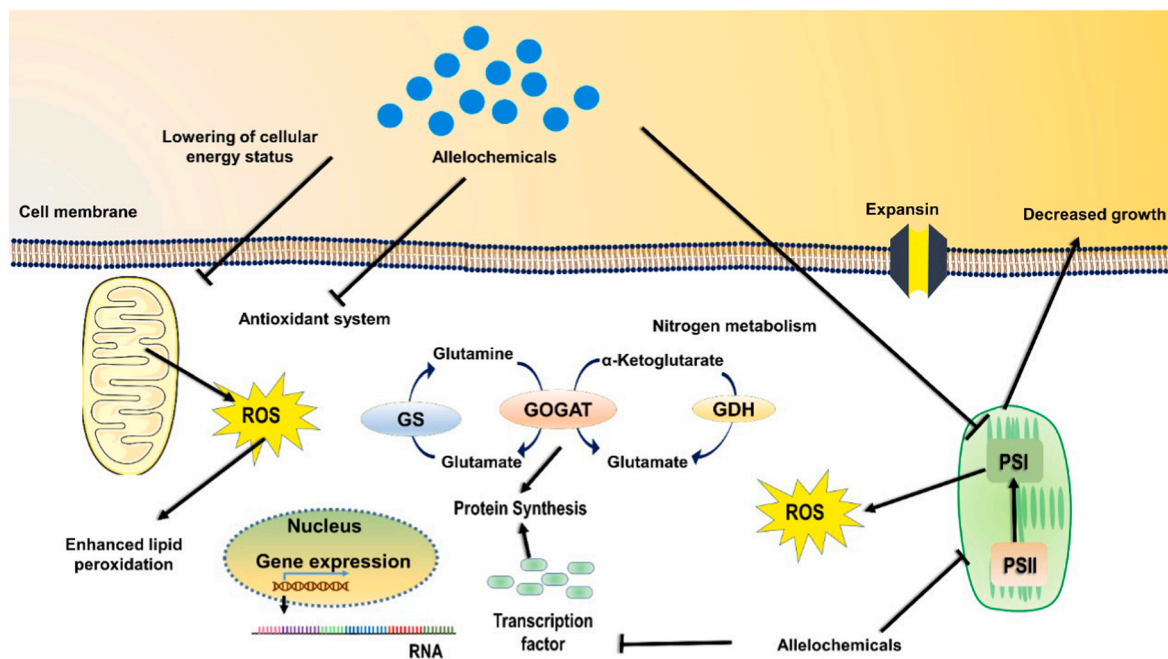


Fig. 4. A schematic model illustrating the effect of allelochemicals on general metabolic function of cell. Allelochemicals affect the growth and development of the receiver plant by regulating the cellular processes and metabolism. Allelochemicals showed to have negative impact on the antioxidant system, photosynthetic systems and ATP synthesis in the mitochondria by inhibiting several rate limiting enzymes in these organelles. Moreover, allelochemical also regulate GS:GOGAT pathway which is a major rate limiting enzyme of nitrogen metabolism. These bioactive compounds also affect the cell wall loosening enzymes such as expansin which disturbs morphological traits and causes reduced growth. All these parameters result in lowering of cell energy status and ultimately deteriorating the growth and development of plant.

Table 1
Effect of allelochemicals on different physiological and biochemical processes in target plants.

Target crop	Allelochemical responsible	Physiological and biochemical process affected	References
<i>Changes in the micro and Ultra-structure of cells</i>			
Cucumber	Cinnamic acid	Disrupted the ultrastructure of chloroplasts and mitochondria	Wu et al. (2004)
Mustard (<i>Brassica juncea</i> L.)	Benzoic acid	Disorganized cell arrangement and disrupted cell organelles in roots	Kaur et al. (2005)
Wheat and <i>Arabidopsis thaliana</i> L.	Citral	Disruption of microtubules	Chaimovitch et al. (2012)
<i>Arabidopsis thaliana</i> L.	Citral	Disorganized cell ultra-structure, reduced intercellular communication and root hair formation	Graña et al. (2013)
<i>Inhibition of cell growth and multiplication</i>			
Lettuce	BOA ^a	Inhibition of the mitosis (mainly at G2-M checkpoint)	Sánchez-Moreiras et al. (2008)
Cucumber	BOA and DIBOA ^b	Slower regeneration of root cap cell	Burgos et al. (2004)
Soybean	Extracts of <i>Datura stramonium</i> L.	Inhibition root growth, reduced root hair length and density, increased chromosomal aberration and micronucleus indices	Cai and Mu (2012)
<i>Allium cepa</i>	Extracts of <i>Aglaia odorata</i> leaves (Ethyl acetate)	Disruption of chromatin organisation and the mitotic spindle along with hindered mitosis in roots.	Teerarak et al. (2012)
<i>Imbalances in the antioxidant system</i>			
Mung bean (<i>Phaseolus aureus</i>)	Caffeic acid	Anomalies in the activities of proteases, peroxidases (PODs), and polyphenol oxidases (PPOs) during root growth, and reduced concentration of total endogenous phenolics in hypocotyl cuttings	Batish et al., (2008)
<i>Increases in cell membrane permeability</i>			
<i>Hordeum spontaneum</i> , <i>Avena ludoviciana</i> , and wild mustard	Extracts of barley aerial parts	Increased lipid peroxidation	Farhoudi et al. (2012); Farhoudi and Lee (2013)
Potato (<i>Solanum tuberosum</i> L.)	Extract of combination of non-sterile shoots of wheat and <i>Alopecurus equalis</i> weed	Accumulation of oxygen radical species (O ₂ ⁻ , H ₂ O ₂ and malondialdehyde) in leaves, increased membrane permeability and altered superoxide dismutase (SOD) and ascorbate peroxidase (APX) activities	Zuo et al. (2012)
Barnyard grass (<i>Echinochloa crusgalli</i> L.)	Lemongrass (<i>Cymbopogon citratus</i>) oil	Lipid peroxidation and electrolyte leakage	Poonpaiboonpipat et al. (2013)
<i>Effect on the plant growth regulator system</i>			
Wheat	Ferulic acid	Accumulation of indole-3-acetic acid (IAA), gibberellic acid (GA3), and cytokinin in seedlings, with a simultaneous increase of ABA concentration	Liu and Hu (2001)
Barnyard grass	Aqueous extract of rice	Stimulate IAA oxidase activity with reduced IAA levels, thereby damaging the plant growth regulation system	Lin et al. (2001)
Tomato	Cyanamide (1.2 mM)	Hormone imbalance in plants (ethylene and auxin) roots' homeostasis	Soltys et al. (2012)
Rice	DTD ^c from <i>Ageratina adenophora</i>	The ABA content in rice seedling roots increased significantly, however this reduced dramatically after 96 h of treatment	Yang et al. (2008)
	HHO ^d from <i>A. adenophora</i>	For 48 and 96 h, HHO ^d significantly increased ABA content	
<i>Effect on enzymatic activity</i>			
Chrysanthemum (<i>Chrysanthemum indicum</i> L.)	Extract of above-ground parts and rhizospheric soil of Chrysanthemum	Root dehydrogenase and nitrate reductase activities were inhibited, the levels of soluble sugar and soluble protein were reduced, and root development of stem cuttings was impeded	Zhou et al. (2010)
Greater duck weed (<i>Spirodela polyrrhiza</i> L.)	Diethyl phthalate (DEP)	DEP is toxic as it inhibits glutamine synthetase (GS) isoenzymes, which are involved in N assimilation and antioxidant enzymes	Cheng (2012)
<i>Effect on respiration</i>			
Corn and soybean	Juglone	Disruption of root oxygen uptake in seedlings	Hejl and Koster (2004b)
Water melon	Ethanol extracts from corn pollen	Inhibits electron pathway and thereby reduced oxygen consumption	Cruz Ortega et al. (1988)
<i>Effect on plant photosynthesis</i>			
<i>Galium spurium</i> , <i>Aeschynomene indica</i> and <i>Rumex japonicus</i>	Sorgoleone	Reduced efficiency of photosystem II (PS-II) of weeds (21 days old seedlings) and growth inhibition	Uddin et al. (2012)
Barnyard grass (<i>Echinochloa crusgalli</i> L.)	Lemongrass (<i>Cymbopogon citratus</i>) oil	Reduced chlorophyll <i>a</i> and <i>b</i> and carotenoid contents, affected seed alpha-amylase activity interfering with photosynthetic metabolism	Poonpaiboonpipat et al. (2013)
<i>Effect on water and nutrient uptake</i>			
Corn	Ferulic acid (250 mM)	Inhibition of NH ₄ ⁺ -N, NO ₃ ⁻ -N and Cl ⁻ uptake in seedlings	Bergmark et al. (1992)
Wheat	Ferulic acid, benzaldehyde and 4-tert-butyl benzoic acid	Affects NH ₄ ⁺ -N absorption by seedlings	Yuan et al. (1998)
Cucumber	Cinnamic acid and the root exudates of cucumber	Inhibits the uptake of NO ₃ ⁻ , SO ₄ ²⁻ , K ⁺ , Ca ²⁺ , Mg ²⁺ , and Fe ²⁺ by seedlings	Yu and Matsui (1997)
Peas (<i>Pisum sativum</i> L.), soybean and corn	Sorgoleone and juglone	Inhibited H ⁺ -ATPase activity and H ⁺ pumping in the root system which interferes with water uptake in plants	Hejli and Koster, 2004a; b
Maize	trans-Cinnamic, ferulic acid and p-coumaric acid	Inhibition of NO ₃ ⁻ -N uptake and plasma membrane H ⁺ -ATPase activity in seedlings	Abenavoli et al. (2010)
Radish	Sunflower (<i>Helianthus annuus</i> L.) residues	Reduced efficiency of assimilate translocation	Barros de Moraes et al. (2014)

(continued on next page)

Table 1 (continued)

Target crop	Allelochemical responsible	Physiological and biochemical process affected	References
Tomato	Diphenylamine	Reduced root P uptake	Geng et al. (2009)
<i>Effect on metabolism of protein and nucleic acid</i>			
<i>Eupatorium adenophorum</i>	HHO ^d	Affected the expression of chalcone synthase (CHS) gene in roots (related to synthesis of amino acids)	Guo et al. (2011)
<i>Arabidopsis</i>	Momilactone A and B (Rice allelochemicals)	Decreased seed germination by inhibition of degradation process of the storage proteins (cruciferin and cruciferina)	Kato-Noguchi et al. (2013)
Tomato	Cyanamide	Altered expression of genes (LeEXPA9 and LeEXPA18) responsible for cell wall re-modelling thus inhibiting the tomato root formation	Soltys et al. (2012)

^a 2(3H)-benzoxazolinone.

^b 2, 4-dihydroxy- 1,4(2H)-benzoxazin-3-one.

^c 4, 7-dimethyl-1-(propan-2-ylidene)1, 4, 4a, 8a-tetrahydronaphthalene-2, 6(1H, 7H)-dione.

^d 6-hydroxyl-5-isopropyl-3, 8-dimethyl-4a, 5, 6, 7, 8, 8a-hexahydronaphthalen-2(1H)-one.

15-day-old saplings. A similar effect was observed in the root cell ultrastructure of cucumber seedlings when exposed to allelochemicals like 2(3H)-benzoxazolinone (BOA) and 2,4-dihydroxy-1,4(2H)-benzoxazin-3-one (DIBOA) released from rye plant causing a decrease in root growth and suppression of cellular metabolisms (Burgos et al., 2004). These compounds exhibit such deleterious effects because of their ability to impede energy transduction and decrease ATPase activity in the cell membrane and chloroplasts (Burgos et al., 2004). Polyphenolic chemicals isolated from dodder plant inhibited mitotic activity in barley seedlings and onion root meristematic cells, with findings similar to treatments using 8-Hydroxyquinoline, a common cytotoxic drug (Ataei Azimi and Delnavaz Hashemloian, 2017). However, it should be noted that the concentration of the allelochemicals released into the soil environment is critical for staging such inhibitory effects in the growth of target plants. This was apparent when diallyl disulfide released from garlic at low concentrations showed growth promotion in tomatoes, while at higher levels inhibited root growth by affecting the activity of meristematic cells (Cheng et al., 2016).

5.2. Cell membrane integrity and its permeability

The cell membrane is an important component of the cell that serves as a barrier between the inside and outside environments. The integrity of the membrane is critical to protect the cell from external adverse environmental conditions (Xue et al., 2018). Allelopathy-induced alteration in membrane permeability and polarization triggers electrolyte leakage and lipid peroxidation, leading to decreased mineral nutrient uptake (Xue et al., 2018; Scavo et al., 2019; M'barek et al., 2019). Such changes in membrane permeability cause cell contents to spill and, as a result, plant tissues grow slowly or die (Li et al., 2010). The concentration of malonaldehyde (MDA) which is produced during lipid peroxidation, is often used as an indicator of cell membrane integrity. Early work on benzoic and cinnamic acids, commonly found allelochemicals in soil, showed increased electrolyte leakage and decreased catalase and peroxidase activity in soybean seedlings (Baziramakenga et al., 1995). They also cause a decrease in the electrochemical potential and depolarization of the plasma membrane resulting in the efflux of ions accompanying the increased membrane permeability (Blum, 1996; Ambika, 2013). In a study by Andriana et al. (2018), an increase in MDA activity was observed in radish seedlings in response to the oxidative stress caused by allelochemicals released from *Tridax procumbens* L. A similar effect was observed when leaf extracts of *Tetralinis articulata* (Vahl) Mast. was treated with lettuce resulting in aberrations in the cell membrane, causing substantial electrolyte leakage as indicated by an increase in MDA activity (M'barek et al., 2019).

