



Incorporating knowledge of allelopathic interactions can improve productivity and sustainability of crop rotations in the semi-arid tropics

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ABSTRACT

Allelopathy in rainfed crop production systems can be a boon or bane for smallholder farmers depending on their crop choices in intercrops, sequences, and rotations. Crop and weed allelopathy can lead to serious problems like poor germination, low crop stand, and reduced crop growth and productivity. Residual toxicity in soil due to allelopathic monocultures and detrimental impacts on ecosystems, human habitats and health are other problems caused by allelopathy. Allelopathy can be exploited to control weeds, reduce herbicide use, avoid herbicide resistance, stimulate crop growth, and enhance nutrient availability.

This review aims to provide practical knowledge that can improve the management of farming systems in the semi-arid tropics of the Indian subcontinent, a region prone to allelopathic effects induced by biotic and abiotic stresses. We focus on synergistic and antagonistic allelopathic effects of major cereals, legumes, oilseeds, commercial crops, and weeds and summarise the current knowledge on the mode of release and properties of allelochemicals in crops, residue management and their impacts on crops and weeds. We then list options to effectively suppress weeds, reduce risks of residual toxicity in soil and environmental hazards and outline synergistic crop rotations that reduce disease build up and eradicate parasitic weeds in rainfed production systems of the semi-arid tropics. Finally, we highlight research gaps to further improve and employ knowledge of allelopathy of weeds and crops for improved crop production, with reduced synthetic herbicide usage.

1. Introduction

Every season, farmers in the semi-arid tropics (SAT) must make important decisions about their cropping options to minimize climate risks and improve productivity through crop intensification or diversification. This includes considering practices such as no-tillage, conservation agriculture, cover cropping and green manuring. Effective eco-friendly crop management options such as the retention of crop residues as mulches, require sound knowledge of synergistic and antagonistic allelopathic processes and their effects in crop rotations. However, much of this knowledge is not easily accessible. Allelochemical production in plants is enhanced by environmental stressors such as water

limitations, nutrient deficiencies, and extreme temperatures, all of which are typical in the SAT. These stresses are expected to occur more frequently with climate change and increased variability. Hence, we reviewed currently known crop allelopathic effects with an emphasis on the SAT in India, an area comprising approximately 131 M ha [1], a large proportion of which is cultivated by smallholder farmers. Our review is meant to inform choices of suitable crops for inclusion as intercrops or sequential crops, while also improving weed management in rotations.

Hans Molisch coined the word “Allelopathy” from the Greek words, *allelon* meaning “of each other” and *pathós* meaning “to suffer” to define “the harmful effect of one plant upon another.” A more comprehensive

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definition of “Allelopathy” encompasses the positive and the negative effects of chemical compounds produced mainly from the secondary metabolism of plants, micro-organisms, viruses, and fungi. Allelochemicals influence growth and development of agricultural and biological ecosystems [2,3]. Allelochemicals can be involved in plant to plant, plant to insect, or plant to herbivore chemical communication [4]. Yields of crops may be affected by synergistic or antagonistic effects of a crop on the subsequent crop, potency of a crop to suppress weeds and the capacity to minimize the growth and development by allelopathic weeds [5,6]. However, in the process, agronomic practices such as selection of cover crops relay or intercrop combinations, sequential crop combinations, residue mulching and crop rotations need careful consideration to avoid the risk of negative allelopathic effects [7,8]. Positive allelopathic effects include enhancing water-use efficiency, moisture-stress tolerance, and tolerance to specific soil-borne diseases [9,10]. Kostina-Bednarz et al. [6] suggested that combining allelopathy with GM technology could lead to more sustainable weed management practices, improve yields and environmental health. However, they cautioned that progress might be slow due to the polygenic nature of allelopathic properties.

Allelopathy can have particularly large effects when exotic weeds become invasive. In the absence of natural enemies, these weeds can become abundant and develop high local population densities from which they can spread further. This process can be facilitated and aggravated by exudation of various biochemical compounds by the invading plants. Often such exudates have inhibitory properties on local plant and soil microbes across large areas (e.g. *Parthenium hysterophorus* L.). In their natural environment, where other plants have had time to adapt, the invader species usually occur at much lower densities, i.e. their allelopathic defence strategies are less effective [11,12]. With the isolation of bioactive molecules using modern techniques and identification of allelochemicals from various crops, the chemical evidence for allelopathic effects have been well established and known to affect growth and development mechanisms. However, the understanding of agronomic aspects of crop management on allelopathic interactions and management at the field level has been limited. Therefore, this review is specifically aimed at collating and organising knowledge on allelopathic chemicals and mechanisms of the negative and the positive effects, caused by agronomic practices in rainfed cropping systems. The process used for the review was unstructured and iterative, which enabled us to explore the topic broadly, using academic databases but also drawing on our background experience in the study region. There was no specific time-frame for the review – we endeavoured to present the current knowledge, whether it was first published in the 1960s or the 2020s.

1.1. Production, release, and properties of allelochemicals in soil-plant systems

Plants release allelochemicals through exudation and leaf surface deposition, volatile compound exudation, decay of plant residues, and root exudation [7,13]. These allelochemicals are primarily produced during active plant growth, especially in early stages or under stress conditions. Environmental stresses such as drought, extreme temperatures, and nutrient limitations can increase allelochemical release [14].

Although there is considerable diversity in allelochemicals, they primarily originate from four precursors: acetyl coenzyme-A, shikimic acid, mevalonic acid and deoxyxylulose phosphate. Based on these precursors, secondary metabolites can be grouped into three main chemical classes: terpenoids, N-containing compounds, and phenolic compounds [15]. Cinnamic acid (a derivative of phenylalanine), Vanillic acid, and 5-sulfosalicylic acid are derivatives of benzoic acid. Gallic acid, a derivative of dehydro-shikimic acid is the most common phenolic acid component of the hydrolysable tannins. Para-hydroxy-benzaldehyde is a product from hydrolysis of the cyanogenic glycoside dhurrin found in sorghum (*Sorghum bicolor* (L.) Moench). It is also a common oxidation

product of lignin in grasses. Vanillin is also an oxidation product of lignin [16,17]. All these compounds, except 5-sulfosalicylic acid, have been found in crop residues and many have been isolated from field soils [16]. Whitehead [18] identified Ferulic, *p*-coumaric, and Vanillic acids in soil extracts. Guenzi and McCalla [19] isolated these same compounds from residues of maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), and sorghum. The authors estimated that the residue from a single crop of sorghum could return as much as 100 kg ha⁻¹ of *p*-coumaric acid to the soil. Wang et al. [20] reported maximum values of 30.3 g for *p*-coumaric, 6.9 g for Vanillic, and 6.5 g Ferulic acids per 100 g soil in sugarcane (*Saccharum officinarum* L.) field soils. In this review, we focused on phenolic acids and related compounds which are more commonly produced by tropical field crops, weeds, and decaying crop residues, with the aim of detailing allelopathic mechanisms of compounds, their production, and implications for crops. The allelopathic compounds from various plant sources reported in literature to have allelopathic properties are summarized in Table 1.

