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REVIEW ARTICLE

Cereal allelopathy as a natural herbicide: A review of mechanisms and weed control potential

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Abstract

Weed infestation remains one of the primary challenges in global crop production, causing substantial yield losses. Conventional reliance on synthetic herbicides raises concerns regarding environmental safety, herbicide resistance and long-term soil health. Therefore, there is an urgent need for sustainable and eco-friendly weed control alternatives. Allelopathy, defined as the biochemical interaction among plants via secondary metabolites, has emerged as a promising natural mechanism for suppressing weed growth. Among various crops, cereals such as rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and rye (*Secale cereale* L.) have demonstrated significant allelopathic potential. This review analyses and synthesises recent findings on the allelopathic properties of cereal crops. It evaluates literature describing the types of allelochemicals released by cereals and the plant parts involved, including roots, stems, leaves and decomposing residues. The study also emphasises the mechanisms through which these allelochemicals influence weed suppression and the role of cereal cover crops, root exudates and leaf litter in natural weed control. Evidence shows that cereal crops release a wide range of allelochemicals capable of inhibiting weed seed germination and seedling growth. These compounds are exuded through roots, volatilized from leaves or released during the decomposition of crop residues. The integration of allelopathic cereals into crop rotation and cover cropping systems can reduce weed pressure, minimise chemical herbicide dependency and enhance soil health. Particularly, root exudates and surface residues of rye and wheat have demonstrated consistent weed-suppressive effects. Allelopathy in cereal crops represents a natural and sustainable strategy for weed suppression. By reducing reliance on chemical herbicides, cereal-based allelopathy supports eco-friendly and resilient agricultural systems. To maximise its practical application, further research is required to elucidate allelochemical modes of action, optimise management practices and integrate allelopathy into holistic weed management programs.

Keywords: allelopathy; biodegradable; cereals; sustainable agriculture; weed management

Introduction

Weed infestation is one of the major constraints in agricultural productivity, leading to significant yield losses (1). Conventional weed management strategies, such as synthetic herbicides, have raised environmental and health concerns, including herbicide resistance, soil degradation and contamination of water sources. In this context, allelopathy, the chemical interaction between plants through the release of bioactive secondary metabolites (allelochemicals), has gained attention as an eco-friendly strategy for weed suppression (2). Allelopathy, a biological phenomenon where plants release biochemicals that influence the growth of other organisms, offers a promising approach to weed suppression. Allelopathy refers to the production and release of allelochemicals by donor plants (e.g., cereals) into the environment, which can inhibit germination, growth, or physiological functions of neighbouring weeds. These compounds include phenolics, flavonoids, terpenoids, benzoxazinoids and alkaloids. However, the effectiveness of allelopathic crops in diverse agroecosystems remains underexplored.

Allelopathy has been widely studied in plant-plant interactions, particularly in natural ecosystems. Allelochemicals have the most diverse mode of action on crops and always show the secondary indicator of primary changes on target plants. Several crops, such as rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and rye (*Secale cereale* L.), brassica (*Brassica napus*) have demonstrated allelopathic properties by releasing secondary metabolites that inhibit weed growth and increase crop growth (3–5). Allelochemicals are also considered as biodegradable herbicides. These allelochemicals include phenolics, flavonoids and terpenoids, which can affect seed germination, root elongation and overall weed development (6). Phenolic acids such as ferulic acid, p-coumaric acid, caffeic acid and vanillic acid are the most commonly reported allelochemicals. They interfere with vital physiological processes in weeds by disrupting enzyme activity and hormonal balance, generating Reactive Oxygen Species (ROS) and leading to weed growth retardation. Research has demonstrated that phenolic acids from wheat and rice straw residues significantly inhibited seed germination and seedling vigour of *Amaranthus retroflexus* and *Echinochloa crus-galli* (7). Terpenoids, including monoterpenes (e.g., cineole, limonene) and diterpenes, are volatile or non-volatile compounds that inhibit root and cell elongation and cause oxidative damage in the cell membrane. Research has demonstrated that monoterpenes from *Eucalyptus globulus* and *Mentha spp.* disrupted cell division and membrane integrity in *Lolium multiflorum* seedlings (8). These qualities of allelochemicals make them promising alternatives or complements to synthetic herbicides. Research on allelopathic interactions suggests that specific agronomic practices like crop rotations, cropping systems and cover cropping can enhance weed suppression while reducing reliance on chemical herbicides (9,10). Breeding allelopathic crop varieties like wheat, rice and maize secretes benzoxazinoids and thus suppresses weed growth effectively (11). The use of allelopathic cover crops like rye (secale cereal), sorghum (*Sorghum bicolor*) can reduce weed seed bank by releasing 2,4-dihydroxy-1,4-benzoxazin-3 -one (DIBOA) and Benzoxazolin-2-one (BOA) (12). Plant-microbe interaction also amplifies the allelopathic potential by supporting the stability and bioavailability of allelochemicals. Despite these findings, challenges such as variability in allelopathic potential among crop cultivars, environmental influences on allelochemical production and the mechanisms underlying their effectiveness need further investigation. Research has demonstrated that decomposed residues reduced the allelopathic effect compared to leftover residues in the soil (13). By assessing allelopathic crops, this review supports the development of Integrated Weed Management (IWM) strategies that reduce chemical herbicide dependency. Understanding allelopathy can help minimise herbicide residues in soil and water, promoting a healthier ecosystem. Knowledge of allelopathy can enhance crop competitiveness, improving overall farm productivity and profitability. Incorporating allelopathic crops in weed management can delay or prevent herbicide resistance development in weed populations.

