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Review

Allelopathy activity under laboratory, greenhouse and field conditions: A review

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Abstract: Weeds are one of the significant problems that impact agriculture production. Farmers have been using synthetic herbicides to control weed infestations in the field. However, the excessive usage of herbicides has led to various environmental concerns, including the emergence of herbicide resistant weeds. Allelopathy is an environment-friendly alternative that can control weeds. Here, we performed a systematic literature review to assess the potential and effects of allelopathy under laboratory, greenhouse and field conditions. Articles were collected by searching the SCOPUS database and guided by PRISMA. Of 371 studies identified, forty-three articles used allelopathy to control weeds under greenhouse and field conditions, with Poaceae being the prominent family studied as donor plants. Six articles reported up to 80% weed growth suppression when spraying allelopathy extract under greenhouse conditions, while mulch and soil incorporated with donor plants contributed over 50% suppression under field conditions. The findings revealed that 20 studies had conducted metabolite identification to determine the allelochemicals with phytotoxic activity against target plants. However, the mechanism of allelopathy was not thoroughly investigated. In conclusion, we found an increasing trend of allelopathy experiments conducted under greenhouse and field conditions. Furthermore, field trials should be included to validate laboratory data and to provide insight into allelochemical action and its relationship with the environment.

Keywords: allelopathy activity; field trials; greenhouse; phytotoxicity; allelochemicals

1. Introduction

Weeds pose significant threats to agriculture production systems, and they not only reduce crop yields but also increase weed management costs. They are usually controlled either manually or by chemicals. Currently, the preferred method farmers use to control weeds is chemical control with synthetic herbicides because of their availability and specific modes of action. However, the dependency on synthetic herbicides has led to weed herbicide-resistant species. Resistance occurs when a rare mutation happens in the weed population due to repeated herbicide spraying [1,2]. Currently, there are 502 weed species recorded, showing herbicide resistance ability [3]. The use of synthetic herbicides is becoming more prevalent in agricultural systems. Synthetic herbicides can contaminate water bodies, contributing to pollution and harming soil microbiomes, animals and humans. Compared to allelopathy which is easily degradable [4,5], herbicide usually requires a more extended period to disintegrate in the environment. Therefore, alternative ways to manage weeds in sustainable ways are needed.

Allelopathy is one of the natural phenomena that happen in the environment. Specifically, allelopathy involves inhibitory or stimulatory effects of allelochemicals released by the donor plant to the receiver plant [6]. Allelopathy plays an essential role in regulating plant diversity and sustainable agriculture through releasing allelochemicals. [7]. Allelochemicals are released into the surroundings through leaching, washed down by rain, volatile compounds, decomposition of plant material in the soil, and root exudation [8]. Allelochemicals are secondary plant metabolites [4,9] and can be classified into 10 groups based on their structures: (1) water-soluble organic acids, straight-chain alcohols, aliphatic aldehydes and ketones, (2) simple lactones, (3) long-chain fatty acids and polyacetylenes, (4) quinines, (5) phenolics, (6) cinnamic acid and its derivatives, (7) coumarins, (8) flavonoids, (9) tannins and (10) steroids and terpenoids. These allelochemicals can interfere with seed germination and plant growth by disrupting physiological processes, such as photosynthesis, respiration and water balance, and hormones [8]. The actions of allelochemicals are unique due to the complex organic chemical classes involved [10]. It has been reported that phytotoxins disrupt redox equilibrium and cause secondary oxidative stress. As a result, Reactive Oxygen Species (ROS) are produced in the target species [11]. The most notable and dominant class of plant allelochemicals in the ecosystem is phenolic compounds, and the availability of these compounds in soil influences nutrient availability and affects the growth of plants [9]. A previous study on plants treated with phenolic compounds, such as benzoic and cinnamic acids, found that they can disrupt the respiratory process, hindering plants' growth [12].

Weed management is the system that incorporates several approaches to prevent, eradicate and control weeds in the crop system. Weed control comprises multiple methods, such as biological, chemical, cultural, or physical methods, to minimise weed infestations and competition [13]. These methods reduce agricultural production costs and crop yield loss. However, weed control is only applied after the issue has already arisen; it is not a preventative measure. Allelopathy is therefore considered a practical yet environmentally acceptable method for weed control. There are four methods of harnessing the allelopathic potential in a donor plant: 1) integration of allelopathic plants in crop rotation to determine the secondary metabolites that reside in the soil, 2) identification and extraction of allelochemicals and their effectiveness as bioherbicide, 3) development of crop cultivars with allelopathic capabilities and 4) association of allelopathic plants in the farm as weed control [14,15]. The exudation of allelochemicals from allelopathic plants during crop rotation will help in inhibiting germination of weeds' seeds. Meanwhile, the selection of crops with allelopathic capabilities will help in mitigating weeds and reducing cost. Soil incorporated with the plant having allelopathic potential after harvesting will increase the availability of phytotoxins in soil, reducing weed germination and growth.