5.3. Interference with various enzymes activities and endogenous hormone synthesis

Allelopathic substances released from the weed and other plants

which is grown in the vicinity of main crops leads to the inhibition of various enzymatic system in the plant (Weston and Duke, 2003). The mechanism of allelopathy related to phenolic compounds has been extensively explored, and data show that phenolics interfere with a number of rate-limiting enzymes and physiological processes in plants. For instance, cinnamic and benzoic acids inhibit hormone function, membrane permeability, photosynthesis, respiration, and organic compound synthesis. The allelopathic molecules were reported to inhibit different enzymes which are present in the plant system, such as pectolytic enzymes, catalases, cellulases, phosphorylases, ATPases, peroxidases, phosphatases, proteinases, invertases, decarboxylases, and nitrates. According to Cheng (2012), diethyl phthalate inhibits glutamine synthetase isoenzymes in nitrogen for nitrogen absorption and antioxidant enzymes in larger duckweed (*Spirodela polyrhiza* L.). Moreover, the study by Mahdavia and Saharkhiz (2016) suggested the beneficial effects of water extracts derived from peppermint leads to an improved morphological, physiological, and biochemical response of tomato. The extract concentration of about 10 percent (v/v) showed higher inhibitory action on proline, soluble sugar, and starch. Moreover, the phenolic compounds present in the extract also showed higher activities of antioxidant enzymes, including ascorbate peroxidase, catalase, peroxidase, and superoxide dismutase (SOD). Other reports suggest that the alkaloids might be considered to hinder the development of plants by various multiple mechanisms, which include interference with DNA, enzyme function, protein production, and membrane integrity in growing crops (Wink, 2004). Similarly, phytohormones like indole-3-acetic acid (IAA) and gibberellic acid (GA) are also affected by the allelopathic substances that regulate cell expansion. The earlier report also suggests that diverse allelochemicals inhibit the enzyme IAA-oxidase (Chou, 1980). Allelopathy stress enhanced ethylene and ABA (abscisic acid) synthesis (Bogatek et al., 2005). In their investigation of the influence of ferulic acid (FA) on the levels of endogenous hormones in wheat seedlings, FA caused a build-up of IAA, gibberellin, and cytokinin at doses of 2.50 mmol L⁻¹, but the accumulation of these four hormones created an accretion of abscisic acid. Brunn et al. (1992) revealed that the auxin transport is inhibited by some flavonoid aglycones that promote lateral root growth and inhibits negative geotropic growth.

5.4. Interference with plant respiration

Allelochemicals can either stimulate or inhibit respiration, thereby diminishing the vitality of the energy-producing mechanism (Batish et al., 2001). The allelochemical substances might inhibit the majority of the metabolic process, including O₂ uptake and the three phases of dark respiration, viz., glycolysis, the Krebs' cycle, and oxidative phosphorylation (Weir et al., 2004). Benzoxazolinone (BOA) is a benzoxazinone that is secreted by the roots of certain cultivated grasses and has a variety of physiological effects on plants. The generation of excessive reactive oxygen species (ROS) results in oxidative stress, which is a

crucial event in the mode of action of BOA in the plant (Schulz et al., 2013). According to Burgos et al. (2004), the allelochemicals BOA and DIBOA from rye decreased the number of mitochondria, protein synthesis, and lipid catabolism in cucumber seedlings. However, photorespiration in chloroplasts obscures a number of allelochemical impacts on mitochondrial respiration (Weir et al., 2004). It is conceptualized that certain allelopathic substances interact directly with the mitochondrial membrane and impede mitochondrial respiration. The monoterpenes like camphor, pinene, and limonene significantly affected the respiratory activity of soybean radicular hypocotyl mitochondria, but their modes of action appeared distinct (Abraham et al., 2003). Similarly, secondary metabolites such as flavonoid quercetin were reported to inhibit respiration in soybean hypocotyl mitochondria via three suggested hypothesized pathways. Quercetin appears to restrict substrate oxidation by directly interfering with electron transport, inhibiting phosphate intake and decoupling oxidative phosphorylation (Abraham et al., 2000).

It has been demonstrated that allelochemicals have a deleterious effect on photosynthesis, while the underlying mechanisms are unknown. Allelochemicals can affect three primary photosynthetic processes (Zhou and Yu, 2006): (i) stomatal conductance and consequently gas exchanges between plant and atmosphere; (ii) "light reactions," which refer to electron transport; and (iii) "dark reactions" which refer to carbon reduction. Allelochemicals have a substantial effect on plant photosynthesis by accelerating the degradation of photosynthetic pigments, specifically chlorophyll (Pan et al., 2015). By decreasing chlorophyll content, benzoic and cinnamic acids inhibited soybean photosynthesis (Baziramakenga et al., 1994). The inhibition of photosynthesis and oxygen evolution via interactions with photosystem II (PSII) components is one of the best-studied phytotoxic effects of allelochemicals (Einhellig et al., 1993). Photosynthetic inhibitors consist of electron or uncouplers, energy-exchange inhibitors, electron acceptors, or a combination of these. Numerous PSII components are necessary for the formation of a flexible membrane-embedded scaffold. This scaffold organizes the ligands that bind an excitonically linked network of pigments and cofactors that capture, transmit, and utilize solar energy to drive water-splitting processes. Sorgoleone, a lipophilic benzoquinone found in the root exudates of *S. bicolor*, is a well-documented PSII inhibitor (Gonzalez et al., 1997; Nimbale et al., 1996). As a plastoquinone analogue, sorgoleone inhibits plastoquinone binding at the D1 protein of PSII (Czarnota et al., 2001) and also inhibits hydroxyphenylpyruvate dioxygenase (HPPD), which interrupts carotenoids biosynthesis and results in foliar bleaching (Meazza et al., 2002).

5.5. Inhibition of protein synthesis and nucleic acid metabolism

The phytotoxicity of certain allelochemicals is associated with their susceptibility to disturb normal metabolic processes in plants. This may also be a mode of action for other allelochemicals. For instance, L-canavanine, a L-arginine analogue identified in *Canavalia ensiformis*, inhibits plant growth because of its ability to disrupt L-arginine metabolism, resulting in a deficiency of L-arginine-derived compounds (Nakajima et al., 2001). In a study, radio-labeled C-14 sugars or amino acids were used to examine the effect of absorption of allelochemicals into protein, and the result showed an inhibition of protein synthesis (Bertin et al., 2007). Allelochemical reactions may generate ROS such as superoxide anions (O_2^-), hydroxyl (OH^-), or hydroperoxyl (HO_2) radicals, which can affect membrane permeability, nucleic acid structure, and protein synthesis, ultimately resulting in cell death (Weir et al., 2004). Allelochemicals can also interfere with gene expression (He et al., 2012; Fang et al., 2015; Ma et al., 2015), which is typically induced in recipient plants in response to an attack by the donor plants. Sarmentine and some other fatty acids, namely pelargonic acid, have the ability to improve the fluidity of leaf cuticle and the activity of peroxidase, which might be used as a potential desiccant (Huang et al., 2010).

5.6. Interference with plant-water relationship

There are many allelochemicals that might influence the water balance and target by clogging the xylem component, reduction of stomatal conductance, lowering of plant water potential, and thereby reducing the water uptake by the root system. Reports by Barkosky and Einhellig (2003) suggested that the concentration of 0.75 mM 4-hydroxybenzoic acid (p-HBA) significantly reduced water productivity and stomatal conductance in soybean seedlings. Sorgoleone and juglone affected cell permeability in crops like pea, maize and soybean by affecting the H^+ -ATPase activity and proton-pumping across the root cell plasma membrane (Hejli and Koster, 2004a; b). Bergmark et al. (1992) observed that ferulic acid (250 μ M) lowered NH_4^+ and NO_3^- absorption in maize seedlings, with inhibition of NH_4^+ absorption being less responsive than NO_3^- absorption.

5.7. Interference with soil microbial activity

The allelochemicals have a diversified effect on microorganisms dwelling in the rhizospheric soil. These plant-microbe interactions can be either stimulatory or affect the growth of microbes, influencing plant growth. The allelopathic effect of *Alliaria petiolata* (*Alliaria*) on mutualistic microbes has been widely studied. A study revealed that breakdown products generated during the decomposition of glucosinolate secreted by *Alliaria* might have harmful effects on mycorrhizal fungi (Vaughn and Berhow, 1999). Later on, various studies were conducted affirming the adverse role played by *Alliaria* on mycorrhizal species (Stinson et al., 2006; Wolfe et al., 2008; Barto et al., 2012a,b). However, the change in the community structure of soil microbes under the effect of allelopathic plant species varies with the age shift in plant population (Lankau, 2011). Evidences of the negative impact of allelopathic plant species on the beneficial soil bacteria are also replete. An early report by Mallik and Tesfai (1988) showed that shoot extracts of several weed species, including *Chenopodium album*, *Cyperus esculentus*, and *Helianthus annuus* inhibited nodulation by *Bradyrhizobium japonicum*. Similar works related to growth inhibition of various symbiotic (*Rhizobium*) and free-living (*Azotobacter*) bacteria in the presence of plant allelochemicals have been reported (Kloepper et al., 2004; Pollock et al., 2011). Such a relationship between allelopathic plant species and beneficial rhizospheric microbes will provide an added advantage to these plant species while competing with plants that are symbionts with such microbes (Cipollini et al., 2012). However, it must be noted that the adverse effect of allelopathy on soil microbes will also impact the growth of allelopathic plants, which also tend to benefit from the ecosystem services provided by these beneficial microbes (Devi et al., 2021). Allelopathy induces a series of physiological and biochemical changes in plants. Understanding the mode of action of different allelochemicals may aid in obtaining the basic information on the structure and biochemical forms of different allelochemicals for developing new bio-herbicides.

6. Application of allelopathy in weed management

Allelopathy plays an important role in overall weed suppression, and the residue of allelopathic plants enhances nutrient cycling processes in soil, thus having a significant effect on crop productivity. Application of water extract of sunflower curbed the problem of weeds like *Avena fatua* and *Phalaris minor*, thereby reducing the weed dry weight (10–62.0%) and increasing the yield (18.55–62.0%) of sunflower compared to control (Jamil et al., 2009). In a recent study by Sahoo et al. (2023) the positive effect of sunflower crop residue incorporation was observed on subsequent rice crop yield, which could be attributed to better weed suppression, nutrient availability and improved microbial activity. However, it must be noted that allelopathy of most of the crops is species-specific and discriminatory in their action, i.e., they inhibit the growth of some species but might not affect certain species and may have stimulatory effects (Cheema, 1988). Sorghum allelochemicals are

specific in action and concentration-dependent in their effect (Cheema and Ahmad, 1992). Sturm et al. (2018) found that allelopathic effects were species-specific, with the weed *Stellaria media* showing greater sensitivity to allelopathy than *Alopecurus myosuroides* and volunteer wheat (*T. aestivum*). The release of allelochemicals and their activity depends on the environmental conditions, plant species, soil microbial properties etc. However, similar to synthetic herbicides, some allelochemicals also exhibit selectivity. Numerous woody and herbaceous plants, in addition to weeds, have allelopathic effects on both crops and weeds (Tesio and Ferrero, 2010). The most recent estimate showed 240 allelopathic weeds (Qasem and Foy, 2001), although many more plant species have been discovered to exhibit allelopathic qualities in the last two decades. Examples of allelopathic interactions between various plant species are given in Tables 2 and 3, including crops on weeds, crops on crops, weeds on weeds, and weeds on crops.