1.2. Mode of action and disintegration of allelopathic compounds

Although modes of action for allelopathic chemicals are not fully understood, phenolic acids have been the focus of many studies designed to establish the basis of their allelopathy [51,52]. Research with phenolic acids indicate that some phenolic acids function through increasing cell membrane permeability, thus affecting ion transport and metabolism [53]. Reduced respiration and reduced photosynthetic rates due to decrease in chlorophyll have also been reported in the presence of phenolic acids [54,55]. Other studies cited altered plant enzymatic functions, inhibited protein synthesis, and inactivated plant hormones as inhibitory mechanisms from these phenolic allelochemicals [56]. Li et al. [53] reported disruption of cell division and malformed cellular structures in plants when exposed to phenolic acids. The mechanism of allelochemical inhibition from phenolics acids can lead to the reduced growth and death of exposed plants. However, it is most likely that multiple functions within a plant are affected due to the mixture of allelochemicals released from plant species. Although traditional breeding methods have not been successful in producing high yielding crops with greater allelopathy, Kostina-Bednarz et al. [6] and Duke et al. [51] expressed optimism that genetic engineering may have the potential to overcome this impasse.

Allelochemicals, once released, enter a complex plant-soil system, and several factors affect their disintegration and persistence. The amount of allelochemicals added depends on donor plant density and biomass, phenological stage, and the concentration and solubility of specific allelochemicals [57,58]. Consequently, these allelochemicals influence the surrounding plants concurrently or germinating plants subsequently [59]. On the other hand, physiochemical processes such as leaching, microbial breakdown and uptake by plants are factors that can reduce the soil concentration of allelochemicals [60]. Weidenhamer [61] argued that like herbicides, allelochemicals can be inactivated when they bind to organic matter and clay in the soil. Tharayil et al. [62] found that oxidation and sorption are the primary factors involved in the breakdown of these allelochemicals. Soil microbes take up the compounds released from plants and degrade them through the action of extra-cellular and intercellular microbial enzymes for their own energy-building processes. Such microbiological transformations can either detoxify the soil of these compounds or produce more phytotoxic allelochemicals [63]. Adsorption by activated carbon, disintegration by higher temperatures and exposure to bright sunshine are important, as are dilution and leaching with rainfall or irrigation water use [59].

We reviewed allelopathic effects in most of the cereals, legumes, oilseeds, and some other commercial crops and weeds of allelopathic importance in the SAT. Our findings are reported sequentially and summarized as follows: capability of crops and weeds to produce allelochemicals (Table 1), crops affected by released allelochemicals and their impacts on subsequent crops (Table 2), and effects arising from

Table 1

Allelopathic chemicals produced by rainfed crops and their residues affecting companion or succeeding crops and weeds.

Crop	Source, Allelochemicals	Affected species	Impact	References
Rice (<i>Oryza sativa</i> L.)	Cinnamic acid.	<i>Echinochloa crus-galli</i> (L.) P.Beauv.; <i>Chenopodium album</i> L.	Seed bank reduction; suppresses growth of weeds.	[21]
Wheat (<i>Triticum aestivum</i> L.)	Hydroxamic acid, 2, 4-Dihydroxy-7-methoxy, 1, 4- benzoxazin-3-one (DIMBOA). Aqueous extract of wheat residues. Wheat straw.	Several weeds: <i>Convolvulus arvensis</i> L.; <i>Dactyloctenium aegyptium</i> (L.) Willd.; <i>Amaranthus albus</i> L. Rice, barley, rye, and soybean. Maize, sorghum, pearl millet, cowpea (<i>Vigna unguiculata</i> (L.) Walp.), and cluster bean (<i>Cyamopsis tetragonoloba</i> (L.) Taub.).	Inhibiting ryegrass seedling root growth, affecting germination and growth of several weeds. Suppressed growth of crops. Adversely affects germination and seedling growth of forage crops.	[22,23] [24] [25,26]
Maize (<i>Zea mays</i> L.)	Maize root extracts contain 2,4-dihydroxy-1,4-benzoxazin-3-one (DIBOA)	Weeds.	Increase catalysis and peroxidase activity of weeds which inhibit growth of weed roots, hypocotyls of lettuce.	[27]
Sorghum (<i>Sorghum bicolor</i> (L.) Moench; Johnson grass (<i>Sorghum halepense</i> (L.) Pers.)	p-cumaric acid, sorgoleone, dhurrin.	Wheat, peanut, and weeds: <i>Phalaris minor</i> Retz., <i>Chenopodium album</i> L., <i>Rumex dentatus</i> L., <i>Convolvulus arvensis</i> L.	Root exudate, sorgoleone is a potent inhibitor of oxygen evolution of broadleaf and grass weeds, similar to diuron herbicide.	[28,29, 30]
Rye (<i>Secale cereale</i> L.) Rye residue	Root exudates, aqueous extracts, phenolics of plant residues.	<i>Stellaria media</i> (L.) Vill., <i>Echinochloa crus-galli</i> (L.) P.Beauv.; <i>Chenopodium album</i> L., <i>Avena fatua</i> L., <i>Amaranthus retroflexus</i> L.	Weed suppression.	[31,32]
Barley (<i>Hordeum vulgare</i> L.)	Barley straw and roots contain ferulic, vanillic and p-hydroxybenzoic acids; hardenine, gramine.	Durum wheat and bread wheat.	Preceding crop of barley depresses the growth of durum wheat or bread wheat.	[33,34]
Pearl millet (<i>Cenchrus americanus</i> (L.) Morrone)	Phenolic compounds: hydroxybenzoic acid, hydroxycinnamic acid, catechol, coumarique, ferulique, gallique, gentisique, hydroxybenzoic, syringique, vanillique acids.	Germinating seed, embryos, and seed coat of grains.	Disrupts litter nitrogen nutrition, also affects photosynthesis and mitochondrial metabolism.	[35,36, 37]
Soybean (<i>Glycine max</i> (L.) Merr.)	Soybean leaf extracts.	Spear grass (<i>Imperata cylindrica</i> L.)	Soybean allelopathic effects inhibit spear grass germination and growth.	[38]
	Undiluted soybean root exudates.	Cucumber (<i>Cucumis sativus</i> L.),	Promoted germination of cucumber.	[39]
Soybean	Diluted soybean root exudates. Soybean root exudates.	<i>Fusarium semitectum</i> , <i>Clonostachys rosea</i> f. <i>rosea</i> , and <i>Fusarium oxysporum</i> . Lettuce (<i>Lactuca sativa</i> L.) seed germination	Inhibited cucumber germination. Promote the growth of soil borne fungi.	[40]
Mung bean (<i>Vigna radiata</i> (L.) R.Wilczek.)	Glucosyl flavonoids, thioglycerols, aglycon.		Small-flower umbrella plant (<i>Cyperus difformis</i> L.), a weed of rice.	[41]
Black gram (<i>Vigna mungo</i> (L.) Hepper)	Germinating seeds and leachates.	Wheat, maize, chickpea, and lentil (<i>Vicia lens</i> (L.) Coss. & Germ.) crops	Inhibitory effect on the germination and root elongation of specified crops.	[42]
Sunflower (<i>Helianthus annuus</i> L.; <i>Helianthus tuberosus</i> L.)	Aqueous extracts and leachates, soil incorporation of plant root, stem, leaf, and seed hulls. Heliannuols and sesquiterpenoids.	Reduction of seed germination of sunflower, <i>Erigeron Canadensis</i> L., <i>Mutarda arvensis</i> (L.) D. A.German, <i>Amaranthus retroflexus</i> L., <i>Chenopodium album</i> L., <i>Nicotiana tabacum</i> L., <i>Solanum nigrum</i> L.	Soil toxicity, autotoxic and inhibitory effects on broad leaf crops and weeds. Stimulatory effects on germination and growth of monocots.	[43–46]
Peanut (<i>Arachis hypogaea</i> L.)	Root exudates, residues.	Cotton (<i>Gossypium hirsutum</i> L.)	Peanut, chickpea and other leguminous crops affect cotton emergence, growth; reduced lint yield and fibre quality due to leguminous crops preceding cotton.	[47]
Black mustard (<i>Brassica nigra</i> L. (<i>Brassica nigra</i> (L.) Czern., <i>B. juncea</i> (L.) Czern., and <i>B. napus</i> L.)	Residues, aqueous extracts contain higher concentration of glucosinolates, isothiocyanates from residues and aqueous extracts.	Spiny sowthistle (<i>Sonchus asper</i> (L.) Hill), scentless mayweed (<i>Tripleurospermum inodorum</i> (L.) Sch.Bip.), Smooth pigweed (<i>Amaranthus retroflexus</i> L.), barnyard grass (<i>Echinochloa crus-galli</i> (L.) P.Beauv.), black grass (<i>Alopecurus myosuroides</i> Huds), wheat and soybean	In addition to many weeds, wheat and soybean germination and growth are adversely affected preceding black mustard.	[48,49]
Onion (<i>Allium cepa</i> L.)	Mature plant parts.	<i>Amaranthus spinosus</i> L, <i>Bassia scoparia</i> (L.) Beck.	Weed suppression and management.	[50]
Chickpea (<i>Cicer arietinum</i> LK.)	Root exudates from <i>Fusarium</i> wilt resistant cultivars.	Affecting chickpea fungal wilt (<i>Fusarium oxysporum</i> f. sp. <i>Cicerio</i>)	Synergistic disease management.	[10]