Typically, allelopathic assessment begins with environmental observation and is further explored using laboratory bioassay and field assessments. The most common plant traits associated with significant allelopathy activity are the absence of neighbouring plants in the vicinity of the observed plants and their invasiveness. The bioassay method, including the sandwich and Petri dish methods, is used to study the allelopathic effects of potential plants in the laboratory. Meanwhile, field assessments such as foliar spray, mulching and soil amendments are used to evaluate the bioavailability and effectiveness of allelochemicals under field conditions. Many allelopathy studies showed that the laboratory bioassay and field assessments yielded different results, implying that allelochemicals easily varied under field conditions due to biological decomposition [8]. Thus, there is a significant need for laboratory data to be tested under field conditions to implement the allelopathic concept best.

In this article, we systematically reviewed studies that emphasised allelopathic application as weed management research under greenhouse and field conditions and organised with the following goals: a) application of plant extract/donor plant toward weed species and b) allelochemicals identified from donor plants. These methods allowed us to provide comparisons and critical analyses of the potential and effects of allelopathy under laboratory, greenhouse and field conditions.

2. Review Protocols-PRISMA

This review was guided by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [16]. There are three main procedures involved: (i) identification, (ii) screening/elimination, (iii) eligibility and inclusion, which are briefly described below.

2.1. Identification

The SCOPUS database was used to search and identify the literature intended for the review. Identification is a method of finding synonyms, related terms and variations for the most important keywords for the study. The keywords used in this study were developed from synonyms from the thesaurus, expert suggestion and keywords from the previous article [17]. The search string used for the analysis using the TITLE-ABS-KEY function was as follows:

TITLE-ABS-KEY (("Allelopathy extract*" OR "Allelopathy substance*" OR "Allelopathy plant*" OR "Allelopathy effect*" OR "Allelopathy activity*" OR "Allelopathy substance*" OR "Bioherbicide* potential*" OR "Bioherbicide* properties" OR "Allelochemical*" OR "Allelochemical* activity*" OR "Allelochemical* effect*" OR "Bioherbicidal" OR "Phytotoxicity*" OR "plant extract*" OR "Phenolic acid*" OR "Secondary metabolite*" OR "plant* secondary metabolite*" OR "Terpenes") AND ("controlling weed*" OR "weed* management" OR "kill* weed*" OR "common weed*" OR "weed germination" OR "weed growth" OR "weed species") AND ("Greenhouse" OR "Field" OR "Field application" OR "Field trial*" OR "farm*")).

2.2. Article screening and elimination

Results from the search string used were screened according to the following criteria: 1) excluded articles published before 2010; 2) published in the form of article reviews, chapters in books, books series or conference proceedings; 3) non-English articles; and 4) articles excluded based on title and abstract review (report on bioassay screening). The articles published from 2010 onwards were the focus of this review to see the trend of this topic.

2.3. Article eligibility

Eligibility involves manual verification of the retrieved manuscripts to ensure that the articles are consistent with the review's objective [17]. The exclusion criteria in the eligibility process are the following: 1) articles without field trials or greenhouse assay as supportive data; 2) treatment/donor are not plant and plant allelochemicals; 3) weeds are not as the bioassay; 4) and the articles that only focus on the allelopathic effect on the crop.

3. Results

3.1. Screened and eligible articles

Based on the search string used, 371 studies were found that can be considered for the review. After the screening and eligibility processes, only 43 studies are included in this article (Figure 1). From the 43 selected studies, 53 species from 19 families were identified as plant donors and used to test the allelopathy activity against weeds under greenhouse or field conditions. Twenty-three studies were done in greenhouses, and 20 were conducted in the field (Table 1). Additionally, two studies were tested under all conditions (laboratory, greenhouse and field). The results showed an increasing trend of experiments conducted under greenhouse and field conditions (Figure 2).