While previous research has focused on individual allelopathic crops or specific allelochemicals, this review presents a holistic analysis of various allelopathic mechanisms of major cereal crops, their practical applications and their potential synergies with other weed control methods. Future studies should focus on breeding programs for enhanced allelopathic potential, understanding the environmental influences on allelochemical production and developing IWM strategies that leverage allelopathy alongside other eco-friendly methods. This review provides a foundational understanding of allelopathy in crops and serves as a guide for researchers, agronomists and policymakers working towards sustainable and efficient weed management solutions. There are lots of plants with their allelopathy potential, but here are listed a few cereal crops for their allelopathy potential and further research work.

Application of cereal crop allelopathy to weed suppression

Cereal crops such as wheat (*Triticum aestivum*), rice (*Oryza sativa*), barley (*Hordeum vulgare*), rye (*Secale cereale*), maize (*Zea mays*) and sorghum (*Sorghum bicolor*) have demonstrated varying degrees of allelopathic potential (14). Their incorporation into cropping systems is being explored for practical weed management. The residues of cereal crops, particularly sorghum, rye and wheat, contain allelochemicals such as sorgoleone, benzoxazinoids (e.g., DIMBOA) and phenolic acids, which suppress weed seed germination and early growth. These allelochemicals are synthesised in plant leaves, roots and suppress the growth of weeds by disrupting water relations of plants in the root cell membrane (15). Research has demonstrated that corn and sorghum mulches showed significant decline in weed seedbank, with improved wheat yield and reduced herbicide resistance in *Phalaris minor* when mulches were combined with low-dose post-emergence herbicides (16). Millet residues suppressed weed density more than corn residues, while sorghum mulch significantly decreased weed biomass (17). Again, wheat and rice straw mulches have shown inhibitory effects on weeds like *Amaranthus retroflexus* and *Echinochloa crus-galli* due to the slow release of phenolic compounds. Rye is commonly used as a winter cover crop in temperate regions. Upon termination (e.g., rolling-crimping or mowing), the allelochemicals in rye suppress summer annual weeds.

Allelopathic potentiality of cereal crops for weed management

Rice allelopathy

Allelopathic compounds found in rice plants : Rice plants produce a wide range of allelochemicals that contribute to their natural weed-suppressing abilities. These compounds are primarily sourced from different parts of the rice plant, including roots, straw, husks and leaves. More than 200 different compounds have been identified in rice root exudates, spanning diverse chemical classes such as carbohydrates (e.g., glucose, fructose), fatty acids (e.g., linoleic acid, palmitic acid), essential amino acids (e.g., phenylalanine, tyrosine), vitamins (e.g., vitamin E, vitamin C), flavonoids, polyphenols, sterols and Volatile Organic Compounds (VOCs) (18). Among these, phenolic acids, flavones and terpenoids have been discovered as potent allelochemicals (19). Notably, momilactones A and B, which are found in rice husks, exhibit the most significant allelopathic activity among all the chemicals. These diterpenoid compounds are primarily synthesised in the husks, leaves and roots of rice and are released into the soil environment via root exudation and residue decomposition. Besides their allelopathic properties, momilactones also function as phytoalexins and provide rice plants with enhanced resistance against various pathogens (20–22). Other important compounds include p-coumaric acid, p-hydroxybenzoic acid, syringic acid and vanillic acid, which are produced through the microbial decomposition of rice husks (23). Additionally, flavonoids such as 5,7,4′-trihydroxy-3′,5′-dimethoxyflavone (tricin) and diterpenoids like 3-isopropyl-5-acetoxycyclohex-2-enone contribute to rice's allelopathic effects (24). Leaf exudates of rice varieties also contain phenolic compounds such as p-hydroxybenzoic acid, ferulic acid and syringic acid, which have been demonstrated to inhibit weed growth (25). Among all identified allelochemicals, momilactone B has emerged as one of the most potent, surpassing the effectiveness of phenolic acids in suppressing weed growth (26). Systematic studies of allelopathic rice seedlings further confirmed that a combination of compounds, including momilactone B, 5,7,4′-trihydroxy-3,5-dimethoxyflavone and 3-isopropyl-5-acetoxycyclohexene-2-one-1, significantly contributes to the inhibition of major weed species, which are shown in Table 1 (27).

Weed suppression mechanism of rice plants

Rice plants exert allelopathic effects on weeds primarily through root exudates, as the root contains most of the allelochemicals. The root exudates of rice plants release a complex mixture of allelochemicals that influence the rhizosphere and eventually affect targeted weeds. Decomposed residues and leaf exudates also show significant