preceding crop or weed residues and allelochemicals (Table 3, Fig. 1). We conclude with a discussion about desirable and undesirable crop combinations. Although the allelopathic effects may be inhibitory or stimulatory, adverse effects of allelopathic plants have been observed both in monocultures and multiple cropping systems [64,65].

2. Allelopathy in crops

2.1. Allelopathy in cereal crops

2.1.1. Rice

Many rice (*Oryza sativa* L.) allelochemicals have been screened in various studies [64–67]. More than ten phytotoxic compounds from

several chemical classes have been identified in rice extracts and exudates [68]. Momilactone B diterpenoid is an important allelochemical of rice for weed suppression [69], just as flavone and cyclohexenone are used for weed control [70]. Moreover, momilactone A and B may be involved in physiological defence strategies in the rice rhizosphere, preventing competition from neighbouring plant roots [65]. According to these authors, momilactone, flavone and cyclohexenone can inhibit the growth of the weeds barnyard grass (*Echinochloa crus-galli* (L.) Beauv) and small-flower umbrella plant (*Cyperus difformis* L.), even at low concentrations.

2.1.2. Wheat

There is considerable genetic variation of allelopathic activity in

Table 2

Allelopathic chemicals produced by weeds inhibiting or stimulating companion or succeeding crops, weed seed germination and growth.

Weeds	Crops Affected	Impact
Quack grass (<i>Agropyron repens</i> (L.) Gould)	Important weed affecting field crops like maize and potato.	Interferes with uptake of N and K in maize by generating ethylene from rhizomes due to microbial activity.
Wild oats (<i>Avena fatua</i> L.)	Serious weed of winter annuals including wheat, barley, and oats.	Wild oat residues inhibit germination of herbaceous shrubs. Wild oat root exudates reduce leaf and root growth of wheat. Germination and growth of weeds.
Johnson grass (<i>Sorghum halepense</i> (L.) Pers.)	Perennial weed in sugarcane, maize, and soybean.	Root exudates and decaying residues of Johnson grass inhibit both root and shoot growth of field crops. Leaves, and rhizomes (living and decaying) inhibit the growth of weeds.
Bermuda grass (<i>Cynodon dactylon</i> (L.) Pers.)	Affects barley.	Bermuda grass residues in the field inhibit seed germination, root, and shoot growth of barley.
Yellow nut sedge (<i>Cyperus esculentus</i> L.)	Nut sedge infests grain crops and soybean.	Inhibits root and shoot growth of maize and soybean.
Giant foxtail weed (<i>Setaria viridis</i> P.Beauv.)	Reduced yield in maize.	Due to the inhibitory effect of root exudates of mature giant foxtail roots and leachates of dead roots.
Congress weed (<i>Parthenium hysterophorus</i> L.)	Parthenin released from leaf litter. Soils containing dried leaf and root material of Parthenium reduces crop yield by 30–40 %.	Specific inhibitory effects of Parthenium on root and shoot growth of <i>Crotalaria pallida</i> var. <i>obovata</i> , <i>Senna tora</i> (L.) Roxb., <i>Ocimum basilicum</i> L., and barley.
Cogon grass weed (<i>Imperata cylindrica</i> L.)	Inhibits emergence and growth of annual button weed (<i>Spermacoce hispida</i> L.), tomato, cucumber	Rhizomes exudate inhibitory substances.
Weeds: <i>Chenopodium album</i> L., <i>Medicago polymorpha</i> L., <i>Melilotus indicus</i> L., <i>Convolvulus arvensis</i> L.	<i>Phalaris minor</i> Retz.	100 % inhibiting seed germination compared with control.
<i>Vicia hirsuta</i> (L.) Gray, <i>Cirsium arvense</i> L., <i>Lathyrus aphaca</i> L. and <i>Rumex acetosella</i> L.		Reduction in seed germination compared to control
<i>Amaranthus retroflexus</i> L., <i>Chenopodium album</i> L., <i>Erigeron canadensis</i> L. and <i>Solanum nigrum</i> L.	Soybean (<i>Glycine max</i> (L.) Merr.), peas (<i>Lathyrus oleraceus</i> Lam.), and spring vetch (<i>Vicia sativa</i> L.)	The water extracts from fresh and dry biomass of weeds had an inhibitory effect on the seed germination of soybean, peas, and vetch.

wheat germplasm with enhanced allelopathy for weed suppression. The allelopathic activity of wheat is due to the release of a broad set of allelochemicals, including phenolic acids, hydroxamic acids and short-chain fatty acids such as 2, 4-dihydroxy-7-methoxy-1, 4- benzoxazin-3-one [71,72]. The allelopathic effect of wheat on weeds has been attributed to phenolic acids, hydroxamic acids and related compounds [73]. Wu et al. [74] evaluated wheat seedling allelopathy against annual ryegrass (*Lolium rigidum* Gaudin) in a collection of 453 wheat accessions originating from 50 countries. The effectiveness of different wheat

Table 3

Some synergistic (S) crops with neutralizing or stimulatory allelopathic effects and some antagonistic (A) crops with inhibitory allelopathic effects on germination, root elongation and growth of other crops in various cropping systems. # refers to the numbered processes in Fig. 1, which can either be synergistic or antagonistic.