This review also found that Poaceae is the most studied family for its allelopathic activity (Figure 3). Sorghum is one of the most well-known plants in the Poaceae family for its allelopathic potential, and it has been studied extensively [18–23]. The variety of allelochemicals in Poaceae species (*Oryza sativa*, *Sorghum bicolor*, *Sorghum halepenses* and *Zea mays*) has led researchers to use them as plant donors. For Asteraceae (6 studies were identified), one study was conducted focusing on the invasive weed *Parthenium hysterophorus* [24], and two studies were with common weed (*Ambrosia artemisiifolia*) [23,25]. For Brassicaceae, *Sinapis alba* was studied and discussed in six articles: [12,26–30].

3.2. Application of allelopathic plant extract/residue

Allelochemicals can be utilised in different ways to manage weed infestation. In this review, we discovered five methods for applying allelochemicals to target plants (Table 2). Soil integrated with donor plants or their parts was prominent in the field experiments (23 studies). Furthermore, several of the experiments had more than a one-year duration. In comparison to greenhouse research, spraying application trials are still minimal.

Various factors such as solvent type, plant parts and extraction methods can influence the allelopathic activity in the experiments. Choosing a suitable extraction method is one of the significant factors that can impact the allelopathic effects. The use of essential oils and aqueous and organic solvents as foliar applications has demonstrated great success in post-emergence; more than 80% suppression was exhibited under greenhouse trials, as recorded by six studies (Table 2). In the field trials, mulch and soil incorporated with plant donors demonstrated more than 50% weed inhibition in weed density and biomass [20,22,26,33,35,39,42,47,48,57]. In addition, a study by Meksawat and Pornprom [31] discovered that a mixed treatment of aqueous sorghum extract and sorghum mulch inhibited weed growth by up to 72.6% compared to aqueous extract alone. The result also found that 22 studies out of 43 have used crops or food plants as their donor species (Table 1), with *Sinapis alba*, *Sorghum bicolor* and *Oryza sativa* being the most studied crop species. The application method is also an essential factor influencing the extract's efficacy. According to Pardo-Muras et al. [59], the spraying method is more effective towards dicotyledon weed (*Portulaca oleracea*) while supplying via irrigation for monocotyledons (*Avena fatua* and *Echinochloa crus-galli*).

Based on the articles reviewed, 20 of 43 studies have conducted allelochemical identification (Table 3), with a focus on the phenolic acids (syringic acid, vanillic acid, gallic acid, p-coumaric and ferulic acid) [20,33,34,36,45,49,57]. In addition, glucosinolate and its breakdown product thiocyanate were studied and reported to be the source of phytotoxicity towards the target plant in soil incorporated with Brassicaceae family such as *Sinapis alba* [26,29]. Wang et al. [39] also recorded that the application of *Ambrosia artemisiifolia* essential oil caused the oxidative stress of target species and reduced the enzymatic activity and root viability of the weeds tested.