In general, manual removal of weeds or manual weed management operations is arduous, time-consuming, and expensive in this modern era. Developing several herbicide chemicals paved the way for more efficient and timely weed control. However, despite increased crop productivity due to herbicides, their uncontrolled usage has resulted in ecological threats such as the emergence of herbicide-resistant weeds and weed flora shifts in different ecologies. In order to overcome these issues, research should focus on alternative weed management strategies to reduce the use of synthetic chemicals for weed control. One of the strategies can be allelopathic weed management which is an effective plausible way toward sustainable weed management. These allelochemicals effectively inhibit weeds, leaving less to no phytotoxic residues and can substitute chemical formulations for weed control, thereby minimizing environmental pollution and ensuring better ecosystem functioning (Macias et al., 2003; Bhadoria, 2011). Allelochemicals can be used to develop novel eco-friendly bio-herbicides to inhibit weed germination and growth. However, some shortcomings that limit the use of natural herbicides are, (a) expensive due to structural complexity, (b) short environmental half-life, (c) non-target specific toxicity, and (d) potential mammalian toxicity (like AAL-toxin, fumonisin) and allergy (like sorgholeone) (Duke et al., 2000). The allelopathic weed management can be deployed at the field scale through a spatio-temporal arrangement of crops. However, heavy fieldwork and other interferences, such as competition for inputs, soil microbial impact, nutrient immobilization, etc., may make its execution difficult at the field scale (Cheng and Cheng, 2015). However, it must be noted that the selection of high-value crops with allelopathic properties (Sahoo et al., 2023) can provide better remuneration, which may pay off the laborious work incurred. Additionally, allelopathy could be a green alternative to hazardous chemical herbicides, thus maintaining and stimulating ecosystem functions and environmental health. The allelopathic weed management following different agronomic management methods is briefly discussed hereunder.

6.1. Crop rotation

Crop rotation gives the best results in reducing weed seed bank, i.e., maintaining weed communities at low densities, hindering weed establishment in early crop season and is most useful in avoiding invasive or noxious weed flora development (Buhler et al., 2000; Scavo and Mauromicale, 2020). Some crops commonly used in rotations with allelopathic potential are rice, wheat, sorghum, barley, rye, and sunflower (Abbas et al., 2021; Sahoo et al., 2023). Inclusion of these allelopathic crops in the cropping sequence controls weeds by releasing allelochemicals which will act against inhibition of weed seed germination and prevent the establishment of weeds (Scavo et al., 2019). Various studies report different crop rotations successfully suppressing the weed growth and establishment, for instance, sorghum-wheat (Shahzad et al., 2016); winter wheat-spring barley-peas (Schermer et al., 2016); and corn-soybean-oat/alfalfa-alfalfa (Hunt et al., 2017). All these studies agree upon the suppression of weeds through

diversified crop rotations.

6.2. Cover crops

Allelopathic cover crops have several advantages in weed control, soil fertility improvement, soil erosion control and higher yield for subsequent crops (Tursun et al., 2018). Most noteworthy cover crops include canola, rapeseed, brown mustard, black mustard, oats, rye, crimson clover, red clover, cowpea, fodder radish, wheat, annual ryegrass, mustard, hairy vetch, and buckwheat, where all these crops may be employed in different cropping systems to inhibit the growth of weeds due to their vigorous initial growth, space capture ability and allelopathic effect (Mirsky et al., 2013). Some crops exude different allelochemicals, which may have serious implications on the seed germination and growth of weed seedlings (DeVore et al., 2012). For instance, taking up rye as a cover crop with cotton can control the establishment of the noxious weed *Amaranthus* by 67% over control (Tabaglio et al., 2013). This allelopathic weed management tactic of using cover crops can keep a check on the weed population below economic threshold levels but may not completely suppress the weed growth and reduces the use of existing herbicide formulations for weed management (Narwal and Haouala, 2013).

6.3. Green manuring

Green manuring includes the incorporation of crop biomass into the soil, mostly before taking the main crop. This practice of green manuring ushers diversification in crop rotational sequences. The aqueous extracts of some green manure crops show allelopathic weed control through their inhibitory action on weed growth (Adler and Chase, 2007; Purohit and Pandya, 2013; Anese et al., 2015; Rugare et al., 2021). Crop-specific allelochemicals are mostly responsible for weed suppression. For instance, black sunn hemp roots can have dehydropyrrolidizine alkaloids, while the leaves, stem, and seeds have isohemijunceines A, B, C, trichodesmine, junceine, and acetylisohehijunceines (Morris et al., 2015). The cruciferous plants contain ample quantities of glucosinolate chemicals which when hydrolyzed to isothiocyanates (Boydston and Hang, 1995) have potential to reduce weed growth and establishment. On the whole, green manuring helps in early-season weed control and thereby reduces the dependency on post-emergence herbicides.

6.4. Mulching

Allelopathic weed control using mulches has two main approaches, i.e., through the cultivation of live crops as mulch in the field, which covers the maximum ground space inhibiting the growth of weeds and the second approach being surface retention of crop residues to suppress the establishment of weeds (Scavo and Mauromicale, 2020). These cover crop residues used as mulch can hinder the growth of weeds by their physical presence on the surface of the soil or by releasing allelochemicals during microbial decomposition of residues (Weston, 1996). Mulches can be introduced into cropping systems in different ways, such as conservation agriculture, crop rotations, strip cropping, intercropping, and cover crops. Many research studies on different crop residue mulches, viz. rye (Schulz et al., 2013; Tabaglio et al., 2013), maize (Bajgai et al., 2015), sunflower (Rawat et al., 2017), have shown that they can be potentially used as a weed control strategy in field crops.

6.5. Intercropping

Allelopathic crops primarily aid in lowering weed intensity and therefore increase agricultural production when intercropped with other crop species. Because intercropping suppresses weeds more effectively than solo cropping, it provides the opportunity to employ crops as an efficient weed management strategy. By increasing the diversity of the soil microbial population and promoting the movement of

Table 2
Allelopathic effect of crops on other plants.

Allelopathic Crop (Donor)	Target plant (Receiver)	Response of weeds	Allelochemical	Type of experiment	References
<i>Effect of cereal crops on weed</i>					
Rice	<i>Echinochloa crusgalli</i> , <i>Cyperus difformis</i> , <i>Cyperus iria</i> , <i>Fimbristylis miliacea</i>	Inhibition the seed germination and seedling shoot length and root length	Phenolic acid, indoles and terpenes	Pot experiment in glass house	Alam et al. (2018)
Rice	<i>E. crusgalli</i>	Inhibition of weed grass development by more than ~41%	–	Laboratory	Rahaman et al. (2021)
Sorghum	<i>Amaranthus hybridus</i>	Reduce the emergence, plant height, leaf area and dry weight	Sorgoleone	Pot experiment in glass house	Tibugari et al. (2019)
Barley	<i>Hordeum spontaneum</i>	Reduced hypocotyl length, hypocotyl weight, radicle weight, seed germination and radicle length	Water soluble allelochemical	Green house and laboratory	Ashrafi et al. (2007)
Rye	<i>Amaranthus retroflexus</i> and <i>Portulaca oleracea</i>	Reduced germination and seedling growth	Benzoxazinones	Field experiment	Tabaglio et al. (2013)
<i>Effect of legumes crops on weed</i>					
Faba bean	<i>E. crusgalli</i> and <i>A. retroflexus</i>	Reduced the germination, root and shoot elongation and aerial biomass	–	Pot experiment	Álvarez-Iglesias et al. (2018)
Cow pea	<i>Eleusine indica</i> (L.) Gaertn.	Reduced germination, plant height and dry weight	–	Green house experiment	Adler and Chase (2007)
Common bean	<i>Bidens pilosa</i> , <i>E. indica</i> and <i>Acanthospermum hispidum</i>	Reduced germination percentage, radicle and plumule length	–	Laboratory and green house experiment	Runzika et al. (2013)
<i>Effect of oil seed crops on weeds</i>					
Black mustard	<i>Phalaris paradoxa</i>	Decreased plant biomass and leaf area by 94% and 92%, respectively	Ferulic acid, syringic acid and caffeic acid	Laboratory and green house	Al-Sherif et al. (2013)
Groundnut	<i>Lathyrus hirsutus</i> L. and <i>Anagallis arvensis</i> L.	Reduced germination percentage	–	Petri dishes in controlled chamber	Abou El-Enin and Abdel-Ghffa (2017)
Sunflower	<i>Parthenium hysterophorus</i> L.	Reduced germination, root length, root and shoot biomass	–	Petri dishes in growth chamber and pot in green house	Javaid et al. (2006)
<i>Effect of crop on crop</i>					
Sunflower	Wheat and maize	Germination percentage germination index radicle and plumule length and seedling dry biomass	Alkaloids, phenolic compounds, flavonoids and terpenoids	Petri dishes in laboratory	Muhammad and Majeed (2014)
GM maize	Wheat	Decreased chlorophyll <i>a</i> , carotenoid, leaf soluble sugar, proline and activity of POD	-	Field experiment	Ibrahim et al. (2013)
Rice Straw	Rice	Reduction chlorophyll content	Phenolic acids	Field experiment	Asaduzzaman and Pramanik (2005)

allelochemicals into the soil, intercropping is said to improve the interactions between allelopathic weeds and cover crops and, as a result, the phytotoxic consequences (Brooker et al., 2015). Common mycorrhizal networks have been found to be operating as “superhighways” that directly connect plants underneath and transport allelochemicals to target plants (Barto et al., 2012a,b). Many researchers have witnessed reduced weed density and biomass production with intercropping in different cropping systems, viz. intercropping maize with fodder legumes (Khan et al., 2002); intercropping sesame, soybean, and sorghum with cotton (Iqbal et al., 2007); and pea intercropped with false flax (Saucke and Ackermann, 2006). Crops with allelopathic potential should be chosen for agronomic interventions like green manuring, crop rotation, cover crops, intercropping, mulches etc., in cropping systems. Research towards identifying and screening suitable or compatible allelopathic plant species in combination with other crop species in cropping systems can be a promising option for successful implementation of allelopathic weed control.

7. Conclusions and way forward

Dependency on synthetic herbicides in this modern era of agriculture severely affects the environment and the ecosystem. Alternate sustainable weed management strategies like allelopathy could be included in integrated weed management programs to reduce the usage of synthetic herbicides. The identification and augmentation of allelochemical synthesis and release pathways in donor plants could increase their

concentration in the target environment. The allelochemicals interact differently with the soil environment based on their chemical nature, which could be used for inducing selectivity in weed management. Agronomic cultural practices like crop rotation, intercropping, and cover crops with crop species having allelopathic potential could be a part of conventional farming practices for economical and effective weed control. The extraction of allelochemicals from donor plants and their use as bioherbicide could be another approach to using allelopathy for weed management. Allelopathic weed management provides an opportunity to maintain ecological diversity while fulfilling the terms of sustainable agriculture. Promoting cross-disciplinary research on allelopathy and its application in agro-ecosystems will not only clarify the intricate role of allelochemicals in natural systems but also help us understand the communication channels between different organisms in soil environments that are prevalent at the micro level. Future research should address this and, in addition, should explore the application of biotechnological tools to enable plants to overcome biotic and abiotic stress in order to ensure a sustained defense mechanism system. Research must be done on introducing and regulating a multigene expression system to synthesize and localize the compatible allelochemicals in the appropriate plant tissue or organ. Using allelochemical consortia for weed management could be a more effective option for controlling weed growth for a sustainable agriculture.

Table 3

Allelopathic effect of weeds on other plants.

Allelopathic weed (Donor)	Target plant (Receiver)	Response of weeds	Allelochemical	Type of experiment	References
<i>Effect of weeds on weeds</i>					
<i>Persicaria lapathifolia</i>	<i>Echinochloa colona</i>	Reduced germination, seedling root and shoot growth	n-Dodecanal, α -humulene and limonene	Petri dishes in growth chamber	Abd-ElGawad et al. (2021)
<i>Achyranthes aspera</i> L.	<i>Digera arvensis</i> , <i>Chenopodium album</i> , <i>Trianthema portulacastrum</i> , <i>Parthenium hysterophorus</i> , <i>Convolvulus arvensis</i> , <i>Rhynchosia capitata</i>	Reduced seedling establishment, emergence index and emergence energy	Gallic acid, caffeic acid, 4-hydroxy-3-methoxy benzoic acid, m-coumaric acid, chromatotropic acid and syringic acid	Laboratory condition	Safdar et al. (2021)
<i>Ipomoea cairica</i>	<i>P. hysterophorus</i>	Decrease chlorophyll content	3'-3'-5-Trihydroxy-4'-7-dimethoxyflavone	Pot experiment	Srivastava and Shukla (2016)
<i>Lantana camara</i>	<i>Rumex dentatus</i>	Suppression of seed germination and decreased radicle and plumule length	Flavonoids, iridoid glycoside, furanaphoquinones	Laboratory condition	Anwar et al. (2018)
<i>Allelopathic effect of weed on crop</i>					
<i>Tridax procumbens</i>	Mung bean and cowpea	Inhibitory effect on germination, root and shoot elongation	Aqueous leaf extract	Petri plates in laboratory	Femina et al. (2012)
<i>Eupatorium odoratum</i>	Rice and groundnut	Reduced seed germination and seedling growth	Weed debris	Pot culture in Net house	Begum et al. (2021)
<i>Lantana camara</i>	Oat	Reduced germination		Petri plates in laboratory	Hayyat et al. (2020)
<i>Polypogon hissaricus</i>	Wheat	Reduced germination, growth and chlorophyll content	Aqueous leaf extract	Petri dish and pot culture	Siyar et al. (2019)
<i>Phalaris minor</i> L.	Wheat	Inhibition seed germination; reduced seedling dry weight	Alkaloids, quinines, phenolics	Petri dishes in laboratory condition	Ankita and Chabbi (2012)
<i>Echinochloa colona</i> L. and <i>Cyperus iria</i> L.	Rice and soybean	Reduced germination and suppressed early seedling growth		Petri dishes in laboratory condition	Chopra et al. (2017)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

This review article has referred already published research work with due citations in the text.