Table 1. Allelopathic compounds in rice and their weed suppression effects

Source	Allelochemicals	Weed species inhibited	Inhibition stage	References
Husks	Momilactones A & B, p-coumaric acid, p-hydroxybenzoic acid, syringic acid and vanillic acid	*E.chinochloa crus-galli*, *C.yperus difformis*, *Monochoria vaginalis*, *Solidago altissima* and *Lemna paucicostata*	Seed germination and growth inhibition	(23)
Leaves	p-Hydroxybenzoic acid, ferulic acid and syringic acid	General weed suppression	Growth inhibition	(27)
Root exudates	Phenolic acids, flavones, terpenoids, carbohydrates and fatty acids	*E.chinochloa crus-galli*, *C.yperus difformis*, *C.yperus iria*, *Fimbristylis milliacea* and weedy rice	Seed germination, shoot and root growth inhibition	(28)
Decomposing straw	Phenolic acids, flavonoids and terpenoids	*Convolvulus arvensis*, *Avena ludoviciana*, *Phalaris minor*, *Avena sativa*, *Triticum aestivum* and *E. chinochloa crus-galli*	Seed germination and inhibition	(29)
Exudates of allelopathic cultivars	Phenolic compounds and bioactive substances	*Avena ludoviciana*, *Sagittaria montevidensis* and *Echinochloa crus-galli* and *Cyperus difformis*	Seed germination, shoot and root growth inhibition	(30)
Plant extract	Momilactone B	*Lactuca sativa*, *Leptochloa chinensis* and *Amaranthus retroflexus*	Growth inhibition	(22)

effects against weeds. The aqueous extracts from various rice cultivars have been shown to inhibit seed germination and reduce both shoot and root length in multiple weed species, including barnyard grass (*Echinochloa crus-galli*), small flower umbrella sedge (*Cyperus difformis*), rice flat sedge (*Cyperus iria*), grass-like fimbry (*Fimbristylis miliacea*) and weedy rice (*Oryza sativa f. spontanea*) (3). Root exudates from allelopathic rice cultivars release phenolic compounds and other bioactive substances that suppress the growth of arrowhead (*Sagittaria montevidensis*), barnyard grass (*E. crus-galli*) and rice sedge (*C. difformis*) as these compounds alter the weed's physiological processes and create abnormality in cell signalling (20,28,31). Decomposing rice straw also serves as a significant source of allelopathic compounds, inhibiting the germination of bindweed (*Convolvulus arvensis*), wild oats (*Avena ludoviciana*), little seed canary grass (*Phalaris minor* Retz), oats (*Avena sativa*), wheat (*T. aestivum*) and barnyard grass (*E. crus-galli*) through several chemicals as they work to inhibit the germination mechanism through hindering hormonal activities (32). Similarly, rice husks contain momilactones A and B, which effectively inhibit the growth of barnyard grass, rice sedge, pickerelweed (*Monochoria vaginalis*), tall goldenrod (*Solidago altissima*) and duckweed (*Lemna paucicostata*) (14,15). Additional research has demonstrated the inhibitory effects of momilactone B on other problematic weeds, such as lettuce (*Lactuca sativa*), red sprangletop (*Leptochloa chinensis*) and redroot pigweed (*A. retroflexus*) through suppressing their growth and hindering life cycle completion. These compounds disrupt the cell division, enzyme activity and membrane integrity of target weeds as they work as natural bioherbicides (13). The allelopathic effects of rice plants are not solely due to individual compounds but rather the combined action of multiple allelochemicals. Studies indicate that while phenolic acids contribute to weed suppression, their concentrations may not reach phytotoxic thresholds alone (33). Instead, a synergistic interaction between different allelochemicals, such as terpenoids and flavonoids, enhances their suppressive effects at lower concentrations (22,34).

Maize allelopathy

Allelopathic compounds found in maize plants

Maize produces a range of allelopathic compounds that play a significant role in suppressing the growth of weeds and other competing plants (Table 2). One of the most important allelochemicals in maize is benzoxazinoids (BXs), specifically 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA) and 6-methoxy-benzoxazolin-2-one (MBOA). These compounds are known for their strong phytotoxic effects (35). In addition to benzoxazinoids, maize leaf extracts contain other phenolic compounds, such as benzoic acid, salicylic acid, tannic acid and p-hydroxybenzoic acid. These compounds have been found to inhibit the germination and growth of various plants, including different wheat cultivars. However, at low concentrations, these extracts can stimulate the germination and growth of maize and wheat (36). Further preliminary phytochemical screening of maize root and shoot aqueous extracts has revealed the presence of several additional bioactive compounds, such as tannins, phlobatannins, flavonoids, terpenoids and alkaloids, all of which contribute to maize's allelopathic potential (4). Furthermore, decomposed maize straw produces a variety of allelopathic compounds. Research has demonstrated that decomposed maize straw contains organic acids, esters, hydrocarbons, amides, aldehydes, phenols, ketones, alcohols and heterocyclic compounds (37). Key phenolic acids, such as p-hydroxybenzoic acid, 4-hydroxy-3 -methoxy-benzoic acid and 4-hydroxy-3,5-dimethoxybenzoic acid,

Table 2. Allelopathic compounds in maize and their weed suppression effects

Source	Allelochemicals	Weed species inhibited	Inhibition stage	References
Roots	DIMBOA, MBOA (Benzoxazinoids)	*Cucumis sativus*, *Lactuca sativa*, *Capsicum annuum* and Lolium perenne	Seedling growth and germination	(36)
Leaves	Benzoic acid, salicylic acid, tannic acid and p-hydroxybenzoic acid	Wheat cultivars, various weed species	Seed germination and seedling growth	(37)
Straw (Decomposed)	p-Hydroxybenzoic acid, 4-Hydroxy-3-methoxy-benzoic acid, 4-Hydroxy-3,5-dimethoxybenzoic acid, Hexanoic acid and Palmitoleic acid	Wheat seedlings and various weed species	Seedling growth	(38)
Leachates	Various phenolic compounds	*Ageratum conyzoides*, *Borreria pilosa* and *Galinsoga parviflora*	Root growth, biomass and height	(40)
Stem Aqueous Extracts	Phenolic compounds	*Abelmoschus esculentus*	Seed germination	(41)

as well as fatty acids like hexanoic acid, palmitoleic acid and 8-octadecenoic acid, were identified, all of which further contribute to the allelopathic activity of maize.