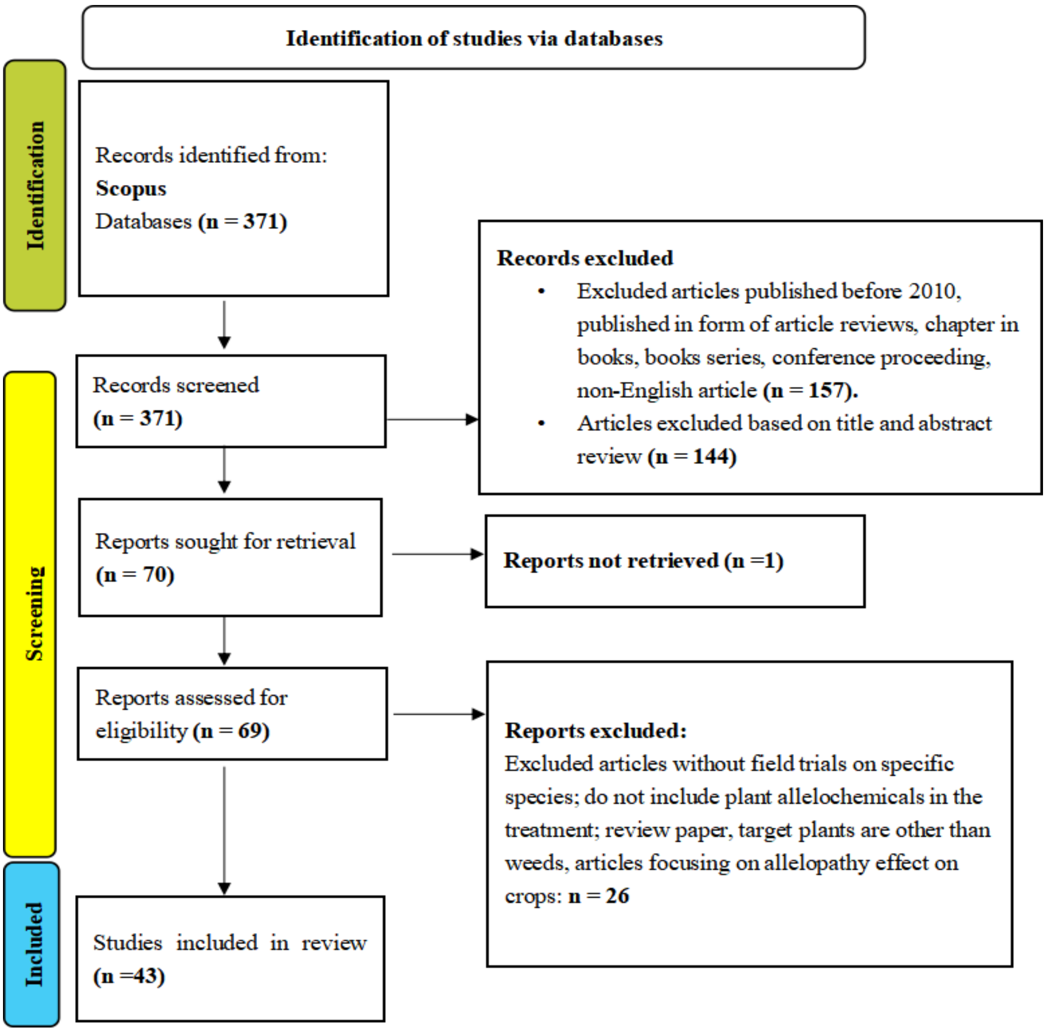

Figure 1. Flowchart diagram (Adapted from [12]).

Table 1. Articles included in the review (F: Field trial, G: Greenhouse, L: Lab).

Studies	Year	Place of experiment	Donor family/species
[31]	2010	L + G	Poaceae/*Rottboellia cochinchinensis*
[26]	2011	G + F	Brassicaceae/*Sinapis alba*
[32]	2011	G	Myrtaceae/*Leptospermum scoparium*
[33]	2011	L + F	Asteraceae/*Helianthus tuberosus*
[34]	2012	G + F	Poaceae/*Secale cereale, Avena sativa, Lolium multiflorum*
[35]	2012	L + F	Poaceae/*Festuca arundinacea*
[36]	2012	L + G	Myrtaceae/*Psidium guava*
[37]	2012	L + G	Fabaceae/*Crotalaria juncea*
[18]	2012	L + G	Poaceae/*Sorghum bicolor*
[20]	2013	F	Poaceae/*Sorghum bicolor*
[38]	2013	F	Poaceae/*Secale cereale*
[19]	2013	G	Poaceae/*Sorghum bicolor* Polygonaceae/*Fagopyrum tataricum*
[39]	2014	L + G + F	Apocynaceae/*Alstonia scholaris*
[12]	2014	G	Brassicaceae/*Sinapis alba* Poaceae/*Zea mays*
[40]	2015	F	Limnanthaceae/*Limnanthes alba*
[41]	2015	L + G	Lamiaceae/*Nepeta meyeri*
[42]	2015	L + G	Poaceae/*Oryza sativa*
[27]	2016	G	Brassicaceae/*Eruca sativa, Raphanus sativus*
[43]	2016	G + F	Menispermaceae/*Tinospora crispa*
[28]	2016	G	Amaranthaceae/*Chenopodium album*
[44]	2016	L + G + F	Asteraceae/*Helianthus annuus* Boraginaceae/*Guizotia abyssinica* Brassicaceae/*Sinapis alba, Raphanus sativus* Cannabaceae/*Cannabis sativa* Fabaceae/*Vicia sativa, Trifolium subterraneum, Pisum sativum, Lupinus angustifolius, Trifolium alexandrinum*. Linaceae/*Linum usitatissimum* Poaceae/*Avena trigose* Polygonaceae/*Fagopyrum esculentum*
[45]	2017	L + G	Myrtaceae/*Callistemon viminalis*
[46]	2017	L + G	Lamiaceae/*Satureja hortensis*
[47]	2018	L + G	Poaceae/*Oryza sativa, Zea mays, Sorghum bicolor* Asteraceae/*Helianthus annuus*
[48]	2018	G + F	Fabaceae/*Vicia faba*
[49]	2018	G	Apiaceae/*Apium graveolens*
[50]	2018	L + F	Apiaceae/*Cuminum cyminum*