Rainfed cropping system	#	Synergistic/antagonistic combination	Allelopathic effects in the systems
Sorghum systems (S)	1, 5	Sorghum + chickpea - sorghum + safflower	Weed control in sequential chickpea and safflower because of sorgoleone.
	2	Sorghum/pigeonpea	Weed control in intercrop of pigeonpea due to sorgoleone.
Short season legume systems (S)	1	Sorghum + mung bean + sorghum; Sorghum + black gram	Weed control in mung bean due to sorghum allelochemicals. Reduced soil toxicity due to rotation of two allelopathic crops.
Short season legume systems (A)	3	Black gram + chickpea	Chickpea germination and root elongation and growth affected by black gram allelopathic effects.
Rainfed rice systems (S)	1	Rice + mung bean; Rice + black gram; rice + maize + wheat; Sugarcane + maize + wheat	Mung bean and black gram relay cropping in rice fields helps to control <i>Cynodon dactylon</i> L. Maize in rice-wheat or sugarcane-wheat sequences improves wheat yields.
Rainfed rice systems (A)	4	Tobacco - rainfed rice	Tobacco allelochemicals affect the growth and tillering of rice.
Groundnut systems (S)	2, 1	Groundnut/pigeonpea; groundnut/pearl millet Groundnut + sorghum	Groundnut provides competition for weeds in intercrops with pigeonpea and pearl millet, and acts as a trap crop for striga parasitic weed of sorghum.
Cotton systems (A)	3, 4	Groundnut + cotton, Cotton - Chickpea - Cotton	Groundnut allelochemicals affect the cotton germination and growth. Chickpea allelochemicals affect succeeding cotton.
Soybean systems (S)	1	Soybean + sunflower; soybean + safflower; Soybean + maize; soybean + cucumber	Sunflower broomrape parasitic weed controlled by soybean as a trap crop. Weed control in soybean because of preceding sunflower allelochemicals.
Soybean systems (A)	3	Sunflower + soybean, mung bean + soybean; canola + soybean	Mung bean and canola allelochemicals adversely affect soybean.
Wheat systems (S)	1	Sunflower + wheat; Pearl millet + wheat	Sunflower and pearl millet allelochemicals in residues affects broad leaved crops and weeds in wheat.
Wheat systems (A)	4	Wheat-soybean; wheat-wheat	Soybean after wheat is affected by wheat allelochemicals; crop stand, and growth is affected.
Sunflower systems (S)	1	Sunflower + pearl millet; sunflower + maize; sunflower + sorghum	Sunflower allelochemicals can have a stimulatory effect on small seeded cereal crops.
Sunflower systems (A)	3	Sunflower + cowpea; sunflower + mung bean; sunflower + cluster bean; sunflower + Tobacco; sunflower + cotton	Sunflower allelochemicals affect legume germination and their growth.

Note: + denotes sequential cropping systems;/denotes intercrop; - denotes an annual crop rotation in a cropping system.

accessions in their ability to inhibit root growth of ryegrass ranged from 10 % to 91 %. Wynne et al. [75] reported that allelopathic properties of wheat residues do not affect emergence and early growth of canola (*Brassica napus* L.). The negative impacts of wheat autotoxicity on

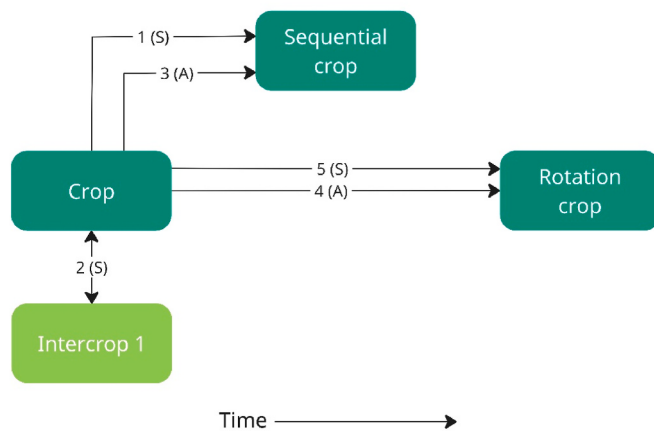


Fig. 1. Pathways of synergistic (S) and antagonistic (A) interactions between crops. [Table 1](#) provides example cropping systems that relate to each unique numbered pathway. A sequential crop is one sown soon after the initial crop, within the same growing season; whereas, a rotation crop is sown after a longer delay, in the following growing season.

agricultural production systems have also been identified when wheat straw was retained on the soil surface for conservation farming purposes. Continuous cropping of wheat leads to autotoxicity and residual toxicity in soil, which should be avoided by crop rotation with allelopathic tolerant or non-allelopathic crops [71].

2.1.3. Barley and rye

Barley (*Hordeum vulgare* L.) is known as a ‘smother’ crop due to its early vigour and the associated ability to effectively compete for nutrients and water but also due to release of allelochemicals [33,34]. Ben-Hammouda et al. [76] reported that a cultivar of barley was autotoxic to other cultivars of barley, but not to itself, an intriguing example of kin dependent interaction. Similarly, Bouhaouel et al. [77] reported that the allelopathic effect of barley was more potent against weeds than itself. Leaves and roots of barley are the most important sources of allelopathic, phytotoxic substances [76]. These plant parts contain ferulic, vanillic and p-hydroxybenzoic acids. The allelopathic action of two alkaloids, gramine and hordenine, have been confirmed. Hence, barley tends to negatively impact durum wheat and bread wheat if it precedes them in a cropping sequence.

Allelopathy activity of rye (*Secale cereale* L.) has been investigated for its ability to suppress weeds when sown as a cover crop and its biomass residue incorporated as green manure. Effective allelochemicals known in rye exudates include beta-phenyl-lactic acid (PLA), beta-hydroxybutyric acid (HBA), hydroxamic acids (DIBOA), benzoxazolinone (BOA), and azobenzene (AZOB). These natural products can contribute to the herbicidal activity of rye residues [59]. Reberg-Horton et al. [78] identified seasonal changes in the production of allelochemicals in rye that varied depending on the cultivar and harvesting time, with lower production at harvest. Chlorosis was a symptom of damage to crops from rye residues and may be related to the effect of DIBOA and BOA on photosynthetic mechanisms such as photophosphorylation and electron transport [79]. Thus, rye could be grown as an effective allelopathic cover crop during fallow periods, providing the crop is harvested early (at flowering) and its residues incorporated for weed control.