References

- Abbas, T., Ahmad, A., Kamal, A., Nawaz, M.Y., Jamil, M.A., Saeed, T., Abid, M.A., Ali, H. H., Ateeq, M., 2021. Ways to use allelopathic potential for weed management: a review. *Int. J. Food Sci. Agric.* 5, 492–498. <https://doi.org/10.26855/ijfsa.2021.09.020>.
- Abd-ElGawad, A.M., Bonanomi, G., Al-Rashed, S.A., Elshamy, A.I., 2021. *Persicaria lapathifolia* essential oil: chemical constituents, antioxidant activity, and allelopathic effect on the weed *Echinochloa colona*. *Plants* 10, 1798. <https://doi.org/10.3390/plants10091798>.
- Abenavoli, M.R., Lupini, A., Oliva, S., Sorgonà, A., 2010. Allelochemical effects on net nitrate uptake and plasma membrane H⁺-ATPase activity in maize seedlings. *Biol. Plant. (Prague)* 54, 149–153. <https://doi.org/10.1007/s10535-010-0024-0>.
- Abou El-Enin, M.M., Abdel-Ghffia, M.A.F., 2017. Allelopathic effect of peanut, sunflower and corn crops on germination and growth of some winter weeds. *Arch. Agri. Environ. Sci.* 2, 257–263. <https://doi.org/10.26832/24566632.2017.020402>.
- Abraham, D., Braguini, W.L., Kelmer-Bracht, A.M., Ishii-Iwamoto, E.L., 2000. Effects of four monoterpenes on germination, primary root growth, and mitochondrial respiration of maize. *J. Chem. Ecol.* 26, 611–624. <https://doi.org/10.1023/A:1005467903297>.
- Abraham, D., Takahashi, L., Kelmer-Bracht, A.M., Ishii-Iwamoto, E.L., 2003. Effects of phenolic acids and monoterpenes on the mitochondrial respiration of soybean hypocotyl axes. *Allelopathy J.* 11, 21–30.
- Adler, M.J., Chase, C.A., 2007. Comparison of the allelopathic potential of leguminous summer cover crops: cowpea, sunn hemp, and velvetbean. *Hortscience* 42, 289–293. <https://doi.org/10.21273/HORTSCI.42.2.289>.
- Al Harun, M.A.Y., Robinson, R.W., Johnson, J., Uddin, M.N., 2014. Allelopathic potential of *Chrysanthemoides monilifera* subsp. *monilifera* (boneseed): a novel weapon in the invasion processes. *South Afr. J. Bot.* 93, 157–166.
- Al-Sherif, E., Hegazy, A.K., Gomaa, N.H., Hassan, M.O., 2013. Allelopathic effect of black mustard tissues and root exudates on some crops and weeds. *Planta Daninha* 31, 11–19. <https://doi.org/10.1590/S0100-83582013000100002>.
- Alam, M.A., Hakim, M.A., Juraimi, A.S., Rafii, M.Y., Hasan, M.M., Aslani, F., 2018. Potential allelopathic effects of rice plant aqueous extracts on germination and seedling growth of some rice field common weeds. *Ital. J. Agron.* 13, 134–140. <https://doi.org/10.4081/ija.2018.1066>.
- Albuquerque, M.B., Santos, R.C., Lima, L.M., Melo Filho, PdA., Nogueira, R.J.M.C., Câmara, C.A.G., Ramos, A., 2011. Allelopathy, an alternative tool to improve cropping systems. A review. *Agron. Sustain. Dev.* 31, 379–395. <https://doi.org/10.1051/agro/2010031>.
- Aldrich, R.J., 1984. *Weed-Crop Ecology: Principles in Weed Management*. Breton publishers, north Scituate, Massachusetts, USA.
- Álvarez-Iglesias, L., Puig, C.G., Revilla, P., Reigosa, M.J., Pedrol, N., 2018. Faba bean as green manure for field weed control in maize. *Weed Res.* 58, 437–449. <https://doi.org/10.1111/wre.12335>.
- Ambika, S.R., 2013. Multifaceted attributes of allelochemicals and mechanism of allelopathy. In: *Allelopathy*. Springer, pp. 389–405.
- Andriana, Y., Xuan, T.D., Quan, N.V., Quy, T.N., 2018. Allelopathic potential of *Tridax procumbens* L. on radish and identification of allelochemicals. *Allelopathy J.* 43, 223–238. <https://doi.org/10.26651/alleloj.2018-43-2-1143>.
- Anese, S., Grisi, P.U., Jatobá, LdJ., Pereira, VdC., Gualtieri, S.C.J., 2015. Phytotoxic activity of different plant parts of *Drimys brasiliensis* miers on germination and seedling development. *Biosci. J.* 31, 923–933. <https://doi.org/10.14393/BJ-v31n3a2015-26056>.
- Ankita, G., Chabbi, M., 2012. Effect of allelopathic leaf extract of some selected weed flora of Ajmer district on seed germination of *Triticum aestivum*. *Sci. Res.* 2, 311–315.
- Anwar, T., Ilyas, N., Qureshi, R., Maqsood, M., Munazir, M., Anwar, P., Rahim, B.Z., Ansari, K.A., Panni, M.K., 2018. Allelopathic potential of *Lantana camara* against selected weeds of wheat crop. *Appl. Ecol. Environ. Res.* 16, 6741–6760. https://doi.org/10.15666/aer/1605_67416760.
- Asaduzzaman, M., Pramanik, M.H.R., 2005. Allelopathic effect of rice straw in soil on nutrient and chlorophyll contents of transplanted aman rice. *Bangladesh J. Environ. Sci.* 11, 359–363.
- Ashrafi, Y.Z., Sadeghi, S., Mashhadi, H.R., 2007. Allelopathic effect of Barley (*Hordeum vulgare*) on germination and growth of wild Barley (*Hordeum spontaneum*). *Pakistan J. Weed Sci. Res.* 13, 99–112.
- Ataei Azimi, A., Delnavaz Hashemloian, B., 2017. Allelopathy and antimicrobial effects of *Cuscuta campestris* and *Cuscuta monogyna* extracts on plant cell division. *J. Med. Plants Prod.* 6, 131–138.
- Aulakh, M.S., Wassmann, R., Bueno, C., Kreuzwieser, J., Rennenberg, H., 2001. Characterization of root exudates at different growth stages of ten rice (*Oryza sativa* L.) cultivars. *Plant Biol.* 3, 139–148. <https://doi.org/10.1055/s-2001-12905>.