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Studies	Year	Place of experiment	Donor family/species
[51]	2018	G	Solanaceae/*Solanum nigrum* Poaceae/*Avena fatua*
[29]	2018	F	Brassicaceae/*Sinapis alba*
[24]	2019	F	Asteraceae/*Parthenium hysterophorus*
[52]	2019	L + F	Fabaceae/*Glycine max* Poaceae/*Zea mays*
[53]	2019	F	Myrtaceae/*Eucalyptus citriodora*
[30]	2019	G	Brassicaceae/*Eruca sativa*
[54]	2019	F	Lamiaceae/*Origanum vulgare, Salvia rosmarinus*
[21]	2019	L + G	Poaceae/*Eruca sativa*
[55]	2020	G + F	47 families screened; Rutaceae/*Ruta graveolens**
[56]	2020	L + G	67 families screened: Lecythidaceae/*Couroupita guianensis** Phyllanthaceae/*Phyllanthus emblica**
[22]	2020	F	Poaceae/*Sorghum bicolor*
[57]	2020	G + F	Poaceae/*Miscanthus sacchariflorus*
[58]	2020	G	Fabaceae/*Ulex europaeus, Cytisus scoparius*
[59]	2020	L + G	Lamiaceae/*Thymbra capitata*
[25]	2021	L + G	Asteraceae/*Ambrosia artemisiifolia*
[23]	2021	G	Asteraceae/*Ambrosia artemisiifolia* Poaceae/*Sorghum halepenses*

*Selected based on the inhibition.

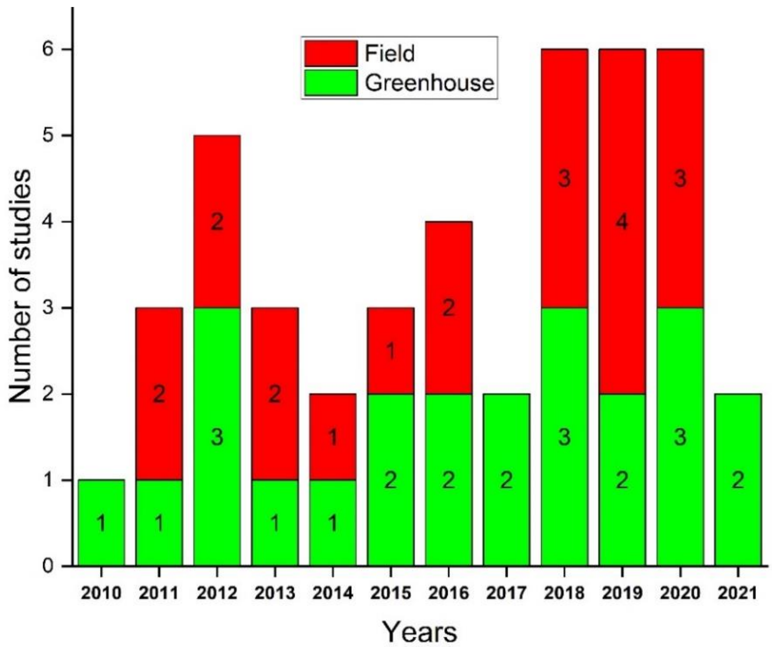

Figure 2. Number of articles and places of experiments by year.