2.1.4. Maize

Kato-Noguchi [27] observed allelopathic potential of maize seedlings enhanced with visible light and observed six substances in germinating maize seedlings with inhibitory activity in the acetone extract. One of these substances, DIBOA, was higher in light-grown maize than in dark-grown maize. At concentrations greater than 0.3 mol kg^{-1} , DIBOA

inhibited the growth of roots and hypocotyls of lettuce (*Lactuca sativa* L.) seedlings. The mean concentration of DIBOA in the light-grown maize seedlings was 0.38 mol kg⁻¹ fresh weight and concentration in the dark-grown seedlings was 0.17 mol kg⁻¹ fresh weight. The level of DIBOA in the dark-grown seedlings increased rapidly upon exposure to light irradiation, indicative of enhanced allelopathic activity of germinating maize exposed to visible light that might have increased the DIBOA concentration. Kato-Noguchi et al. [80] identified other allelochemicals in the seedlings of maize that inhibit growth of roots and shoots of oats, lettuce, and other species.

Jabran [81] suggested that maize cultivars with high allelopathic potential may be used to suppress weeds – the characteristics can be employed by using allelopathic plant parts and/or intercropping with non-allelopathic crops.

2.1.5. Sorghum

Several allelochemicals are found in roots, stems, leaves, flowers, and grain of sorghum. These include chlorogenic acids p-coumaric and p-hydroxybenzaldehyde [82] and dhurrin [83] found in sorghum, Johnson grass (*S. halepense* (L.) Pers), and Sudan grass (*Sorghum bicolor* nothosubsp. *Drummondii* (Nees ex Steud.) de Wet ex Davidse) [84]. However, the most studied metabolite exudate by the living roots of sorghum is sorgoleone [85–89], a compound also known to inhibit ammonia-oxidizing archaea and bacteria responsible for the rate-limiting nitrification [90]. It also increases P uptake by influencing mycorrhizal colonization [91]. Sorgoleone exhibits selective activity with inhibition of many germinating seedlings but little activity against certain species such as morning glory (*Ipomoea* spp.). Studies on sorghum root exudates compared sorgoleone activity to that of the herbicide Diuron. It has potential as a natural herbicide that could be developed as an alternative to synthetic herbicides. Kostina-Bednarz et al. (2023) [6] show that sorgoleone can be compared to the action of the soil herbicide pendimethalin.

Further, Cheema [28] reported that mature sorghum plants produce at least nine water-soluble allelochemicals phytotoxic to weeds such as *Phalaris minor* Retz., *Chenopodium album* L., *Rumex dentatus* L., and *Convolvulus arvensis* L.

Sorghum allelopathy frequently harms wheat and peanuts (*Arachis hypogaea* L.) when these crops are grown in rotation with sorghum. Roth et al. [92] found that prompt tillage of the mature sorghum stalks delayed development of the following wheat crop but did not affect grain yields, probably because allelopathic compounds degraded in the soil. No-till sorghum stover had negligible effect on stand establishment of wheat but frequently reduced grain yields, possibly because allelopathic compounds leached slowly. Sorgoleone formulations have shown weed control efficacy on several crops and weeds under different growth conditions [93]. Sène et al. [94] found that peanut seedling establishment was better between rows than within rows of a previous sorghum crop. They proposed a geometrical pattern of sowing for peanuts between two rows of the previous sorghum crop to escape the sorghum's "allelopathic heritage." The above studies indicate that introduction of sorghum into a crop rotation can often be detrimental to the yield of other crops because of its allelopathy. However, the so-called "allelopathic heritage" inhibits weed growth more than it affects companion or succeeding crops. Consequently, sorghum crops can grow better because of the reduced weed competition.

2.1.6. Pearl millet

Numerous studies have demonstrated that pearl millet (*Cenchrus americanus* (L.) Morrone) whole grains are rich sources of phenolic compounds [35]. Several studies have demonstrated that the outermost layers of the grains possess a high phenolic content [95,96]. These compounds are also found in embryos and seed coat of grains [36,37]. Phenolic compounds (Hydroxybenzoic acids) present in pearl millet cause slow degradation and disrupt litter nitrogen nutrition [97]. A recent study by Al Hijab et al. [98] showed that priming pearl millet

seeds with soil microorganisms can bolster the seeds' tolerance against allelochemicals originating from weed residue treatments.

2.1.7. Options to manage allelopathy of cereals

In summary, allelopathy in cereals is important for their inhibitory or stimulatory effects on companion or sequential crops in crop rotations. In rice, allelochemicals create competition in the rhizosphere for weeds that are associated with rice cultivation. Thus, rice allelochemicals can reduce expenditure on weed control in rice production systems. Continuous cropping of wheat results in soil residual toxicity due to autotoxicity, hence continuous wheat cropping should be avoided. Allelopathic tolerant or non-allelopathic crops are advisable in rotations with wheat. Barley tends to suppress companion crops due to its high vigour and the associated ability to effectively compete for water and nutrients. Its residues are detrimental to succeeding durum wheat or bread wheat. Hydro-priming and osmo-hardening of maize hybrid seed are advised to mitigate inhibition of maize seedling emergence, which delays and suppresses seedling growth due to allelopathic stress of the preceding sorghum. Sorghum in cropping systems reduces weed growth, and thus helps companion or succeeding crops to grow better without weed competition. With various manifestations of allelopathic cereal crops, suitable choice of these cereals in various cropping systems can be beneficial to farmers.

2.2. Allelopathy in legumes

2.2.1. Cowpea, mung bean and black gram

Hill et al. [99] studied the effect of methanol and ethyl acetate extracts of cowpea (*Vigna unguiculata* Walp.) residue on germination and root elongation of vegetables and weed species, confirming the presence of allelochemicals. The effects of the extracts varied with their concentrations and plant species. Previous studies by Hill et al. [100] showed the susceptibility of several crops and weed species to aqueous extracts of cowpea and mung bean (*Vigna radiata* (L.) R. Wilczek.) cover crops.

Mung bean produces allelochemicals which can either inhibit or stimulate the growth and yield of subsequent crops. They are affected by their own toxic exudates and by phytotoxins produced when mung bean residues decompose in the soil [101]. Continuous cropping of mung bean can therefore lead to plant growth inhibition. Allelochemicals from mung bean inhibit as much as 10–25 % of crop growth when mung bean is planted following a previous crop of mung bean. Inclusion of mung bean in a cropping system requires knowledge of the allelopathic effects of mung bean on subsequent crop germination and growth. In a laboratory study, Lertmongkol et al. [102] reported that mung bean root and stem contained the allelochemicals thioglycerol, aglycone and three other compounds. A three-year study using a rice-mung bean cropping sequence revealed that the population of lowland weeds, like small-flower umbrella plant, was drastically reduced by the relay crop of mung bean in the sequence [103]. HPLC analysis revealed that there were five compounds involved in the allelopathic action of mung bean root extracts, including saponin (thioglycerol).