Weed suppression mechanism of maize plants

Maize exerts significant weed suppression through the release of allelopathic compounds from various plant parts, including the roots, shoots and decomposed straw, through multiple mechanisms. These bioactive compounds inhibit seed germination, root elongation and overall growth of surrounding weeds by disrupting physiological and biochemical processes (34). When used as a cover crop, maize further enhances weed suppression by creating a dense canopy that limits sunlight penetration, reducing the availability of light essential for weed growth. Additionally, the decomposition of maize residues enriches the soil with allelopathic chemicals, which continue to suppress weed emergence and establishment even after the cover crop is terminated (38). Allelochemicals of maize, such as benzoxazinoids like DIMBOA and MBOA, have been shown to exhibit strong effects against several weed species. These allelochemicals are secreted primarily from the roots and inhibit the growth of a range of crops and weeds, such as cucumber (*Cucumis sativus*), lettuce (*Lactuca sativa*), pepper (*Capsicum annuum*) and ryegrass (*Lolium perenne*) seedlings. The compounds show phytotoxic effects to weeds and damage their photosynthetic mechanism, which results in reduced growth (34). Several phenolic compounds released from maize leaves inhibit the germination and growth of weeds and other plants, including various wheat cultivars. These chemicals suppress the germination process by altering their growing mechanism. For instance, tannins and phlobatannins interfere by inhibiting enzyme activity and disrupting cell membrane integrity. Terpenoids suppress the germination and growth of surrounding vegetation by interfering with plant hormonal balance and exerting direct toxicity. Alkaloids can hinder cell division and metabolic processes in competing plant species, ultimately reducing their ability to establish and thrive near maize (39). The decomposed maize straw contains several allelopathic compounds, including phenolic acids like p-hydroxybenzoic acid and 4-hydroxy-3-methoxy-benzoic acid and fatty acids like palmitoleic acid, which contribute to the suppression of weed growth by interrupting the weed's physiological processes (40). Additionally, maize leachates, derived from both the roots and shoots, exhibit allelopathic effects on weeds through several volatile compounds and allelochemicals. Research has demonstrated that maize leachates reduce the root length, height and biomass of various weeds, including tropical horseweed (*Ageratum conyzoides*), stickywilly (*Borreria pilosa*) and quickweed (*Galinsoga parviflora*) (41). Aqueous stem extracts from maize also inhibit seed germination in crops like okra (*Abelmoschus esculentus*) (42). Both maize and wheat residues showed a significant level of germination inhibition in different weed species, which further confirms their allelopathic properties (43).

Wheat allelopathy

Allelopathic compounds found in wheat plants

Wheat (*Triticum aestivum* L.) produces various allelopathic compounds that contribute to its ability to suppress the growth of weeds (Table 3). These allelochemicals include phenolic acids, flavonoids, benzoxazinones (BXZs) and phenoxazinones (PXZs) (44). One of the primary allelopathic compounds in wheat is DIMBOA, a benzoxazinone, which is activated by root secretions and increased in the presence of weeds (45,46). DIMBOA has been shown to inhibit germination and growth in various weed species. 2,4-dihydroxy-(2*H*) 1,4-benzoxazin-3(4*H*)-one (DIBOA) is another prominent allelopathic compound released by the root exudates. Additionally, wheat plants release jasmonic acid, methyl jasmonate and loliolide from root exudates, which enhance their allelopathic effects when in the presence of weeds (47). Several polyphenolic compounds, including both phenolics and flavonoids, have been identified in wheat extracts. These bioactive compounds are known for their antioxidant properties and play an important role in allelopathic interactions (48). The phenolic compounds released by wheat include ferulic acid, vanillic acid, syringic acid and p-coumaric acid (49,50). As flavonoids, catechin, luteolin and quercetin are detected in wheat extracts, which interfere with metabolic processes in target weeds and consequently induce oxidative stress (4). Additionally, compounds like L-tryptophan and syringyl glycerol 9-O-β-D-glucopyranoside are involved in inhibiting root growth in certain crops, demonstrating wheat's allelopathic potential. L-tryptophan is known to interfere with root elongation and cellular division in certain plant species, thereby inhibiting weed growth. Similarly, syringyl glycerol 9-O-β-D-glucopyranoside has been implicated in the suppression of root development in competing crops through its involvement in oxidative stress and hormonal imbalance (51–53).