- Badri, D.V., Vivanco, J.M., 2009. Regulation and function of root exudates. *Plant Cell Environ.* 32, 666–681. <https://doi.org/10.1111/j.1365-3040.2008.01926.x>.
- Bajgai, Y., Kristiansen, P., Hulugalle, N., McHenry, M., 2015. Comparison of organic and conventional managements on yields, nutrients and weeds in a corn-cabbage rotation. *Renew. Agric. Food Syst.* 30, 132–142. <https://doi.org/10.1017/S1742170513000264>.
- Barkosky, R.R., Einhellig, F.A., 2003. Allelopathic interference of plant-water relationships by parahydroxybenzoic acid. *Bot. Bull. Acad. Sin. (Taipei)* 44.
- Barros de Moraes, C.S., Silva Dos Santos, L.A., Vieira Rossetto, C.A., 2014. Oil radish development agronomic affected by sunflower plants reduces. *Biosci. J.* 30, 117–128.
- Barto, E.K., Weidenhamer, J.D., Cipollini, D., Rillig, M.C., 2012a. Fungal superhighways: do common mycorrhizal networks enhance below ground communication? *Trends Plant Sci.* 17, 633–637. <https://doi.org/10.1016/j.tplants.2012.06.007>.
- Barto, E.K., Weidenhamer, J.D., Cipollini, D., Rillig, M.C., 2012b. Fungal superhighways: do common mycorrhizal networks enhance below ground communication? *Trends Plant Sci.* 17 (11), 633–637.
- Bashir, K., Ishimaru, Y., Shimo, H., Kakei, Y., Senoura, T., Takahashi, R., Sato, Y., Sato, Y., Uozumi, N., Nakanishi, H., Nishizawa, N.K., 2011. Rice phenolics efflux transporter 2 (PEZ2) plays an important role in solubilizing apoplasmic iron. *Soil Sci. Plant Nutr.* 57, 803–812. <https://doi.org/10.1080/00380768.2011.637305>.
- Batish, D.R., Singh, H.P., Kaur, S., 2001. Crop allelopathy and its role in ecological agriculture. *J. Crop Prod.* 4, 121–161. <https://doi.org/10.1300/J144v04n02.03>.
- Batish, D.R., Lavanya, K., Singh, H.P., Kohli, R.K., 2007. Phenolic allelochemicals released by *Chenopodium murale* affect the growth, nodulation and macromolecule content in chickpea and pea. *Plant Growth Regul.* 51, 119–128. <https://doi.org/10.1007/s10725-006-9153-z>.
- Batish, D.R., Singh, H.P., Kaur, S., Kohli, R.K., Yadav, S.S., 2008. Caffeic acid affects early growth, and morphogenetic response of hypocotyl cuttings of mung bean (*Phaseolus aureus*). *J. Plant Physiol.* 165, 297–305. <https://doi.org/10.1016/j.jplph.2007.05.003>.
- Baziramakenga, R., Simard, R.R., Leroux, G.D., 1994. Effects of benzoic and cinnamic acids on growth, mineral composition, and chlorophyll content of soybean. *J. Chem. Ecol.* 20, 2821–2833. <https://doi.org/10.1007/BF02098391>.
- Baziramakenga, R., Leroux, G.D., Simard, R.R., 1995. Effects of benzoic and cinnamic acids on membrane permeability of soybean roots. *J. Chem. Ecol.* 21, 1271–1285. <https://doi.org/10.1007/BF02027561>.
- Begum, M., Salam, M.A., Zaman, F., 2021. Allelopathic effect of siam weed debris on seed germination and seedling growth of three test crop species. *Acta Sci. Malays. (ASM)* 5, 1–4. <https://doi.org/10.26480/asm.01.2021.01.04>.
- Behera, B., Das, T.K., 2019. Brown manure species, weeds and maize in a Co-culture in the field: who stands more competitive? *Pestic. Res. J.* 31, 129–134.
- Behera, B., Das, T.K., Rath, N., 2019. Carry-over effect of brown manuring supplemented with nitrogen on productivity and profitability in succeeding wheat (*Triticum aestivum*). *Indian J. Agric. Sci.* 89, 708–713.
- Behera, B., Das, T.K., Raj, R., Ghosh, S., Raza, M., Sen, S., 2021. Microbial consortia for sustaining productivity of non-legume crops: prospects and challenges. *Agric. Res.* 10, 1–14. <https://doi.org/10.1007/s40003-020-00482-3>.
- Belz, R.G., van der Laan, M., Reinhardt, C.F., Hurlle, K., 2009. Soil degradation of parthenin – does it contradict the role of allelopathy in the invasive weed *Parthenium hysterophorus* L. *J. Chem. Ecol.* 35, 1137–1150. <https://doi.org/10.1007/s10886-009-9698-1>.
- Bergmark, C.L., Jackson, W.A., Volk, R.J., Blum, U., 1992. Differential inhibition by ferulic acid of nitrate and ammonium uptake in *Zea mays* L. *Plant Physiol.* 98, 639–645. <https://doi.org/10.1104/pp.98.2.639>.
- Bertin, C., Yang, X., Weston, L.A., 2003. The role of root exudates and allelochemicals in the rhizosphere. *Plant Soil* 256, 67–83. <https://doi.org/10.1023/A:1026290508166>.
- Bertin, C., Weston, L.A., Huang, T., Jander, G., Owens, T., Meinwald, J., Schroeder, F.C., 2007. Grass roots chemistry: meta-tyrosine, an herbicidal nonprotein amino acid. *Proc. Natl. Acad. Sci. U. S. A.* 104, 16964–16969. <https://doi.org/10.1073/pnas.0707198104>.
- Bever, J.D., 2003. Soil community feedback and the coexistence of competitors: conceptual frameworks and empirical tests. *New Phytol.* 157, 465–473. <https://doi.org/10.1046/j.1469-8137.2003.00714.x>.
- Bhadoria, P.B.S., 2011. Allelopathy: a natural way towards weed management. *Am. J. Exp. Agric.* 1, 7–20. <https://doi.org/10.9734/AJEA/2011/002>.
- Blum, A., 1996. Crop responses to drought and the interpretation of adaptation. *Plant Growth Regul.* 20, 135–148. <https://doi.org/10.1007/BF00024010>.
- Bogatek, R., Oracz, K., Gniazdowska, A., 2005. Ethylene and ABA production in germinating seeds during allelopathy stress. In: *Fourth World Congress in Allelopathy*.
- Bouhaouel, I., Gfeller, A., Boudabbous, K., Fauconnier, M.L., Amara, H.S., du Jardin, P., 2018. Physiological and biochemical parameters: new tools to screen barley root exudate allelopathic potential (*Hordeum vulgare* L. subsp. *vulgare*). *Acta Physiol. Plant.* 40 (2), 38. <https://doi.org/10.1007/s11738-018-2604-0>.
- Boydston, R.A., Hang, A., 1995. Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*). *Weed Technol.* 9, 669–675. <https://doi.org/10.1017/S0890037X00024039>.
- Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., White, P.J., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytol.* 206, 107–117. <https://doi.org/10.1111/nph.13132>.
- Brunn, S.A., Muday, G.K., Haworth, P., 1992. Auxin transport and the interaction of phytohormones: probing the properties of a phytohormone binding protein. *Plant Physiol.* 98, 101–107. <https://doi.org/10.1104/pp.98.1.101>.
- Buhler, D.D., Liebman, M., Obrycki, J.J., 2000. Theoretical and practical challenges to an IPM approach to weed management. *Weed Sci.* 48, 274–280. [https://doi.org/10.1614/0043-1745\(2000\)048\[0274:TAPCTA\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2000)048[0274:TAPCTA]2.0.CO;2).
- Burgos, N.R., Talbert, R.E., Kim, K.S., Kuk, Y.I., 2004. Growth inhibition and root ultrastructure of cucumber seedlings exposed to allelochemicals from rye (*Secale cereale*). *J. Chem. Ecol.* 30, 671–689. <https://doi.org/10.1023/b:joec.0000018637.94002.ba>. PubMed: 15139316.
- Cai, S.L., Mu, X.Q., 2012. Allelopathic potential of aqueous leaf extracts of *Datura stramonium* L. on seed germination, seedling growth and root anatomy of *Glycine max* (L.) Merrill. *Allelopathy J.* 30, 235–245.
- Calvet, R., Barriuso, E., Dubus, I.G., 2007. Application of two surface complexation models to the adsorption of weak organic acids by soil: an additive approach. *Eur. J. Soil Sci.* 58, 609–624. <https://doi.org/10.1111/j.1365-2389.2006.00846.x>.
- Campbell, E.J., Schenk, P.M., Kazan, K., Penninckx, I.A., Anderson, J.P., Maclean, D.J., Cammue, B.P., Ebert, P.R., Manners, J.M., 2003. Pathogen-responsive expression of a putative ATP-binding cassette transporter gene conferring resistance to the diterpenoid sclareol is regulated by multiple defense signaling pathways in Arabidopsis. *Plant Physiol.* 133, 1272–1284. <https://doi.org/10.1104/pp.103.024182>.
- Chaimovitch, D., Rogovoy Stelmakh, O., Altshuler, O., Belasov, E., Abu-Abied, M., Rubin, B., Sadot, E., Dudai, N., 2012. The relative effect of citral on mitotic microtubules in wheat roots and BY2 cells. *Plant Biol.* 14, 354–364. <https://doi.org/10.1111/j.1438-8677.2011.00511.x>.
- Cheema, Z.A., 1988. In: *Weed Control in Wheat through Sorghum Allelochemicals*. PhD Thesis. Department of Agronomy, University of Agriculture, Faisalabad, Pakistan.
- Cheema, Z.A., Ahmad, S., 1992. Allelopathy: a potential tool for weed management. In: *Proc. Nat. Seminar on the Role of Plant Health and Care in Agric.*, pp. 151–156.
- Cheng, H.H., 1992. A conceptual framework for assessing allelochemicals in the soil environment. In: Rizvi, S.J.H., Rizvi, V. (Eds.), *Allelopathy*. Chapman & Hall, pp. 21–29.
- Cheng, T.S., 2012. The toxic effects of diethyl phthalate on the activity of glutamine synthetase in greater duckweed (*Spirodela polyrrhiza* L.). *Aquat. Toxicol.* 171–178. <https://doi.org/10.1016/j.aquatox.2012.08.014>.
- Cheng, F., Cheng, Z., 2015. Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy. *Front. Plant Sci.* 6, 1020.
- Cheng, H.H., Koskinen, W.C., 2002. Interactions of minerals-organic matter-living organisms on the fate of allelochemicals and xenobiotics in soil: a methodological evaluation. *Dev. Soil Sci.* 28, 135–145. [https://doi.org/10.1016/S0166-2481\(02\)80012-5](https://doi.org/10.1016/S0166-2481(02)80012-5).
- Cheng, F., Cheng, Z., Meng, H., Tang, X., 2016. The garlic allelochemical diallyl disulfide affects tomato root growth by influencing cell division, phytohormone balance and expansin gene expression. *Front. Plant Sci.* 7, 1199. <https://doi.org/10.3389/fpls.2016.01199>.
- Chopra, N., Tewari, G., Tewari, L.M., Upreti, B., Pandey, N., 2017. Allelopathic effect of *Echinochloa colona* L. and *Cyperus iria* L. weed extracts on the seed germination and seedling growth of rice and soybean. *Adv. Agric.* 1–5. <https://doi.org/10.1155/2017/5748524>.
- Chou, C.H., 1980. Allelopathic researches in the subtropical vegetation in Taiwan. *Comp. Physiol. Ecol.* 5, 222–234.
- Cipollini, D., Rigsby, C.M., Barto, E.K., 2012. Microbes as targets and mediators of allelopathy in plants. *J. Chem. Ecol.* 38, 714–727.
- Croteau, R., Kutchan, T.M., Lewis, N.G., 2000. Natural products (secondary metabolites). In: Buchanan, B., Gruissem, W., Jones, R. (Eds.), *Biochemistry and Molecular Biology of Plants*. American Society of Plant Biologists, pp. 1250–1268.
- Cruz Ortega, R., Anaya, A.L., Ramos, L., 1988. Effects of allelopathic compounds of corn pollen on respiration and cell division of watermelon. *J. Chem. Ecol.* 14 (1), 71–86. <https://doi.org/10.1007/BF01022532>.
- Czarnota, M.A., Paul, R.N., Dayan, F.E., Nimal, C.I., Weston, L.A., 2001. Mode of action, localization of production, chemical nature, and activity of sorgoleone: a potent PSII inhibitor in *Sorghum* spp. root exudates. *Weed Technol.* 15, 813–825. [https://doi.org/10.1614/0890-037X\(2001\)015\[0813:MOALOP\]2.0.CO;2](https://doi.org/10.1614/0890-037X(2001)015[0813:MOALOP]2.0.CO;2).
- Das, T.K., 2008. *Weed Science: Basics and Applications*. Jain Brothers Pub., New Delhi, ISBN 81-8360-096-4, 90136 (reprinted in 2009, 2011, 2013, 2015).
- Das, T.K., Sen, S., Raj, R., Ghosh, S., Behera, B., Roy, A., 2021. Economic threshold concept for weed management in crops: usefulness and limitation. *Indian J. Weed Sci.* 53, 1–13.
- Dayan, F.E., 2006. Factors modulating the levels of the allelochemical sorgoleone in *Sorghum bicolor*. *Planta* 224, 339–346. <https://doi.org/10.1007/s00425-005-0217-5>.
- De La Peña, R., Sattely, E.S., 2021. Rerouting plant terpene biosynthesis enables momilactone pathway elucidation. *Nat. Chem. Biol.* 17, 205–212. <https://doi.org/10.1038/s41589-020-00669-3>.
- Dermauw, W., Van Leeuwen, T., 2014. The ABC gene family in arthropods: comparative genomics and role in insecticide transport and resistance. *Insect Biochem. Mol. Biol.* 45, 89–110. <https://doi.org/10.1016/j.ibmb.2013.11.001>.
- Devi, R., Behera, B., Raza, M.B., Mangal, V., Altaf, M.A., Kumar, R., Kumar, A., Tiwari, R. K., Lal, M.K., Singh, B., 2021. An insight into microbes mediated heavy metal detoxification in plants: a review. *J. Soil Sci. Plant Nutr.* 1–23. <https://doi.org/10.1007/s42729-021-00702-x>.
- DeVore, J.D., Norsworthy, J.K., Brye, K.R., 2012. Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. *Weed Technol.* 26, 832–838. <https://doi.org/10.1614/WT-D-12-00110.1>.