Suman et al. [42] found that black gram (*Vigna mungo* (L.) Hepper) released allelopathic substances and produced an inhibitory effect on the germination of wheat, maize, chickpea (*Cicer arietinum* L.) and lentil (*Vicia lens* (L.) Coss. & Germ.). Hence, black gram should not be sown in mixtures with these species. The germination and early seedling root length of all the tested crops were inhibited by the leachate of black gram seeds. The maximum inhibition was found in lentil and the minimum was in maize. Moreover, well germinated seeds of wheat and maize also showed inhibition of root elongation compared to control plants. Overall, it may be inferred that the presence of a high density of black gram seeds can reduce germination and alter root development of other commercial crops. Identification of methods to counteract these allelopathic effects of black gram leachate may be useful for management of the crop rotations and systems involving black gram as a component crop.

2.2.2. Chickpea and faba beans

Hulugalle et al. [104] reported that cotton (*Gossypium hirsutum* (L.) Merr) emergence, growth, and lint yields were reduced when grown after chickpea and faba bean (*Vicia faba* L.) crops with allelopathic potential. Stevenson et al. [10] found that root exudates containing putative allelochemicals in wilt-resistant chickpea cultivars significantly inhibited spore germination of *Fusarium oxysporum* f. sp. *cicero*, a fungus causing chickpea wilt.

2.2.3. Soybean

Olubunmi et al. [38] observed that soybean (*Glycine max* (L.) Merr.) leaf extracts inhibited spear grass (*Imperata cylindrica* L.) germination and growth. Wang et al. [39] found that undiluted soybean root exudates promoted cucumber (*Cucumis sativus* L.) germination, whereas diluted exudates inhibited cucumber germination. Ju et al. [40] reported that soybean root exudates promote the growth of soil borne fungi such as *Fusarium semitectum*, *Clonostachys rosea* f. *rosea*, and *Fusarium oxysporum*. Xie et al. [105] reported that soybean root exudates contained the allelochemical orobanchyl acetate (a type of strigolactones), which stimulates germination of sunflower broomrape (*Orobanche cumana* Wallr.). Zhang et al. [106] studied the allelopathic effects of soybean root extracts of various cultivars. Soybean root extracts induced germination rates (>60 %) of sunflower broomrape more than stem extracts (<30 %) or leaf extracts (10 %). The allelopathic effects of soybean on sunflower broomrape germination was highest during the early growth stage of soybean and gradually declined as the crop matured.

2.2.4. Options to manage allelopathy of legumes

There are many benefits of including legumes in crop rotations, as they can potentially increase productivity and decrease risk of the cropping system [107]. However, the specifics of the rotations need to be managed. Cowpea residue extracts affect germination and root elongation of some vegetable crops and weeds. Hence, fields grown to cowpea should not be sown to vegetable crops in the subsequent season. Mung bean and black gram germinating seeds and residues exhibit allelopathic effects on various subsequent crops. Mung bean can be autotoxic and toxic to other legume seed germination. Hence, continuous cropping of mung bean or in rotation with soybean should be avoided. Yet, mung bean is useful in rotation, especially with sorghum and paddy rice because it contributes N and reduces weeds. During imbibition and germination, black gram seeds release allelopathic substances that produce inhibitory effects on the germination of wheat, maize, chickpea, and lentil seed. Hence these crops should not be sown as mixtures with black gram. Chickpea allelochemicals affect succeeding cotton seed germination, yield, and lint; hence a chickpea-cotton rotation is not advisable. Soybean allelopathy can be effectively used in soybean-sunflower (*Helianthus annuus* L.) systems to eradicate sunflower broomrape.

2.3. Allelopathy in oilseeds and cotton

2.3.1. Sunflower

Several allelopathic compounds have been identified in sunflower [108,109]. Rawat et al. [110] suggested that growing an oilseed crop such as sunflower before the rice crop in the rice-wheat rotation may reduce the need for the use of herbicides in the rotation. Heliannuol sesquiterpenoids have been isolated from the extract of cultivated sunflowers, believed to be involved in the allelopathic action against dicotyledons [111]. The heliannuols are classified as phenolic sesquiterpenes, recognized for allelopathic and pharmacological activity [108]. Several allelopathic substances such as phenolic compounds, diterpenes, and triterpenes from the crop have also been isolated and characterised [112]. The most notable characteristic of heliannuolic compounds is their ability to suppress plant growth at relatively low concentrations. Although these allelochemicals can inhibit growth of

many broadleaf weed species, heliannuols appear to have a stimulatory effect on monocotyledon species [61,108]. This aspect of heliannuol activity may prove useful when allelochemicals of sunflower are used to develop weed control applications. In another study, Einhellig and Kuan [113] reported that scopoletin and chlorogenic acid reduced stomatal aperture in tobacco (*Nicotiana tabacum* L.) and sunflower.

In the subcontinent, rice-wheat cropping systems are most common due their high yields, however these crops are prone to strong weed pressure. Thus, farmers tend to use herbicides, and this rotation often involves the highest herbicide application rate in the region. In-vitro and in-vivo studies indicate that inclusion of sunflower crops in rotation and intercropping could reduce the weed population [110]. Rawat et al. [110] suggest that the inclusion of sunflower before the rice crop in the rice-wheat rotation may provide satisfactory weed control in the succeeding rice crops and may minimize the use of herbicides. Additionally, the replacement of sorghum with summer sunflower may also help in the control of both summer and winter weeds. Spraying the sunflower extracts in the wheat fields reduces the population of weeds that emerge 3–4 weeks after wheat seedlings [114].

2.3.2. Canola and mustard

Bialy et al. [115] reported that glucosinolate compounds exist in shoots and roots of canola. These compounds could affect the germination of other crops. Petersen et al. [116] reported that isothiocyanate produced in the glucosinolate hydrolysis of canola allelochemicals have an important effect on inhibiting and reducing germination at low concentrations. In crop rotations that include canola, the growth of succeeding crops can be inhibited [117]. Growing canola for green manuring before planting cotton suppressed weeds and allowed growers to reduce herbicide use in cotton cultivation [118]. In a study involving 312 canola cultivars, Asaduzzaman [119] found strong genotypic differences in their allelopathic potential. Several genotypes showed significant weed suppressive ability against shepherd's purse (*Capsella bursa-pastoris* (L.) Medik.), Indian hedge mustard (*Sisymbrium orientale* L.) and barley grass (*Hordeum murinum* subsp. *leporinum* (Link) Arcang.). Crop height and early vigour influenced weed suppression.

2.3.3. Cotton

Gui-Ying et al. [120] identified four phenolic acids (3p-hydroxybenzoic acid, ferulic acid, gallic acid, and vanillin) in soil extracts from long term, monocropped cotton fields. Significant differences were observed in phenolic acid concentrations among the fields with different cultivation histories. Gallic acid concentrations in soil increased with lengthy periods of cotton cultivation. In contrast, the concentrations of both ferulic acid and vanillin were highest in the 5-year continuous cotton treatments. Total phenolic acid concentrations increased during the first 10 years of monocropped cotton but then declined. At 0.5–2 g litre⁻¹ concentrations, the four phenolic acids significantly inhibited the growth, enzyme activities, and root activity of cotton seedlings, confirming the allelopathic nature of chemicals from the cotton crop. At lower concentrations (0.125 g/L), p-hydroxybenzoic acid and vanillin increased the growth of cotton seedlings.