Weed suppression mechanism of wheat plants

Wheat plays a significant role in weed suppression through the release of allelochemicals from various parts of the plant, including roots, shoots and straw. Like maize, wheat has the advantage of producing allelochemicals in different parts of the plant, including its leaves, roots and residues. This widespread distribution of bioactive compounds enhances its allelopathic potential against surrounding weeds. When maize is used as a cover crop, these allelochemicals can be released into the soil through root exudates, leaf leachates, or the decomposition of plant residues. Once in the soil, these compounds interact with weed seeds and seedlings, inhibiting their germination, growth and establishment. The allelochemicals found in wheat work in altering the internal growing mechanism of weeds, which eventually diminishes their existence (54,55). Root exudates

Table 3. Allelopathic compounds in wheat and their weed suppression effects

Source	Allelochemicals	Weed species inhibited	Inhibition stage	References
Roots	DIMBOA, jasmonic acid, methyl jasmonate, (-)-joliolide	*Amaranthus retroflexus* and *Avena fatua*	Germination and seedling growth	(53)
Shoots	Ferulic acid, vanillic acid, syringic acid, p-coumaric acid	*Avena fatua* and *Amaranthus retroflexus*	Seed germination and seedling growth	(48,49)
Straws	Phenolic compounds (e.g., ferulic acid, syringic acid)	*Portulaca oleracea* and *Amaranthus retroflexus*	Germination and seedling growth	(54,55)
Straw aqueous extracts	Phenolic compounds	*Cynodon dactylon*	Seed germination and seedling growth	(55)
Various parts	L-tryptophan, Syringoylglycerol 9-O-β-D-glucopyranoside	*Lactuca sativa* and *Celosia cristata*	Root growth inhibition	(51,52)

have been shown to inhibit the germination and growth of several weed species, including redroot pigweed (*A. retroflexus*), wild oat (*Avena fatua*), common purslane (*Portulaca oleracea*) and ryegrass (*Lolium rigidum*) (53). In these weeds, germination, radicle length, biomass and photosynthetic pigments were affected (48). Wheat also suppresses the growth of spurry (*Spergula arvensis*), docks (*Rumex acetocella*) and annual fescue (*Vulpia bromoides*) through the release of phenolic acids like ferulic acid (55). Flavonoids such as catechin and quercetin, which are released by wheat shoots and roots, contribute to the inhibition of weed seed germination and seedling growth, mainly by inducing oxidative stress in the target weeds (5). Wheat straw, when used as mulch or incorporated into the soil, further enhances weed suppression by releasing phenolic compounds that affect the germination of weed seeds, such as common purslane (*P. oleracea*) and redroot pigweed (*A. retroflexus*) (55). Additionally, wheat straw aqueous extracts have been found to reduce the germination and growth of Bermuda grass (*Cynodon dactylon*) (55). Wheat methanolic extract has been shown to inhibit the germination and growth of several weed species, including wild mustard (*Sinapis arvensis*), Italian ryegrass (*Lolium multiflorum*) and carrot grass (*Parthenium hysterophorus*) (56). The incorporation of wheat straw or its use in intercropping systems helps in reducing weed pressure, contributing to enhanced crop yield. Usage as a cover crop or intercrop can benefit the surrounding crops with its allelopathic effects (49). However, caution is needed in continuous cropping systems to avoid autotoxicity. Wheat's allelochemicals have been shown to sometimes inhibit its own growth. This is especially seen in varieties with strong allelopathic properties (56) (Fig. 1).

Rye allelopathy

Allelopathic compounds found in rye plants

Rye is widely recognised for its strong allelopathic properties (Table 4), particularly due to the BZXs it produces, both during its active growth phase and when used as a cover crop or when its residue is left on the soil (57). Rye's allelopathic effects are primarily driven by glucosylated BZXs, such as DIBOA in the shoots and DIMBOA predominantly in the roots (58-60). Benzoxazolinone (BOA), a key degradation product of benzoxazinoids, is present in both the roots and shoots of rye (61). DIBOA is identified as the major allelochemical in rye and plays a key role in its weed-suppressive activity (62). MBOA was consistently detected at stable concentrations across multiple samples, indicating its significant role as an allelochemical (58). Another important allelochemical identified in both the shoot and root is HBOA-glucoside (HBOA-Glc), a glucosylated benzoxazinoid that serves as a stable, non-toxic storage form of 2-hydroxy-1,4-benzoxazin-3-one (HBOA). Upon plant tissue disruption or degradation, HBOA-Glc can enzymatically release the active HBOA compound, which contributes to rye's chemical defence by inhibiting weed emergence and growth (59). Rye roots release 4-hydroxybenzoic acid and uracil, which are associated with allelopathic interactions. Furthermore, D-pyroglutamic acid has