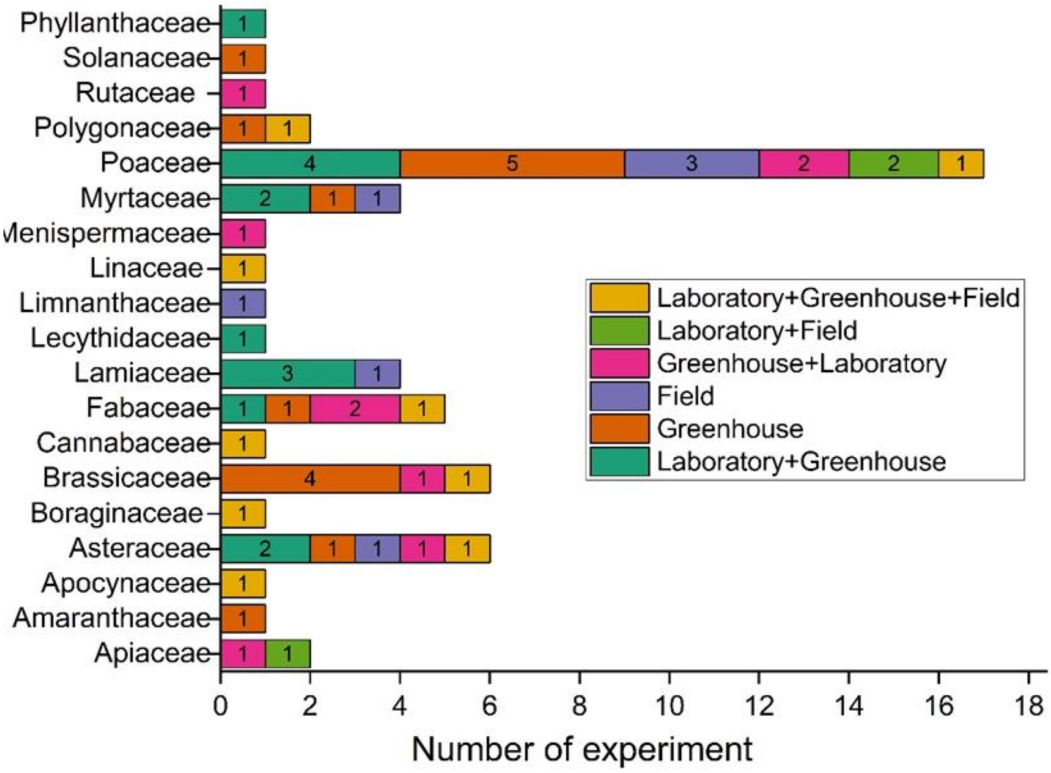

Figure 3. Plant donor families and places of experiments.

3.3. Effect of allelopathy activity on crops

Allelopathy has a negative and positive effect on target plants. Thus, the impact of allelopathic activity on crops should be considered. In this study, we found eighteen studies that reported plant donors' effects on crops, with eight demonstrating positive effects on the crops (Table 4). For example, in maize, treatment of cover crop and Scotch Broom (*Cytisus scoparius*) increased the yield to 53% and 40%, respectively (Table 4). In the study of sorghum residue [20], the reduction in weed density led to a 2.06-t ha^{-1} increase in broad bean yield. For peas, *Eucalyptus citriodora* extract and *Eruca sativa* shoot extracts improved yield by 3–64% and 41–128%, respectively [49]. Several studies have reported the negative effects of donor plants on crops. For instance, sun hemp plant residue could limit lettuce germination by 91%. The increase in crop yield is the outcome of successful weed management in the field [20,53].

Table 2. Application method of donor plant and weed suppression. (G: greenhouse, F: Field trials).

Study	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/	
				G	F
[31]	Poaceae	Plants	Mulch (F) Whole plant (G)	Results based on seed germination compared to control: *Bidens Pilosa*-26.61% () *Echinochloa crus-galli*-66.11% (Gr)	100%-Weed density at field survey) comparing with untreated field
[26]	Brassicaceae	Seed meal	Soil incorporated and powder application (G) (Seed meal)	Pre-emergence-99% Post-mergence-90%	72% reduction of weed density compared to untreated field
[32]	Myrtaceae	Essential oil	Pre- and Post-Spray (F) (Essential oil spray)	Dry weight: (treatment; 1% manuka oil) *Echinochloa crus-galli*-57% *Amaranthus retroflexus*-65% *Digitaria sanguinalis*-72%	ND
[33]	Asteraceae	Plant residue	Plant residue in soil (F)	ND	*Digitaria sanguinalis*-95% *Galinsoga ciliate*-68% (Based on species composition compared to control)
[34]	Poaceae	Plant parts	Mulch (F)	Annual rye grass-up to 90% (Leaf + roots), 86% (roots residue), up to 60% (leaf material) Stooling rye, 90% (Leaf + roots), 86% (roots residue) Oats-90% (Leaf + roots) 86% (roots residue)	48% (Stooling rye mulch)
[35]	Poaceae	Whole plants	Soil incorporation/soil amendments (F)	ND	Results based on reduction of dry weight: *Anagallis* sp. 100% *Sinapis* sp. 100% *Solanum nigrum* L.-88% *Picris echioides*-45%
[36]	Myrtaceae	Water extract	Foliar application (Aqueous extract)	*Portulaca oleracea*-23% (Dry weight)	ND
[37]	Fabaceae	Aerial part	Soil incorporation (aerial dried part)	*Amaranthus hybridus*-95%	ND