- Ding, J., Sun, Y., Xiao, C.L., Shi, K., Zhou, Y.H., Yu, J.Q., 2007. Physiological basis of different allelopathic reactions of cucumber and figleaf gourd plants to cinnamic acid. *J. Exp. Bot.* 58, 3765–3773. <https://doi.org/10.1093/jxb/erm227>.
- Dixon, R.A., Paiva, N.L., 1995. Stress-induced phenylpropanoid metabolism. *Plant Cell* 7, 1085–1097. <https://doi.org/10.1105/tpc.7.7.1085>.
- Dudareva, N., Klemptner, A., Muhlemann, J.K., Kaplan, I., 2013. Biosynthesis, function and metabolic engineering of plant volatile organic compounds. *New Phytol.* 198, 16–32. <https://doi.org/10.1111/nph.12145>.
- Duke, S.O., Dayan, F.E., Romagni, J.G., Rimando, A.M., 2000. Natural products as sources of herbicides: current status and future trends. *Weed Res.* 40, 99–111.
- Ehlers, B.K., 2011. Soil microorganisms alleviate the allelochemical effects of a thyme monoterpene on the performance of an associated grass species. *PLoS One* 6, e26321. <https://doi.org/10.1371/journal.pone.0026321>.
- Einhellig, F.A., Rasmussen, J.A., Hejl, A.M., Souza, I.F., 1993. Effects of root exudate sorgoleone on photosynthesis. *J. Chem. Ecol.* 19, 369–375. <https://doi.org/10.1007/BF00993702>.
- Fageria, N.K., 2012. Role of soil organic matter in maintaining sustainability of cropping systems. *Commun. Soil Sci. Plan.* 43, 2063–2113. <https://doi.org/10.1080/00103624.2012.697234>.
- Fang, C., Li, Y., Li, C., Li, B., Ren, Y., Zheng, H., Zeng, X., Shen, L., Lin, W., 2015. Identification and comparative analysis of microRNAs in barnyardgrass (*Echinochloa crus-galli*) in response to rice allelopathy. *Plant Cell Environ.* 38, 1368–1381. <https://doi.org/10.1111/pce.12492>.
- Farhoudi, R., Lee, D.J., 2013. Allelopathic effects of barley extract (*Hordeum vulgare*) on sucrose synthase activity, lipid peroxidation and antioxidant enzymatic activities of *Hordeum spontaneum* and *Avena ludoviciana*. *Proc. Natl. Acad. Sci. India B Biol. Sci.* 83, 447–452. <https://doi.org/10.1007/s40011-012-0137-7>.
- Farhoudi, R., Zangane, H.S., Saeedipour, S., 2012. Allelopathic effect of barley [*Hordeum vulgare* (L.) cv. Karon] on germination and lipid peroxidation of wild mustard seedling. *Res. Crops.* 13, 467–471.
- Farooq, M., Jabran, K., Cheema, Z.A., Wahid, A., Siddique, K.H., 2011. The role of allelopathy in agricultural pest management. *Pest Manag. Sci.* 67, 493–506. <https://doi.org/10.1002/ps.2091>.
- Femina, D., LakshmiPriya, P., Subha, S., Manonmani, R., 2012. Allelopathic effects of weed (*Tridax procumbens* L.) extract on seed germination and seedling growth of some leguminous plants. *Int. Res. J. Pharm.* 3, 90–95.
- Galán-Pérez, J.A., Gámiz, B., Celis, R., 2021. Determining the effect of soil properties on the stability of scopoletin and its toxicity to target plants. *Biol. Fertil. Soils* 57, 643–655. <https://doi.org/10.1007/s00374-021-01556-2>.
- Gámiz, B., Hermosín, M.C., Celis, R., 2018. Appraising factors governing sorption and dissipation of the monoterpene carvone in agricultural soils. *Geoderma* 321, 61–68. <https://doi.org/10.1016/j.geoderma.2018.02.005>.
- Gámiz, B., Facenda, G., Celis, R., 2019. Modulating the persistence and bioactivity of allelochemicals in the rhizosphere: salicylic acid, a case of study. *Arch. Agron. Soil.* 65, 581–595. <https://doi.org/10.1080/03650340.2018.1512102>.
- Geng, G.D., Zhang, S.Q., Cheng, Z.H., 2009. Effects of different allelochemicals on mineral elements absorption of tomato root. *China Veg.* 4, 48–51.
- Gniazdowska, A., Bogatek, R., 2005. Allelopathic interactions between plants. Multi site action of allelochemicals. *Acta Physiol. Plant.* 27, 395–407. <https://doi.org/10.1007/s11738-005-0017-3>.
- Gonzalez, V.M., Kazimir, J., Nimal, C., Weston, L.A., Cheniae, G.M., 1997. Inhibition of a photosystem II electron transfer reaction by the natural product sorgoleone. *J. Agric. Food Chem.* 45, 1415–1421. <https://doi.org/10.1021/jf960733w>.
- Graña, E., Sotelo, T., Díaz-Tielas, C., Araniti, F., Krasuska, U., Bogatek, R., Reigosa, M.J., Sánchez-Moreiras, A.M., 2013. Citral induces auxin and ethylene-mediated malformations and arrests cell division in *Arabidopsis thaliana* roots. *J. Chem. Ecol.* 39, 271–282. <https://doi.org/10.1007/s10886-013-0250-y>. PubMed: 23389342.
- Grossl, P.R., 2008. Bioavailability of Allelochemicals in Soil. Utah State University dtic. <http://ml/dtic/tr/fulltext/u2/a495629.pdf>.
- Guo, H., Pei, X., Wan, F., Cheng, H., 2011. Molecular cloning of allelopathy related genes and their relation to HHO in *Eupatorium adenophorum*. *Mol. Biol. Rep.* 38, 4651–4656. <https://doi.org/10.1007/s11033-010-0599-8>.
- Harker, K.N., 2013. Slowing weed evolution with integrated weed management. *Can. J. Plant Sci.* 93, 759–764. <https://doi.org/10.4141/cjps2013-049>.
- Hasegawa, M., Mitsuhashi, I., Seo, S., Imai, T., Koga, J., Okada, K., Ohashi, Y., 2010. Phytoalexin accumulation in the interaction between rice and the blast fungus. *Mol. Plant Microbe Interact.* 23, 1000–1011. <https://doi.org/10.1094/MPMI-23-8-1000>.
- Hayyat, M.S., Safdar, M.E., Asif, M., Tanveer, A., Ali, L., Qamar, R., H. Ali, H., Farooq, N., Javeed, M.A., H. H. Tarar, Z., 2020. Allelopathic effect of waste-land weeds on germination and growth of winter crops. *Planta Daninha* 38, 1–8. <https://doi.org/10.1590/s0100-83582020380100076>.
- He, H., Wang, H., Fang, C., Wu, H., Guo, X., Liu, C., Lin, Z., Lin, W., 2012. Barnyard grass stress up regulates the biosynthesis of phenolic compounds in allelopathic rice. *J. Plant Physiol.* 169, 1747–1753. <https://doi.org/10.1016/j.jplph.2012.06.018>.
- Hejl, A.M., Koster, K.L., 2004. Juglone disrupts root plasma membrane H⁺-ATPase activity and impairs water uptake, root respiration, and growth in soybean (*Glycine max*) and corn (*Zea mays*). *J. Chem. Ecol.* 30, 453–471. <https://doi.org/10.1023/B:JOEC.0000017988.20530.d5>.
- Hejl, A.M., Koster, K.L., 2004a. The allelochemical sorgoleone inhibits root H⁺-ATPase and water uptake. *J. Chem. Ecol.* 30, 2181–2191. <https://doi.org/10.1023/B:JOEC.0000048782.87862.7f>.
- Huang, H., Morgan, C.M., Asolkar, R.N., Koivunen, M.E., Marrone, P.G., 2010. Phytotoxicity of sarmentine isolated from long pepper (*Piper longum*) fruit. *J. Agric. Food Chem.* 58, 9994–10000. <https://doi.org/10.1021/jf102087c>.
- Hunt, N.D., Hill, J.D., Liebman, M., 2017. Reducing freshwater toxicity while maintaining weed control, profits, and productivity: effects of increased crop rotation diversity and reduced herbicide usage. *Environ. Sci. Technol.* 51, 1707–1717. <https://doi.org/10.1021/acs.est.6b04086>.
- Hussain, N., Abbasi, T., Abbasi, S.A., 2017. Toxic and allelopathic ipomoea yields plant-friendly organic fertilizer. *J. Clean. Prod.* 148, 826–835. <https://doi.org/10.1016/j.jclepro.2017.01.176>.
- Ibrahim, M., Ahmad, N., Shinwari, Z.K., Bano, A., Ullah, F., 2013. Allelopathic assessment of genetically modified and non-modified maize (*Zea mays* L.) on physiology of wheat (*Triticum aestivum* L.). *Pakistan J. Bot.* 45, 235–240.
- Inderjit, 2005. Soil microorganisms: an important determinant of allelopathic activity. *Plant Soil* 1, 227–236.
- Inderjit, B.P.C., Bhowmik, P.C., 2004. Sorption of benzoic acid onto soil colloids and its implications for allelopathy studies. *Biol. Fertil. Soils* 40, 345–348. <https://doi.org/10.1007/s00374-004-0785-8>.
- Inderjit, W.J., Weiner, J., 2001. Plant allelochemical interference or soil chemical ecology? Perspectives in Plant Ecology. *Evol. Syst.* 4, 3–12. <https://doi.org/10.1078/1433-8319-00011>.
- Iqbal, J., Cheema, Z.A., An, M., 2007. Intercropping of field crops in cotton for the management of purple nutsedge (*Cyperus rotundus* L.). *Plant Soil* 300, 163–171. <https://doi.org/10.1007/s11104-007-9400-8>.
- Iqbal, A., Hamayun, M., Shah, F., Hussain, A., 2020. Role of Plant Bioactives in Sustainable Agriculture. *Environment, Climate, Plant and Vegetation Growth*. Springer, pp. 591–605.
- Jabran, K., Mahajan, G., Sardana, V., Chauhan, B.S., 2015. Allelopathy for weed control in agricultural systems. *Crop Protect.* 72, 57–65. <https://doi.org/10.1016/j.cropro.2015.03.004>.
- Jamil, M., Cheema, Z.A., Mushtaq, M.N., Farooq, M., Cheema, M.A., 2009. Alternative control of wild oat and canary grass in wheat fields by allelopathic plant water extracts. *Agron. Sustain. Dev.* 29, 475–482.
- Jasiński, M., Stukens, Y., Degand, H., Purnelle, B., Marchand-Brynaert, J., Boutry, M., 2001. A plant plasma membrane ATP binding cassette-type transporter is involved in antifungal terpenoid secretion. *Plant Cell* 13, 1095–1107. <https://doi.org/10.1105/tpc.13.5.1095>. PubMed: 11340184.
- Javadi, A., Shafiq, S., Bajwa, R., Shafique, S., 2006. Effect of aqueous extracts of allelopathic crops on germination and growth of *Parthenium hysterophorus* L. *S. Afr. J. Bot.* 72, 609–612. <https://doi.org/10.1016/j.sajb.2006.04.006>.
- Jilani, G., Mahmood, S., Chaudhry, A.N., Hassan, I., Akram, M., 2008. Allelochemicals: sources, toxicity and microbial transformation in soil—a review. *Ann. Microbiol.* 58, 351–357. <https://doi.org/10.1007/BF03175528>.
- Kang, J., Park, J., Choi, H., Burla, B., Kretzschmar, T., Lee, Y., Martinoia, E., 2011. Plant ABC transporters. *Arabidopsis Book* 9, e0153. <https://doi.org/10.1199/tab.0153>.
- Kannan, E., Palayian, L., 2022. Allelopathic potential of *Annona muricata* (L.) on physiological and biochemical changes of *Vigna radiata* (L.) and *Eleusine coracana* (L.) Gaertn. *J. Appl. Biol. Biotechnol.* 10, 1–5.
- Kato-Noguchi, H., 2011. Barnyard grass-induced rice allelopathy and momilactone B. *J. Plant Physiol.* 168, 1016–1020. <https://doi.org/10.1016/j.jplph.2010.12.021>.
- Kato-Noguchi, H., Hasegawa, M., Ino, T., Ota, K., Kujime, H., 2010. Contribution of momilactone A and B to rice allelopathy. *J. Plant Physiol.* 167, 787–791. <https://doi.org/10.1016/j.jplph.2010.01.014>.
- Kato-Noguchi, H., Ota, K., Kujime, H., 2012. Absorption of momilactone A and B by *Arabidopsis thaliana* L. and the growth inhibitory effects. *J. Plant Physiol.* 169, 1471–1476. <https://doi.org/10.1016/j.jplph.2012.05.022>.
- Kato-Noguchi, H., Ota, K., Kujime, H., Ogawa, M., 2013. Effects of momilactone on the protein expression in *Arabidopsis* germination. *Weed Biol. Manag.* 13, 19–23. <https://doi.org/10.1111/wbim.12005>.
- Kaur, H., Inderjit, K.S., Kaushik, S., 2005. Cellular evidence of allelopathic interference of benzoic acid to mustard (*Brassica juncea* L.) seedling growth. *Plant Physiol. Biochem.* 43, 77–81. <https://doi.org/10.1016/j.plaphy.2004.12.007>.
- Kaur, H., Kaur, R., Kaur, S., Baldwin, I.T., Inderjit, 2009. Taking ecological function seriously: soil microbial communities can obviate allelopathic effects of released metabolites. *PLoS One* 4, e4700. <https://doi.org/10.1371/journal.pone.0004700>.
- Khan, Z.R., Hassanali, A., Overholt, W., Khamis, T.M., Hooper, A.M., Pickett, J.A., Wadhams, L.J., Woodcock, C.M., 2002. Control of witchweed *Striga hermonthica* by intercropping with *Desmodium* spp., and the mechanism defined as allelopathic. *J. Chem. Ecol.* 28, 1871–1885. <https://doi.org/10.1023/a:1020525521180>.
- Kidd, P.S., Llugany, M., Poschenrieder, C.H., Gunsé, B., Barceló, J., 2001. The role of root exudates in aluminium resistance and silicon-induced amelioration of aluminium toxicity in three varieties of maize (*Zea mays* L.). *J. Exp. Bot.* 5, 1339–1352. <https://doi.org/10.1093/jxb/52.359.1339>.
- Klopper, J.W., Ryu, C.M., Zhang, S., 2004. Induced systemic resistance and promotion of plant growth by *Bacillus* spp. *Phytopathology* 94, 1259–1266.
- Kobayashi, K., 2004. Factors affecting phytotoxic activity of allelochemicals in soil. *Weed Biol. Manag.* 4, 1–7. <https://doi.org/10.1111/j.1445-6664.2003.00112.x>.
- Kong, C.H., Zhao, H., Xu, X.H., Wang, P., Gu, Y., 2007. Activity and allelopathy of soil of flavone O-glycosides from rice. *J. Agric. Food Chem.* 55, 6007–6012. <https://doi.org/10.1021/jf0703912>.
- Kumar, B., Hasanain, M., Raza, M.B., Yadav, R., Singh, R.K., Mishra, R., Ahmad, G., Singh, D., 2022. Effect of weed management practices on nutrient uptake and productivity of wheat (*Triticum aestivum*). *Indian J. Agric. Sci.* 92, 405–407.
- Lankau, R.A., 2011. Rapid evolutionary change and the coexistence of species. *Annu. Rev. Ecol. Syst.* 42, 335–354.
- Latif, S., Chiapusio, G., Weston, L.A., 2017. Allelopathy and the role of allelochemicals in plant defence. *Adv. Bot. Res.* 82, 19–54. <https://doi.org/10.1016/bs.abr.2016.12.001>.
- Li, L., He, Z., Pandey, G.K., Tsuchiya, T., Luan, S., 2002. Functional cloning and characterization of a plant efflux carrier for multidrug and heavy metal