Cotton emergence, growth, and lint yield were reduced, and fibre quality degraded due to leguminous crops such as chickpea and faba bean preceding cotton in the rotation. The allelopathic effect of these crops on cotton were confirmed by both in-vivo and in-vitro experiments. Germination studies and pot experiments using cold-water extracts of seed of chickpea, faba bean, cowpea, lablab (*Lablab purpureus* (L.) Sweet), wheat, and sorghum found that cotton germination, emergence, and growth were lower with legumes compared to cereals [104]. The authors also found reductions in cotton growth when crop stubble was incorporated, but not when stubble was applied as surface mulch.

2.3.4. Options to manage allelopathy of oilseeds and cotton

Allelochemicals (heliannuols) produced by sunflower inhibit growth of many broadleaf crops and weeds effectively, even at very low

concentrations. However, heliannuols appear to have a stimulatory effect on small seeded cereal species. Hence, cereals like pearl millet and sorghum can successfully be sown in a rotation with sunflower, in contrast to broad leaf crops such as cotton and legumes. Continuous cropping of sunflower results in soil residual toxicity. Canola and mustard allelochemicals inhibit and/or reduce germination of subsequent crops. Growing canola green manure before planting cotton suppresses weeds and reduces herbicide use. Legumes preceding cotton affects cotton germination, emergence, and growth of cotton compared to preceding cereals like sorghum and wheat.

2.3.5. Allelopathic effects of weeds on field crops

Interaction of weeds and crops at systems level is inevitable and can lead to considerable economic and environmental losses and impact on human health [6]. For instance, allelopathic effects of a widely distributed weed, common lantana (*Lantana camara* L.), common throughout the subcontinent, reduce the seed germination and growth of black mustard (*Brassica juncea* (L.) Czern), cucumber and wild radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin) [121]. Allelochemicals from billy goat weed (*Ageratum conyzoides* L.) residues reduce root length, plant height and biomass in chickpea [141]. Even at low rates of billy goat weed residue incorporation, chickpea nodule number, biomass weight and the amount of leghemoglobin were significantly lower. About 240 weed species are reported to be allelopathic and interfere with the growth and production of crops [13].

3. Discussion

3.1. Crop allelopathy as an efficient weed management strategy in rainfed systems

Allelopathy is an underutilized resource and promising strategy to achieve more sustainable weed management in crops. Many potentially allelopathic crops can be grown as cover, smother, and green manure crops for managing weeds by including them in intercrops and rotations. Effective allelopathic weed control can be of considerable benefit to crop rotations, particularly when certain weed species have already taken hold, or soils have become depleted by long-term monoculture crops. This is particularly important for the management of cropping systems of the subcontinent.

3.2. Cropping strategies to manage allelopathy for improved productivity and ecosystem services

In crop rotations seedling emergence and establishment of a subsequent crop to an allelopathic crop is often problematic. In designing cropping systems and their rotations for semi-arid rainfed conditions in the subcontinent, appropriate choice of crops with synergistic allelopathic interactions is vital. Synergistic cropping systems better exploit allelopathy for better crop growth and productivity, efficient management of weeds, soil borne diseases, nutrients, and soil water; thereby avoiding accumulation of allelochemicals [7,122]. Direct drilling of seed is a common conservation agriculture practice and often involves greater levels of surface crop residues from the preceding crop, which may stimulate or inhibit the growth of the following crop.

A cereal preceding a legume or vice versa might not only improve organic matter accumulation, but also result in a stimulatory, allelopathic effect, if antagonistic allelopathic effects can be ruled out. For instance, the allelopathy of sorghum can be used to control germination and growth of weeds; a legume such as chickpea, which is not affected by sorghum allelopathy, would be well-suited as a subsequent crop. Nageswara Rao et al. [9] reported that a sorghum + chickpea - sorghum + safflower rotation was effective in controlling safflower wilt because of chickpea root exudates in the rotation. A legume in the rainy season and sorghum in the post rainy season (mung bean + sorghum sequential or black gram + sorghum sequential) are suitable, as mung bean or black

gram allelochemicals leach or disintegrate in the rainy season before post-rainy season sorghum is sown. However, sowing of sorghum in the legume rows may result in poor germination and growth if rains are insufficient to leach out the allelochemicals. Incorporation of allelopathic legume residues preceding sorghum sowing can lead to poor germination because of allelochemicals. Hence, legume incorporation in such situation is not advisable, and farmers in India generally prefer to use it as fodder if the crop is harvested in the dry season. Sorgoleone or sorghum crop residues with allelopathic properties can harm a succeeding crop of peanut. Hence, alternatively geometric sowing pattern needs to be chosen for peanut, or allelochemicals need to be leached from the root zone before peanut can be sown. Sorghum intercropped with pigeonpea (*Cajanus cajan* (L.) Huth) is a desirable system as sorghum suppresses weed growth in the intercrop, and sorghum residues in the system reduce weed competition with pigeonpea. Similarly, legume intercropping options like sunflower/pigeonpea and maize/cowpea reduce weed pressure in intercrops due to competition and crop allelopathy.

In rice, allelochemicals Momilactone A and B may be involved in physiological competitive strategies in the rice rhizosphere by preventing competition from neighbouring plant roots [65]. These authors hypothesize that a weed control strategy that involves momilactone, flavone and cyclohexenon at low concentrations can inhibit the growth of weeds barnyard grass, and small-flower umbrella plant in rice crops. A study on wetland transplanted rice field, using a rice-mung bean cropping sequence, revealed that the population of lowland weeds, like small-flower umbrella plant, were drastically reduced by the relay crop of mung bean in the sequence [103].

Continuous wheat monoculture is problematic due to autotoxicity. Hence, it is advisable to select cropping systems rotations with allelopathic tolerant crop species or varieties [71,123]. For instance, in a wheat rotation, the inclusion of maize between wheat and rice or wheat and sugarcane can control the establishment of rice weeds. Selection of non-allelopathic wheat varieties or tolerant wheat varieties as succeeding crops for a previous allelopathic wheat crop can be considered as an option for wheat-wheat rotations.

Putnam et al. [124] reported the growth of cabbage (*Brassica oleracea* L.), maize, cucumber, lettuce, pea (*Lathyrus oleraceus* Lam.), and common bean (*Phaseolus vulgaris* L.) responded differentially to wheat residues, and hypothesised that larger seeded crops are more tolerant than smaller seeded species. Dias [123] found that decomposing wheat straw inhibited subsequent wheat and oat crops, but stimulated growth of subterranean clover (*Trifolium subterraneum* L.). Hicks et al. [125] screened 11 varieties of cotton for their tolerance to wheat straw inhibitory effects. They reported that cotton emergence was reduced by an average of 9 % in tolerant varieties, and 21 % in susceptible varieties.