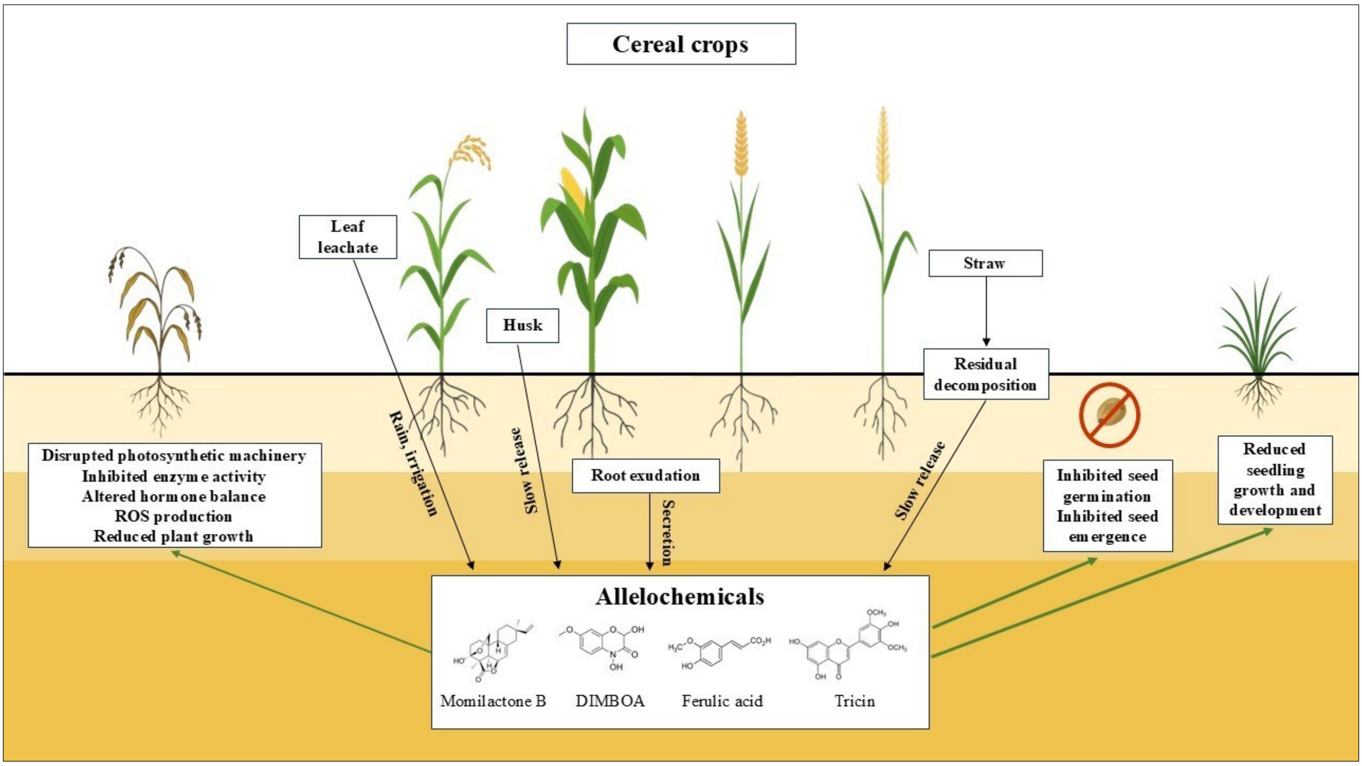

Fig. 1. Mechanism of suppression of weed growth through the allelopathic effect of cereal crops on soil.

Table 4. Allelopathic compounds in rye and their weed suppression effects

Source	Allelochemicals	Weed species inhibited	Inhibition stage	References
Roots	DIBOA, DIMBOA (Benzoxazinones)	*Amaranthus retroflexus*, *Portulaca oleracea* and *Chenopodium album*	Germination, early growth	(57)
Shoots (mulch)	DIBOA, DIMBOA (Benzoxazinones)	*Amaranthus retroflexus* and *Portulaca oleracea*	Seed germination, seedling growth	(57)
Mulches	DIBOA, DIMBOA (Benzoxazinones)	*Amaranthus retroflexus* and *Portulaca oleracea*	Seedling growth	(63)
Aqueous extracts	DIBOA, DIMBOA, BOA (Benzoxazinones, Benzoxazolin-2(3H)-one)	*Amaranthus retroflexus*, *Chenopodium album* and *Polygonum spp.*	Seed germination, Seedling growth	(69,70)

been identified as another important root-exuded compound, functioning as an elicitor of ROS production (63). Several VOCs like methyl salicylate were also found and showed a strong association with the concentrations of benzoxazinoid compounds. Beyond these, a diverse array of other VOCs was detected; including terpenoids such as (1R)-2,6,6-trimethylbicyclo(3.1.1)hept-2-ene, cis-thujopsene, bornyl acetate, limonene and isopulegol; alcohols and acetates like bicyclo(2.2.1)heptan-2-ol, 1,7,7-trimethyl-, acetate (1S-endo)- and 1-hexadecanol acetate; as well as aldehydes and ketones including undecanal, octanal, dodecanal, benzaldehyde and 5,9-undecadien-2-one (6,10-dimethyl) isomers. Hydrocarbons and aromatic compounds such as methyl-substituted undecane, dimethyl-naphthalene derivatives, cyclohexadecane and benzene were identified, alongside other organic compounds like cyclohexanol, 2(3H)-furanone derivatives, propanoic acid and various long-chain alkenes and esters. The complexity and chemical diversity of these VOCs likely contribute synergistically to rye's allelopathic activity (58). These allelochemicals significantly reduce the germination and growth of various weed species.