- detoxification. *J. Biol. Chem.* 277, 5360–5368. <https://doi.org/10.1074/jbc.M108777200>.
- Li, Z.H., Wang, Q., Ruan, X., Pan, C.D., Jiang, D.A., 2010. Phenolics and plant allelopathy. *Molecules* 15, 8933–8952. <https://doi.org/10.3390/molecules15128933>.
- Lin, W.X., He, H.Q., Guo, Y.C., Liang, Y.Y., Chen, F.Y., 2001. Rice allelopathy and its physiochemical characteristics. *Chin. J. Appl. Ecol.* 12, 871–875.
- Liu, X.F., Hu, X.J., 2001. Effects of allelochemical ferulic acid on endogenous hormone level of wheat seedling. *Chin. J. Eco-Agric.* 9, 96–98.
- Lu, X., Zhang, J., Brown, B., Li, R., Rodriguez-Romero, J., Berasategui, A., Liu, B., Xu, M., Luo, D., Pan, Z., Baerson, S.R., Gershenzon, J., Li, Z., Sesma, A., Yang, B., Peters, R.J., 2018. Inferring roles in defense from metabolic allocation of rice diterpenoids. *Plant Cell* 305, 1119–1131. <https://doi.org/10.1105/tpc.18.00205>.
- Lucas García, J.A., Barbas, C., Probanza, A., Barrientos, M.L., Gutierrez Mañero, F.J., 2001. Low molecular weight organic acids and fatty acids in root exudates of two *Lupinus* cultivars at flowering and fruiting stages. *Phytochem. Anal.* 12, 305–311. <https://doi.org/10.1002/pca.596>.
- Ma, D.W., Wang, Y.N., Wang, Y., Zhang, H., Liao, Y., He, B., 2015. Advance in allelochemical stress induced damage to plant cells. *Acta Ecol. Sin.* 35, 1640–1645.
- Macías, F.A., Marín, D., Oliveros-Bastidas, A., Varela, R.M., Simonet, A.M., Carrera, C., Molinillo, J.M., 2003. Allelopathy as a new strategy for sustainable ecosystems development. *Uchu Seibutsu Kagaku* 17, 18–23. <https://doi.org/10.2187/bss.17.18>.
- Macías, F.A., Oliveros-Bastidas, A., Marín, D., Castellano, D., Simonet, A.M., Molinillo, J.M.G., 2005. Degradation studies on benzoxazinoids. soil degradation dynamics of (2R)-2-O-beta-D-glucopyranosyl-4-hydroxy-(2H)-1,4-benzoxazin-3(4H)-one (DIBOA-Glc) and its degradation products, phytotoxic allelochemicals from Gramineae. *J. Agric. Food Chem.* 53, 554–561. <https://doi.org/10.1021/jf048702l>.
- Mahdavi, F., Saharkhiz, M.J., 2016. Secondary metabolites of peppermint change the morphophysiological and biochemical characteristics of tomato. *Biocatal. Agric. Biotechnol.* 7, 127–133. <https://doi.org/10.1016/j.cbab.2016.05.013>.
- Mallik, M.A.B., Tesfai, K., 1988. Allelopathic effect of common weeds on soybean growth and soybean-Bradyrhizobium symbiosis. *Plant Soil* 112, 177–182.
- McErlach, A.F., Boydston, R.A., 2014. Current state of weed management in organic and conventional cropping systems. In: *Automation: the Future of Weed Control in Cropping Systems*. Springer, pp. 11–32.
- Meazza, G., Scheffler, B.E., Tellez, M.R., Rimando, A.M., Romagni, J.G., Duke, S.O., Nanayakkara, D., Khan, I.A., Abourashed, E.A., Dayan, F.E., 2002. The inhibitory activity of natural products on plant p-hydroxyphenylpyruvate dioxygenase. *Phytochemistry* 60, 281–288. [https://doi.org/10.1016/S0031-9422\(02\)00121-8](https://doi.org/10.1016/S0031-9422(02)00121-8).
- Meiners, S.J., Kong, C.H., Ladwig, L.M., Pisula, N.L., Lang, K.A., 2012. Developing an ecological context for allelopathy. *Plant Ecol.* 213, 1221–1227. <https://doi.org/10.1007/s11258-012-0078-5>.
- Mirsky, S.B., Ryan, M.R., Teasdale, J.R., Curran, W.S., Reberg-Horton, C.S., Spargo, J.T., Wells, M.S., Keene, C.L., Moyer, J.W., 2013. Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern United States. *Weed Technol.* 27, 193–203. <https://doi.org/10.1614/WT-D-12-00078.1>.
- Morris, J.B., Chase, C., Treadwell, D., Koenig, R., Cho, A., Morales-Payan, J.P., Murphy, T., Antonious, G.F., 2015. Effect of sunn hemp (*Crotalaria juncea* L.) cutting date and planting density on weed suppression in Georgia, USA. *J. Environ. Sci. Health B.* 50, 614–621. <https://doi.org/10.1080/03601234.2015.1028855>.
- Muhammad, Z., Majeed, A., 2014. Allelopathic effects of aqueous extracts of sunflower on wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). *Pakistan J. Bot.* 46, 1715–1718.
- Murphy, K.M., Zerbe, P., 2020. Specialized diterpenoid metabolism in monocot crops: biosynthesis and chemical diversity. *Phytochemistry* 172, 112289. <https://doi.org/10.1016/j.phytochem.2020.112289>.
- Mushtaq, W., Ain, Q., Siddiqui, M.B., Hakeem, K.R., 2019. Cytotoxic allelochemicals induce ultrastructural modifications in *Cassia tora* L. and mitotic changes in *Allium cepa* L.: a weed versus weed allelopathy approach. *Protoplasma* 256, 857–871. <https://doi.org/10.1007/s00709-018-01343-1>.
- M'barek, K., Zribi, I., Ullah, M.J., Haouala, R., 2019. The mode of action of allelochemicals aqueous leaf extracts of some Cupressaceae species on lettuce. *Sci. Hortic.* 252, 29–37. <https://doi.org/10.1016/j.scienta.2019.03.009>.
- Nakajima, N., Hiradate, S., Fujii, Y., 2001. Plant growth inhibitory activity of L-canavanine and its mode of action. *J. Chem. Ecol.* 27, 19–31. <https://doi.org/10.1023/a:1005659714947>.
- Nakamura, N., Nemoto, M., 1996. cis-Dehydromatricaria Ester Concentration in Plant and its Leaching of *Solidago Altissima* L., vol. 41. WEED Research-Tokyo, pp. 359–361.
- Narwal, S.S., Haouala, R., 2013. Role of allelopathy in weed management for sustainable agriculture. In: *Allelopathy*. Springer, pp. 217–249.
- Neori, A., Reddy, K.R., Čišková-Končalová, H., Agami, M., 2000. Bioactive chemicals and biological—biochemical activities and their functions in rhizospheres of wetland plants. *Bot. Rev.* 66, 350–378. <https://doi.org/10.1007/BF02868922>.
- Nimbal, C.I., Yerkes, C.N., Weston, L.A., Weller, S.C., 1996. Herbicidal activity and site of action of the natural product sorgoleone. *Pestic. Biochem. Physiol.* 54, 73–83. <https://doi.org/10.1006/pest.1996.0011>.
- Norouzi, Y., Mohammadi, G.R., Nosrati, I., 2015. Soil factors affecting the allelopathic activities of some plant species. *Am.-EurAsian J. Agric. Environ. Sci.* 15, 2252–2257. <https://doi.org/10.5829/idosi.aejas.2015.15.11.12594>.
- Oerke, E.C., 2006. Crop losses to pests. *J. Agric. Sci.* 144, 31–43. <https://doi.org/10.1017/S0021859605005708>.
- Ohno, T., First, P.R., 1998. Assessment of the Folin and Ciocalteu's method for determining soil phenolic carbon. *Am. Soc. Agron. Crop Sci. Soc. Am. Soil Sci. Soc. Am.* 27 (4), 776–782.
- Pan, L., Li, X.Z., Yan, Z.Q., Guo, H.R., Qin, B., 2015. Phytotoxicity of umbelliferone and its analogs: structure–activity relationships and action mechanisms. *Plant Physiol. Biochem.* 97, 272–277. <https://doi.org/10.1016/j.plaphy.2015.10.020>.
- Pollock, J.L., Kogan, L.A., Thorpe, A.S., Holben, W.E., 2011. (±)-Catechin, a root exudate of the invasive *Centaurea stoebe* Lam. (spotted knapweed) exhibits bacteriostatic activity against multiple soil bacterial populations. *J. Chem. Ecol.* 37, 1044–1053.
- Poonpaiboonpipat, T., Pangnakorn, U., Suvunnamek, U., Teerarak, M., Charoenying, P., Laosinwattana, C., 2013. Phytotoxic effects of essential oil from *Cymbopogon citratus* and its physiological mechanisms on barnyardgrass (*Echinochloa crus-galli*). *Ind. Crop. Prod.* 41, 403–407. <https://doi.org/10.1016/j.indcrop.2012.04.057>.
- Purohit, S., Pandya, N., 2013. Allelopathic activity of *Ocimum sanctum* L. and *Tephrosia purpurea* (L.) Pers. leaf extracts on few common legumes and weeds. *Int. J. Res. Pharm. Sci.* 3, 5–9.
- Putnam, A.R., Duke, W.B., 1974. Biological suppression of weeds: evidence for allelopathy in accessions of cucumber. *Science* 185, 370–372. <https://doi.org/10.1126/science.185.4148.370>.
- Qasem, J.R., Foy, C.L., 2001. Weed allelopathy, its ecological impacts and future prospects: a review. *J. Crop Prod.* 4, 43–119. https://doi.org/10.1300/J144v04n02_02.
- Rahaman, F., Juraimi, A.S., Rafii, M.Y., Uddin, M.K., Hassan, L., Chowdhury, A.K., Bashar, H.K., 2021. Allelopathic effect of selected rice (*Oryza sativa*) varieties against barnyard grass (*Echinochloa crus-galli*). *Plants* 10. <https://doi.org/10.3390/plants10102017>, 2017.
- Rawat, L.S., Maikhuri, R.K., Bahuguna, Y.M., Jha, N.K., Phondani, P.C., 2017. Sunflower allelopathy for weed control in agriculture systems. *J. Crop Sci. Biotechnol.* 20, 45–60. <https://doi.org/10.1007/s12892-016-0093-0>.
- Rees, D.C., Johnson, E., Lewinson, O., 2009. ABC transporters: the power to change. *Nat. Rev. Mol. Cell Biol.* 10, 218–227. <https://doi.org/10.1038/nrm2646>. PubMed: 19234479.
- Rivoal, A., Fernandez, C., Greff, S., Montes, N., Vila, B., 2011. Does competition stress decrease allelopathic potential? *Biochem. Systemat. Ecol.* 39, 401–407. <https://doi.org/10.1016/j.bse.2011.05.017>.
- Rugare, J.T., Pieterse, P.J., Mabasa, S., 2021. Allelopathic potential of green manure cover crops on germination and early seedling development of goose grass [*Eleusine indica* (L.) Gaertn] and blackjack (*Bidens pilosa* L.). *Int. J. Agron.* 1–13. <https://doi.org/10.1155/2021/6552928>.
- Runzika, M., Rugare, J.T., Mabasa, S., 2013. Screening green manure cover crops for their allelopathic effects on some important weeds found in Zimbabwe. *Asian J. Agric. Rural Dev.* 3, 554–565.
- Safdar, M.E., Aslam, A., Qamar, R., Ali, A., Javaid, M.M., Hayyat, M.S., Raza, A., 2021. Allelopathic effect of prickly chaff flower (*Achyranthes aspera* L.) used as a tool for managing noxious weeds. *Asian J. Agri. Biol.* 10. <https://doi.org/10.35495/ajab.2020.06.370>.
- Sahoo, T.R., Behera, B., Paikaray, R.K., Garnayak, L.M., Sethi, D., Jena, S., Raza, M.B., Panda, R.K., Song, B., Lal, M.K., Kumar, A., 2023. Effects of sunflower residue management options on productivity and profitability of succeeding rice under different crop establishment methods. *Field Crop. Res.* 290, 108763.
- Sánchez-Moreiras, A.M., de la Peña, T.C., Reigosa, M.J., 2008. The natural compound benzoxazinol-2(3H)-one selectively retards cell cycle in lettuce root meristems. *Phytochemistry* 69, 2172–2179. <https://doi.org/10.1016/j.phytochem.2008.05.014>. PubMed: 18597799.
- Saucke, H., Ackermann, K., 2006. Weed suppression in mixed cropped grain peas and false flax (*Camelina sativa*). *Weed Res.* 46, 453–461. <https://doi.org/10.1111/j.1365-3180.2006.00530.x>.
- Scavo, A., Mauromicale, G., 2020. Integrated weed management in herbaceous field crops. *Agronomy* 10, 466. <https://doi.org/10.3390/agronomy10040466>.
- Scavo, A., Restuccia, A., Mauromicale, G., 2018. Allelopathy: principles and basic aspects for agroecosystem control. *J. Sustain. Agric.* 47–101. https://doi.org/10.1007/978-3-319-90309-5_2.
- Scavo, A., Abbate, C., Mauromicale, G., 2019. Plant allelochemicals: agronomic, nutritional and ecological relevance in the soil system. *Plant Soil* 442, 23–48. <https://doi.org/10.1007/s11104-019-04190-y>.
- Scherner, A., Melander, B., Kudsk, P., 2016. Vertical distribution and composition of weed seeds within the plough layer after eleven years of contrasting crop rotation and tillage schemes. *Soil Tillage Res.* 161, 135–142. <https://doi.org/10.1016/j.still.2016.04.005>.
- Schulz, M., Marocco, A., Tabaglio, V., Macías, F.A., Molinillo, J.M., 2013. Benzoxazinoids in rye allelopathy: from discovery to application in sustainable weed control and organic farming. *J. Chem. Ecol.* 39, 154–174. <https://doi.org/10.1007/s10886-013-0235-x>. PubMed: 23385365.
- Shahzad, M., Farooq, M., Jabran, K., Hussain, M., 2016. Impact of different crop rotations and tillage systems on weed infestation and productivity of bread wheat. *Crop Protect.* 89, 161–169. <https://doi.org/10.1016/j.cropro.2016.07.019>.
- Shaukat, S.S., Munir, N., Siddiqui, I.A., 2003. Allelopathic responses of *Coryza canadensis* (L.) Cronquist: a cosmopolitan weed. *Asian J. Plant Sci.* 14, 1034–1039. <https://doi.org/10.3923/ajps.2003.1034.1039>.
- Shimura, K., Okada, A., Okada, K., Jikumaru, Y., Ko, K.W., Toyomasu, T., Yamane, H., 2007. Identification of a biosynthetic gene cluster in rice for momilactones. *J. Biol. Chem.* 282, 34013–34018. <https://doi.org/10.1074/jbc.M703344200>.
- Singh, H.P., Batish, D.R., Kohli, R.K., 2001. Allelopathy in agroecosystems: an overview. *J. Crop Prod.* 4, 1–41. https://doi.org/10.1300/J144v04n02_01.
- Singh, A.A., Rajeswari, G., Nirmal, L.A., Jacob, S., 2021. Synthesis and extraction routes of allelochemicals from plants and microbes: a review. *Rev. Anal. Chem.* 40, 293–311. <https://doi.org/10.1515/revac-2021-0139>.
- Siyar, S., Majeed, A., Muhammad, Z., Ali, H., Inayat, N., 2019. Allelopathic effect of aqueous extracts of three weed species on the growth and leaf chlorophyll content of