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Studies	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/	
				G	F
[18]	Poaceae	Organic solvent extract	Post emergence spraying (G)	Concentration 0.2 mg/L -highest concentration tested *Rumex japonicus*-100% *Galium spurium*-100% *Aeschynomene indica*-100%	ND
[20]	Poaceae	Plant powder	Plant residue and herbicide	ND	Sorghum residue only-up to 61% Sorghum + herbicide-73%
[38]	Poaceae	Mulch	Mulch (F&G)	*Amaranthus retroflexus*-52% (cv. Matador) *Portulaca oleracea*-74% (cv. Protector)	Broadleaf weed reduction-96% (cv. Primiza)
[19]	Poaceae Polygonaceae	Organic solvent extract	Foliar spray- Post emergence (G)	*Rumex japonicus*-96.2% *Galium spurium*-89.7% *Aeschynomene indica*-89.7 (SO 150 µg/mL + 7.5 mg/mL buckwheat)	ND
[39]	Apocynaceae	Water extract, organic solvent extract and powder	Powder incorporated (G) Plant vicinity (F)	ND	Underneath plant, results based on weed diversity: *Bidens pilosa*-100% *Chamaesyce hirta*-100% *Conyza canadensis*-100% Cyperaceae family-100% *Eleusine indica*-100%
[12]	Brassicaceae Poaceae	Seed meal	Soil amendments	Pre emergence: Corn gluten meal *Chenopodium album*-27% *Kochia scoparia*-17% *Echinochloa crus-galli*-34% White mustard seed meal *Chenopodium album*-13% *Kochia scoparia*-4% *Echinochloa crus-galli*-6%	ND

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Studies	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/ G	F
[12]	Brassicaceae Poaceae	Seed meal	Soil amendments	Pre emergence: Corn gluten meal *Chenopodium album*-27% *Kochia scoparia*-17% *Echinochloa crus-galli*-34% White mustard seed meal *Chenopodium album*-13% *Kochia scoparia*-4% *Echinochloa crus-galli*-6%	ND
[40]	Limnanthaceae	Plant parts	Soil incorporated	ND	Activated MSM-51% -71% suppression of background weeds *S. asper* no significant different on application
[41]	Lamiaceae	Water extract and EO	Foliar spray	*Amaranthus retroflexus*-64% *Chenopodium album*-61.33% *Cirsium arvensei*-58.67% *Sinapis arvensisi*-59.33%	ND
[42]	Poaceae	Powder	Soil incorporated (Plant residue)	Over 40% -paddy varieties tested (Ld355, Ld368, Bw400, Bw364)	
[27]	Brassicaceae	Powder	Soil incorporated	*Echinochloa crus-galli* -ESSP (87%) RSSP (89.0%) *Corchorus olitorius*-ESSP (88%) RSSP (89.0%)	ND
[43]	Menispermaceae	Water/methanolic extract and powder	Pre-emergence (G, F); (plant powder soil incorporated and methanolic extract spray) Post-emergence (F) (foliar spray of methanolic extract)	Pre-emergence: Powder: *E. crus-galli*-83.3% *Cyperus difformis*-48.4% *Oryza sativa*-83.3% Methanolic extract: *E. crus-galli*-72.2% *Cyperus difformis*-61% *Oryza sativa*-77.7% Post-emergence: *E. crus-galli*-34% *Cyperus difformis*-40%	Pre-emergence; Powder: 94.3%

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Studies	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/ G	F
[28]	Amaranthaceae	Water extract	Foliar spray	Fresh leaf extract suppression: *Setaria viridis*-90% *Corchorus olitorius*-93.9%	ND
[44]	Asteraceae (3 spp.) Boraginaceae (1 sp.) Brassicaceae (3 spp.) Cannabaceae (1 sp.) Fabaceae (8 spp.) Linaceae (1 sp.) Poaceae (3 spp.) Polygonaceae (1 sp.)	Water extract and mulch	Soil incorporated (Shredded plant)-G	Pre emergence: *Stellaria media*-65% (*F. esculentum* extract) *Chenopodium album*-77% (*F. esculentum* extract) *Matricaria chamomilla*-89% (*H. annuus* extract)	Up to 99% for all the weeds
[45]	Myrtaceae	Water extract	Foliar spray	*Echinochloa crus-galli*-2% extract + Herbicide; 67% *Cyperus rotundus*-1% extract + Herbicide; 51%	ND
[46]	Lamiaceae	Essential oil	Spray (Essential nano emulsion)	*Amaranthus retroflexus*-94.7% (effective dosage) *Chenopodium album*-96.25%	ND
[47]	Poaceae Asteraceae	Powder and plant parts	Soil incorporated	Suppression (crop residue): 100%-sorghum and sunflower 88%-Rice 73%-Maize Suppression (mulch): 16%-maize and rice 39%-sorghum 36%-sunflower	ND
[48]	Fabaceae	Plant parts	Green manure; plant parts incorporated (G, F)	*Amaranthus retroflexus*-77% *Solanum nigrum*-66% *Digitaria sanguinalis*-55% Monocot weeds-52% Dicot weeds-61%	Weed density; 14%–69.8%