Weed suppression mechanism of rye plants

Rye is often considered one of the most effective and widely used cover crops because of its well-documented allelopathic properties (64). As a winter cover crop, rye effectively suppresses weed populations through multiple mechanisms. The dense residue for using as a cover crop creates a physical barrier on the soil surface, which hinders weed seed germination and emergence by limiting light penetration and obstructing seedling growth (65). Rye's allelopathic properties release bioactive compounds into the soil that inhibit the germination and development of various weed species. The allelopathic effects remain speculative with respect to the timing and dosage of plant parts required to exhibit their activity (66). It competes vigorously with weeds for essential resources such as soil nutrients, moisture and light, thereby further reducing weed establishment and growth (67). The suppressive effects of this crop on weed populations have been extensively documented across a variety of production systems. In vegetable production systems, its application has demonstrated significant reductions in weed emergence and biomass, as well as in controlled greenhouse experiments and field studies conducted under diverse environmental conditions (65,68). Rye has been shown to suppress the germination and growth of redroot pigweed (*A retroflexus*) in controlled experiments (6). Root-derived allelochemicals from rye have also been observed to inhibit weeds like common purslane (*P. oleracea*) and lambsquarters (*Chenopodium album*), while having a lesser effect on species like velvetleaf (*Abutilon theophrasti*). The shoots of rye, when used as mulch, also release allelopathic compounds such as DIBOA and DIMBOA, which hinder the growth of weeds like redroot pigweed (*A. retroflexus*) and common purslane (*P. oleracea*) (56). Rye residues and mulches have also been shown to possess similar effects on these weeds (68). Rye residues also reduced the emergence and development of Palmer amaranth (*Amaranthus palmeri* S. Watson), sicklepod (*Senna obtusifolia* L.), ivyleaf morningglory (*Ipomoea hederacea*) and large crabgrass (*Digitaria sanguinalis* L.) (67). The presence of rye in the soil inhibited the germination and growth of other weeds, such as knotweed (69). When used in combination with bioherbicides, rye exhibits a synergistic effect that significantly enhances overall weed suppression. This integrated approach leverages both the natural allelopathic properties and physical barriers provided by rye residues, alongside the targeted action of bioherbicidal agents. This results in more effective and sustained control of weed populations compared to either method applied individually (66). These observations highlight rye's potential as a natural herbicide in agricultural systems for sustainable weed management, highlighting its potential as a natural herbicide.

Crop allelochemicals synergise with other weed control methods

Crop allelochemicals can play a central role in reducing reliance on chemical herbicides when strategically combined with other weed management practices. Synergistic approaches such as integrating allelopathy with cover cropping, mulching, reduced tillage, microbial interventions and precision herbicide use can significantly improve weed control efficacy while promoting agroecological resilience. Future research should focus on quantifying these synergies under diverse field conditions and identifying optimal crop-genotype and management combinations. Cereal crops such as wheat, rice, barley, rye, sorghum and maize are known to release various allelochemicals into the rhizosphere, including phenolic acids (e.g., ferulic acid, p-coumaric acid), flavonoids (e.g., quercetin, apigenin), benzoxazinoids (e.g., DIMBOA in wheat and maize) and terpenoids (e.g., sorgoleone in sorghum). These compounds can inhibit seed germination, suppress root elongation and interfere with photosynthesis and nutrient uptake in weed species (57,70). Integrating allelopathic crops in rotations or as cover crops enhances weed suppression while improving soil health. For instance, rye (*Secale cereale*) used as a cover crop releases DIBOA and BOA, reducing weed emergence before the main crop is planted (57). Some studies also demonstrate that allelopathic crop residues or extracts can lower the required dose of synthetic herbicides, reducing environmental load and cost. For example, sorgoleone from sorghum can enhance the efficacy of pre-emergent herbicides (71). Furthermore, combining residue retention (mulching) with minimal tillage preserves allelochemicals in the soil, extending their suppressive effects. This approach has been effective in conservation agriculture systems, particularly with wheat and barley residues (71). Recent research suggests that rhizosphere microbes can enhance or modulate allelochemical activity. By engineering microbial communities or combining allelopathic crops with microbial biocontrol agents, synergistic weed suppression may be achieved (72).

Limitations of crop allelopathy to weed suppression

Despite its ecological advantages, crop allelopathy faces significant limitations that hinder its standalone use in modern agriculture. These include variability in effectiveness, instability of allelochemicals in soil, risks to non-target species and difficulty in field-level application and measurement. The synthesis and release of allelochemicals are highly influenced by genetic and environmental factors such as crop variety, soil type, temperature, moisture and nutrient availability. Not all cultivars within a species exhibit strong allelopathic traits (e.g., some wheat or rice varieties produce minimal allelochemicals). Drought, salinity, or nutrient stress can suppress allelochemical biosynthesis. Research has demonstrated that many allelochemicals are unstable in the soil environment, undergoing rapid decomposition by microbial action or chemical processes, thereby reducing their persistence and efficacy (73–76). For instance, benzoxazinoids such as DIMBOA degrade quickly, making their suppressive effect short-lived. Sorption and leaching in the soil can further reduce bioavailability. Allelochemicals can have non-selective phytotoxic effects, potentially inhibiting the growth of subsequent crops or beneficial species in intercropping systems. Continuous use of allelopathic residues (e.g., sorghum or rye mulch) can hinder the germination of desirable crops in rotations. There is also a risk of altering soil microbial diversity, affecting long-term soil health (74). Despite decades of research, few allelopathic traits have been successfully incorporated into breeding programs or commercial crop varieties. Lack of robust molecular markers and understanding of biosynthetic pathways limits genetic improvement. Farmers often lack guidelines or decision-support tools for integrating allelopathy into weed management plans. Therefore, the best approach lies in integrating allelopathy into broader IWM frameworks, supported by further research into allelochemical biosynthesis, genetics and soil interactions.