Soybean varieties were found to differ significantly in their ability to tolerate the allelopathic effects of wheat residues [126]. Hozumi et al. [24] claimed that aqueous extracts from wheat residues suppressed growth of rice, barley, and rye. Narwal et al. [25] reported that aqueous extracts of wheat straw adversely affected the germination and seedling growth of maize, sorghum, pearl millet, clusterbean (*Cyamopsis tetragonoloba* (L.) Taub.), and cowpea. Barley preceding wheat suppresses growth of durum and bread wheat, hence a barley-wheat cropping sequence is not advisable.

Soybean intercropped with either cotton or with pigeonpea is a cropping system with positive interactions. Soybean root exudates or leaf extracts have allelopathic effects to inhibit germination and growth of grass, reducing weed competition in the intercrops. Soybean preceding sunflower is another example of a good cropping strategy. Since soybean acts as a trap crop for sunflower downy brome, the parasitic weed germinates by stimulation of soybean. However, it dries up quickly as soybean does not support the growth of sunflower downy brome. Allelopathic effects of sunflower can be negated by growing sorghum or pearl millet in the sequence. Peanut can be grown preceding sorghum as a sequential crop or in rotation, but not in rotation with cotton. Peanut

acts as a trap crop to *Striga* sp., a parasitic weed of sorghum, thereby reducing weed stress within the system.

Soybean is susceptible to sunflower allelochemicals, hence soybean succeeding sunflower should be avoided. A mung bean - soybean rotation should be avoided as mung bean inhibits soybean germination and growth due to its allelochemical residues in the soil. Similarly, a black gram-chickpea sequential system is undesirable due to black gram leachate inhibiting germination and root development of chickpea. It is not advisable to grow legumes after sunflower.

Pre-sowing seed hardening techniques like hydro-priming and osmo-hardening can be exploited to alleviate allelopathic stress of sorghum on maize [127]. Crops stand and establishment are often affected following allelopathic crops like sorghum [128]. Crop emergence, establishment and good stand density of wheat are also suppressed if it is grown after sunflower [129]. Similarly, seedling emergence and growth of barley are suppressed when barley is grown following black mustard [130]. Allelopathic crops like sorghum, wheat, mung bean, black gram, sunflower, and tobacco monocultures lead to residual toxicity in soil because of the accumulation of allelochemicals season after season. Hence, these crops should be rotated with suitable neutralizing crops that can tolerate their allelochemicals.

The above mentioned allelopathic interactions of crop-crop and crop-weed can be important when selecting a cropping system to manage the allelopathic effects of previous crops and weeds in those conditions. A suitable cropping system, together with biological control measures and tillage practices can contribute to more sustainable agricultural practices. Activated carbon, summer-ploughing at elevated temperatures and high rainfall can disintegrate or drain the leachates from the rhizosphere. This alleviates allelopathic effects. Long-term monocultures of crops especially sunflower, sorghum, rye, wheat, mung bean, and black gram, result in soil residual toxicity in rainfed dryland cropping and can be avoided by crop diversification and appropriate crop rotation strategies.

3.3. Researchable issues on allelopathy in rainfed systems

Allelopathic knowledge offers considerable scope to improve the sustainability and productivity of crop rotations in the SAT, particularly on the subcontinent. This requires a better understanding of the complex allelopathic effects and their interactions with crops, weeds, soils, and their environments. While many questions on the operational effectiveness of allelochemicals remain unanswered, the use of allelochemicals for weed suppression seems a promising avenue for reducing herbicide usage.

The effects of different allelochemicals and their interactions under various environmental conditions and in combinations of abiotic and biotic stresses require further research. Better understanding of biosynthesis of allelochemicals and the production of synthetic analogues to natural allelochemicals as herbicides remains an important research issue. The application of crop residues or cover crops with allelopathic properties should become a valued component of sustainable cropping systems in the future. Farmers need to become more aware of the negative impacts of monocultures and low crop yields because of allelopathic crops. Screening of crops for improved highly allelopathic new cultivars, and varieties to withstand environmental stresses in view of ensuing climate changes should be the focus of further studies. The use of biotechnology tools and genetic studies to identify genes responsible for allelopathic exudates and their manipulation are future areas of research in allelopathy.

Other potentially useful tools for applied research in crop allelopathy include proximal and remote sensing. Proximal sensors like Raman spectroscopy can be used for phenotyping and assessing the effects of biotic and abiotic stresses on plants [131]. Hyperspectral imaging can be used to detect and map nutrients [132], abiotic stress including disease [133] and potentially other negative effects of chemicals on plants, including allelopathic exudates. At the field level, remote sensing

technologies such as drones with RGB or multispectral cameras can be used to detect weeds [134] or map the impacts of pathogens or allelopathic chemicals on crops. These technologies hold potential both for future research and also for detection and management in production agriculture.

4. Conclusions

Managing cropping systems in the semi-arid regions of the Indian subcontinent presents significant challenges due to a complex interplay of environmental and socio-economic constraints. Key factors include high climate variability and change, water scarcity, pest and disease pressures, and limitations in resources and infrastructure. A deeper understanding of the synergistic and antagonistic effects of allelochemicals on crop rotations can enhance both economic and environmental outcomes in these systems.

In this review, we summarized various cropping strategies that leverage this knowledge. For example, we identified effective management techniques for parasitic weeds, such as planting soybean followed by sunflower, or peanut followed by sorghum, which can serve as effective trap crops. We also explored the benefits of incorporating allelopathic crops into crop sequences to mitigate weed infestations commonly associated with monocultures.

Our findings highlight the risks of soil toxicity associated with the continuous cultivation of highly autotoxic crops like sunflower, wheat, sorghum, mung bean and black gram in SAT regions. We emphasise the necessity of diversifying crop monocultures to alleviate autotoxicity and reduce the buildup of allelopathic chemical toxicity. Additionally, we identified specific cropping sequences that should be avoided due to detrimental allelopathic interactions, while also listing beneficial cropping sequences and intercrops that can capitalize on positive stimulatory effects.

Ultimately, our review seeks to translate current knowledge of allelopathic compounds into actionable strategies for designing crop rotations that are both sustainable and capable of increasing yields. We conclude that future research must bridge the gap between in vitro and in vivo studies, focusing on the still poorly understood interactions of a wide range of allelochemicals under various stress conditions. Moreover, exploring the potential of naturally produced allelochemicals for the development of environmentally friendly herbicides also appears promising.

CRediT authorship contribution statement

Nageswara Rao Vajja: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Holger Meinke:** Writing – review & editing, Supervision. **Martin J. Kropff:** Writing – review & editing, Supervision. **Niels P. Anten:** Writing – review & editing, Supervision. **Anthony M. Whitbread:** Writing – review & editing, Supervision. **Uttam Kumar:** Writing – review & editing. **David Parsons:** Writing – review & editing, Writing – original draft, Supervision.

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Data availability

No data was used for the research described in the article.

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