- bread wheat. *Acta Ecol. Sin.* 39, 63–68. <https://doi.org/10.1016/j.chnaes.2018.05.007>.
- Soltys, D., Rudzińska-Langwald, A., Gniazdowska, A., Wiśniewska, A., Bogatek, R., 2012. Inhibition of tomato (*Solanum lycopersicum* L.) root growth by cyanamide is due to altered cell division, phytohormone balance and expansin gene expression. *Planta* 236, 1629–1638. <https://doi.org/10.1007/s00425-012-1722-y>.
- Srivastava, D., Shukla, K., 2016. Effect of leaves extract of *Ipomoea cairica* on chlorophyll and carotenoid in *Parthenium hysterophorus* L. *Int. J. Res. –GRANTHAALAYAH*. 4, 103–107. <https://doi.org/10.29121/granthaalayah.v4.i4.2016.2761>.
- Stinson, K.A., Campbell, S.A., Powell, J.R., Wolfe, B.E., Callaway, R.M., Thelen, G.C., Hallett, S.G., Prati, D., Klironomos, J.N., 2006. Invasive plant suppresses the growth of native tree seedlings by disrupting belowground mutualisms. *PLoS Biol.* 4, e140.
- Sturm, D.J., Peteanatos, G., Gerhards, R., 2018. Contribution of allelopathic effects to the overall weed suppression by different cover crops. *Weed Res.* 58, 331–337.
- Tabaglio, V., Marocco, A., Schulz, M., 2013. Allelopathic cover crop of rye for integrated weed control in sustainable agroecosystems. *Ital. J. Agron.* 8, 5. <https://doi.org/10.4081/ija.2013.e5>.
- Teerarak, M., Laosinwattana, C., Charoenying, P., 2010. Evaluation of allelopathic, decomposition and cytogenetic activities of *Jasminum officinale* L. f. var. *grandiflorum* (L.) Kob. on bioassay plants. *Bioresour. Technol.* 101, 5677–5684.
- Teerarak, M., Charoenying, P., Laosinwattana, C., 2012. Physiological and cellular mechanisms of natural herbicide resource from *Aglaia odorata* Lour. on bioassay plants. *Acta Physiol. Plant.* 34, 1277–1285. <https://doi.org/10.1007/s11738-011-0923-5>.
- Tesio, F., Ferrero, A., 2010. Allelopathy, a chance for sustainable weed management. *Int. J. Sustain. Dev. World Ecol.* 17, 377–389. <https://doi.org/10.1080/13504509.2010.507402>.
- Tharayil, N., Bhowmik, P.C., Xing, B., 2008. Bioavailability of allelochemicals as affected by companion compounds in soil matrices. *J. Agric. Food Chem.* 56, 3706–3713. <https://doi.org/10.1021/jf073310a>.
- Tibugari, H., Manyeruke, N., Mafere, G., Chakavarika, M., Nyamuzuwe, L., Marumahoko, P., Mandumbu, R., 2019. Allelopathic effect of stressing sorghum on weed growth. *Cogent. Biol.* 5, 1684865 <https://doi.org/10.1080/23312025.2019.1684865>.
- Toyomasu, T., Kagahara, T., Okada, K., Koga, J., Hasegawa, M., Mitsushashi, W., Sassa, T., Yamane, H., 2008. Diterpenophytoalexins are biosynthesized in and exuded from the roots of rice seedlings. *Biosci. Biotechnol. Biochem.* 72, 562–567. <https://doi.org/10.1271/bbb.70677>.
- Toyomasu, T., Usui, M., Sugawara, C., Otomo, K., Hirose, Y., Miyao, A., Yamane, H., 2014. Reverse-genetic approach to verify physiological roles of rice phytoalexins: characterization of a knockdown mutant of *OscPS4* phytoalexin biosynthetic gene in rice. *Physiol. Plantarum* 150, 55–62. <https://doi.org/10.1111/pp1.12066>.
- Tursun, N., İşik, D., Demir, Z., Jabran, K., 2018. Use of living, mowed, and soil-incorporated cover crops for weed control in apricot orchards. *Agronomy* 8, 150. <https://doi.org/10.3390/agronomy8080150>.
- Uddin, M.R., Park, K.W., Han, S.M., Pyon, J.Y., Park, S.U., 2012. Effects of sorgoleone allelochemical on chlorophyll fluorescence and growth inhibition in weeds. *Allelopathy J.* 30, 61–70.
- Van der Putten, W.H., Vet, L.E.M., Harvey, J.A., Wäckers, F.L., Wäckers, J.A., 2001. Linking above- and belowground multitrophic interactions of plants, herbivores, pathogens, and their antagonists. *Trends Ecol. Evol.* 16, 547–554. [https://doi.org/10.1016/S0169-5347\(01\)02265-0](https://doi.org/10.1016/S0169-5347(01)02265-0).
- Vaughn, S.F., Berhow, M.A., 1999. Allelochemicals isolated from tissues of the invasive weed garlic mustard (*Alliaria petiolata*). *J. Chem. Ecol.* 25, 2495–2504.
- Walker, T.S., Bais, H.P., Grotewold, E., Vivanco, J.M., 2003. Root exudation and rhizosphere biology. *Plant Physiol.* 132, 44–51. <https://doi.org/10.1104/pp.102.019661>.
- Wang, Y., Wang, H., Jiang, Y., 2011. Sorption and retention of phenolic acids in soil of poplar plantation in eastern China. In: *International Conference on Remote Sensing, Environment and Transportation Engineering*. IEEE Publications, pp. 7836–7840.
- Wasternack, C., Parthier, B., 1997. Jasmonate-signalled plant gene expression. *Trends Plant Sci.* 2 (8), 302–307. [https://doi.org/10.1016/S1360-1385\(97\)89952-9](https://doi.org/10.1016/S1360-1385(97)89952-9).
- Weidenhamer, J.D., 1996. Distinguishing resource competition and chemical interference: overcoming the methodological impasse. *Agron. J.* 88, 866–875. <https://doi.org/10.2134/agronj1996.00021962003600060005x>.
- Weil, R.R., Brady, N.C., 2017. *The Nature and Property of Soils*, fifteenth ed. Pearson Education, ISBN 978-0133254488.
- Weir, T.L., Park, S.W., Vivanco, J.M., 2004. Biochemical and physiological mechanisms mediated by allelochemicals. *Curr. Opin. Plant Biol.* 7, 472–479. <https://doi.org/10.1016/j.pbi.2004.05.007>.
- Weston, L.A., 1996. Utilization of allelopathy for weed management in agroecosystems. *Agron. J.* 88, 860–866. <https://doi.org/10.2134/agronj1996.00021962003600060004x>.
- Weston, L.A., 2005. History and current trends in the use of allelopathy for weed management. *Hort. Technol.* 15, 529–534. <https://doi.org/10.21273/HORTTECH.15.3.0529>.
- Weston, L.A., Duke, S.O., 2003. Weed and crop allelopathy. *Crit. Rev. Plant Sci.* 22, 367–389. <https://doi.org/10.1080/713610861>.
- Weston, L.A., Ryan, P.R., Watt, M., 2012. Mechanisms for cellular transport and release of allelochemicals from plant roots into the rhizosphere. *J. Exp. Bot.* 63, 3445–3454. <https://doi.org/10.1093/jxb/ers054>.
- Wink, M., 2004. Allelochemical properties of quinolizidine alkaloids. In: *Allelopathy: Chemistry and Mode of Action of Allelochemicals*. CRC Press, pp. 183–200.
- Wolfe, B.E., Rodgers, V.L., Stinson, K.A., Pringle, A., 2008. The invasive plant *Alliaria petiolata* (garlic mustard) inhibits ectomycorrhizal fungi in its introduced range. *J. Ecol.* 96, 777–783.
- Wu, F.Z., Pan, K., Ma, F.M., Wang, X.D., 2004. Effects of cianamic acid on photosynthesis and cell ultrastructure of cucumber seedlings. *Acta Hort.* 31, 183–188.
- Wu, Y., Wang, Q., Hillwig, M.L., Peters, R.J., 2013. Picking sides: distinct roles for CYP76M6 and CYP76M8 in rice oryzalexin biosynthesis. *Biochem. J.* 454, 209–216. <https://doi.org/10.1042/BJ20130574>.
- Xu, M., Galhano, R., Wiemann, P., Bueno, E., Tiernan, M., Wu, W., Chung, I.M., Gershenzon, J., Tudzynski, B., Sesma, A., Peters, R.J., 2012. Genetic evidence for natural product-mediated plant–plant allelopathy in rice (*Oryza sativa*). *New Phytol.* 193, 570–575. <https://doi.org/10.1111/j.1469-8137.2011.04005.x>.
- Xuan, T.D., Tawata, S., Khanh, T.D., Chung, I.M., 2005. Decomposition of allelopathic plants in soil. *J. Agron. Crop Sci.* 191, 162–171. <https://doi.org/10.1111/j.1439-037X.2005.00170.x>.
- Xue, Q., Wang, R., Xu, W., Wang, J., Tan, L., 2018. The stresses of allelochemicals isolated from culture solution of diatom *Phaeodactylum tricornutum* Bohlin on growth and physiology of two marine algae. *Aquat. Toxicol. (Amst.)* 205, 51–57. <https://doi.org/10.1016/j.aquatox.2018.10.004>.
- Yang, G.Q., Wan, F.H., Liu, W.X., Guo, J.Y., 2008. Influence of two allelochemicals from *Ageratina adenophora* Sprengel on ABA, IAA, and ZR contents in roots of upland rice seedlings. *Allelopathy J.* 21, 253–262.
- Yazaki, K., Arimura, G.I., Ohnishi, T., 2017. ‘Hidden’ terpenoids in plants: their biosynthesis, localization and ecological roles. *Plant Cell Physiol.* 58, 1615–1621. <https://doi.org/10.1093/pcp/pcx123>.
- Yoneya, K., Takabayashi, J., 2014. Plant–plant communication mediated by airborne signals: ecological and plant physiological perspectives. *Plant Biotechnol.* 14–0827.
- Yu, J.Q., Matsui, Y., 1997. Effects of root exudates of cucumber (*Cucumis sativus*) and allelochemicals on ion uptake by cucumber seedlings. *J. Chem. Ecol.* 23, 817–827. <https://doi.org/10.1023/B:JOEC.0000006413.98507.55>.
- Yuan, G.L., Ma, R.X., Liu, X.F., Sun, S.S., 1998. Effect of allelochemicals on nitrogen absorption of wheat seedling. *Chin. J. Eco-Agric.* 39–41.
- Zaimenko, N.V., Pavliuchenko, N.A., Ellanska, N.E., Ivanytska, B.O., Kharytonova, I.P., Yunosheva, O.P., Skrypchenko, N.V., Zhang, P., Liu, D., Shen, J., Tian, L., 2020. Comparative analysis of agrochemical, allelopathic and microbiological characteristics of the soil environment for *Actinidia arguta* (Siebold et Zucc.) Planch. ex Miq. cultivated in Ukraine and two provinces of China. *Plant Introduct.* 85–86, 3–14. <https://doi.org/10.46341/PI2020002>.
- Zhang, X., Long, Y., Huang, J., Xia, J., 2019. Molecular mechanisms for coping with Al toxicity in plants. *Int. J. Mol. Sci.* 20, 1551. <https://doi.org/10.3390/ijms20071551>.
- Zhou, Y.H., Yu, J.Q., 2006. Allelochemicals and photosynthesis. In: Reigosa, M.J., Pedrol, N., Gonza'lez, L. (Eds.), *Allelopathy: A Physiological Process with Ecological Implications*, P, pp. 127–139.
- Zhou, K., Wang, Z.F., Hao, F.G., Guo, W.M., 2010. Effects of aquatic extracts from different parts and rhizospheric soil of chrysanthemum on the rooting of stem cuttings of the same species. *Acta Bot. Boreali Occident. Sin.* 762–768.
- Zuo, S.P., Liu, G.B., Li, M., 2012. Genetic basis of allelopathic potential of winter wheat based on the perspective of quantitative trait locus. *Field Crop. Res.* 135, 67–73. <https://doi.org/10.1016/j.fcr.2012.07.005>.