Future prospects of allelopathy in weed suppression

As agriculture transitions toward more sustainable, eco-friendly practices, allelopathy-the natural plant mechanism of chemical interference-presents growing potential in the future of weed management. Synthetic herbicides, while effective in the short term, contribute significantly to environmental degradation through soil and water contamination, harm to non-target organisms and disruption of ecosystems. Compounding this issue is the alarming rise in herbicide-resistant weed biotypes, rendering many chemical tools increasingly ineffective and threatening global agricultural productivity (75). Within this critical context, crop allelopathy emerges as a highly promising ecological tool for IWM. While its practical application currently faces challenges, advances in plant science, biotechnology and agroecology are opening new avenues to harness allelopathy more effectively and predictably. Marker-Assisted Selection (MAS) and CRISPR-Cas9 gene editing could help introduce or enhance allelopathic traits without compromising yield or quality. On the other hand, allelopathic crops can be integrated into intercropping, cover cropping and crop rotation systems to reduce weed seed banks and chemical input. Such integration supports agroecological intensification, promoting biodiversity, soil health and resilience. Certain species deliver dual benefits: suppressing weeds through allelochemical release while simultaneously improving soil health, enhancing nutrient cycling (e.g., through nitrogen fixation in legume cover crops), increasing organic matter via residue incorporation and protecting against erosion (17). Utilising plant residues from allelopathic species as surface mulches facilitates the gradual release of inhibitory compounds, providing sustained weed suppression while conserving soil moisture and moderating temperature. Extracts rich in allelochemicals derived from plant tissues can be formulated and applied directly as foliar sprays or soil amendments, offering a renewable and biodegradable alternative to synthetic herbicides (76). Again, allelochemicals can be used as a natural herbicide and thus these products may offer target specificity, biodegradability and lower environmental toxicity compared to synthetic herbicides. Soil microbial communities can also influence the stability, release and activity of allelochemicals. Engineering or managing the rhizosphere microbiome may boost the effectiveness of allelopathic crops. Combining allelopathic strategies with remote sensing, weed mapping and predictive models could help farmers time residue application or crop rotation for maximum weed suppression. The future of allelopathy in weed suppression is promising, especially when integrated into broader biological and ecological weed management frameworks. Realising the full potential of crop allelopathy requires careful optimisation. It is imperative to exploit cultivation systems strategically to ascertain the optimal deployment of allelopathic species and the timing of allelochemical release for maximum weed suppression efficacy while minimising any potential autotoxic effects or negative impacts on subsequent crops (7). This necessitates research into species selection, planting densities, termination timing for cover crops and residue management practices. Allelopathy is most powerful not as a standalone solution, but as a core component within IWM strategies, complementing cultural, mechanical and limited chemical controls to reduce overall herbicide reliance and manage resistance. By harnessing the natural biochemical defences of plants through strategic agronomic practices, residue utilisation, extract application and potential biotechnological advances, allelopathy offers a viable pathway to contribute to the development of truly sustainable agricultural systems for the future. Continued research into genetics, soil ecology and crop system design, along with technological innovation and policy support, will be essential to move allelopathy from theoretical potential to widespread practical application.

Conclusion

The allelopathic potential of cereal crops such as rice, maize, wheat and rye offers a promising and environmentally sustainable approach to weed management. These crops naturally produce a wide range of bioactive compounds that can suppress the germination, growth and establishment of competing weed species. Allelochemicals such as momilactones in rice, benzoxazinoids in maize and rye and phenolic acids and flavonoids in wheat act through various mechanisms that interfere with key physiological and biochemical processes in weeds. The adoption of allelopathic crops in agricultural systems presents several advantages. It reduces the need for chemical herbicides, which are often expensive, harmful to non-target organisms and contribute to environmental degradation. Additionally, the use of allelopathic crops can improve soil health by increasing organic matter content and supporting beneficial soil microorganisms. Despite these advantages, several challenges remain in fully utilising allelopathy in modern agriculture. The strength and consistency of allelopathic effects can vary significantly between different crop cultivars, environmental conditions, soil types and weed species. In many cases, the concentration of naturally released allelochemicals in the field may not always reach levels sufficient to achieve complete weed control. Furthermore, some allelochemicals may have unintended effects on non-target crops or beneficial soil organisms. There is also a risk of autotoxicity in some cereal crops. To overcome these limitations, more research is needed to identify and breed high-allelopathy crop varieties that consistently express stronger weed-suppressing traits. Advances in plant biotechnology, molecular genetics and soil science can help enhance the production and release of allelochemicals in key crops. Additionally, understanding the interaction between allelochemicals, soil microbiota and environmental factors is essential for optimising field performance. Combining allelopathic crops with other sustainable practices, such as crop rotation, cover cropping and reduced tillage, can create IWM systems that are both effective and environmentally responsible. The strategic use of allelopathic cereal crops offers a valuable pathway toward reducing chemical inputs, promoting biodiversity and enhancing the sustainability of agricultural systems. With continued research, innovation and responsible application, allelopathy has the potential to play a central role in shaping the future of sustainable weed management.

Authors' contributions

IJI contributed to preparation of the manuscript draft and revision of the manuscript. SBZ contributed to preparation of the manuscript draft and revision of the manuscript. SS contributed to revision of the manuscript. SSI contributed to revision of the manuscript. All authors read and approved the final manuscript.

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