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Studies	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/	
				G	F
[49]	Apiaceae	Water extract	Foliar spray (Aqueous extract and fraction)	No effect as post emergence	ND
[50]	Apiaceae	Whole plant	Plant vicinity	ND	58.33% suppression
[51]	Solanaceae Poaceae	Organic solvent extract	Foliar spray (Methanolic extract)	*S. nigrum* extract: *Viola arvensis*-53.9% *Chenopodium album*-29.2% *A. fatua* extract: *Viola arvensis*-51.3% *Chenopodium album*-53.9% *Stellaria media*-62.5%	ND
[29]	Brassicaceae	Water extract and organic solvent extract	Foliar spray (Aqueous extract)	Pre-emergence: *Setaria viridis*-82% *Amaranthus powellii*-97% Post-emergence: *Setaria viridis*-23% (94 kg/ha) *Amaranthus powellii*-46%	ND
[24]	Asteraceae	Water extract	Spray-pre- and post-emergence	ND	Leaf extract-85.50% (Pre-emergence) Whole plant extract-79.94% (pre- and post-emergence)
[52]	Fabaceae Poaceae	Water extract and plant parts	Plant and weed in a pot.	ND	*Bidens* sp. And *Eleusine* sp.-81% (fresh weight)
[53]	Myrtaceae	Water extract	Foliar application	ND	91%–91.65% (Conc. of extract at 25%)
[30]	Brassicaceae	Organic solvent extract and powder	Powder incorporated and foliar spray (alcoholic extract)	Powder *Phalaris minor* 84.85% *Beta vulgaris* 80.68% Spray avg. *Phalaris minor* 86% *Beta vulgaris* 81%	ND

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Studies	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/ G	F
[54]	Lamiaceae	Essential oil	Spraying	ND	*Portulaca oleracea*-63% *Amaranthus retroflexus*-68% *Convolvulus arvensis*-75% *Eruca sativa*-58% *Papaver rhoeas*-73%Spr
[21]	Poaceae	Water extract	Foliar application (Aqueous extract)	Only extract: *Biden pilosa*-39% Extract + herbicide *Biden pilosa*-100%	ND
[55]	47 families (Rutaceae based on toxicity reported)	Water extract	Foliar application (Aqueous extract)	ND	Based on mixture of herbicide and extract: 100%
[56]	Lecythidaceae	Fruit pulp amendments	Soil incorporation (Fruit parts amendments)	*Lolium multiflorum*-6.67%	ND
[22]	Poaceae	Water extract, mulch	Water extract and mulch	ND	Suppression total weed density: 70.7% *Eleusine indica*-78% *Cynodon dactylon*-75% *Dactyloctenium aegyptium*-84% *Cyperus rotundus*-66% *Trianthema portulacastrum*-66%
[57]	Poaceae	Slashed plants	Slashed plant as mulch	ND	Suppression based on fresh weight. *Amaranthus viridis*-78% *Chenopodium album*-71% *Commelina communis*-72% *Digitaria ciliaris*-98% *Echinochloa crus-galli*-98%

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Studies	Plant donor family	Treatment	Method of application	Weed suppression/inhibition/	
				G	F
[58]	Fabaceae	Slashed plants	Soil amendments of slashed plants.	Overall: Gorse treatment-53.9% Scotch-broom-72.1% Suppression based plants emergence/pot: Gorse: *Amaranthus retroflexus*-31.56% Scotch-broom: *Amaranthus retroflexus*-71.65% *Digitaria sanguinalis*-36.92%	ND
[59]	Lamiaceae	Essential oil	Injection into the soil by irrigation and spraying for pre-emergence.	Injection into soil: Monocot (higher dosage) *Avena fatua*-100% *Echinochloa crus-galli*-100% Spraying application: Dicot (lowest dosage) *Portulaca oleracea*-100% *Erigeron canadensis*-100%	ND
[25]	Asteraceae	Essential oil	Foliar application (Post emergence-essential oil)	*Poa annua*-87.16% *Setaria viridis*-51.18% *Amaranthus retroflexus*-62.86% *Medicago sativa*-54.99%	ND
[23]	Asteraceae Poaceae	Water extract	Foliar application (aqueous extract)	ND	ND

*ND: Not determined.

Table 3. Allelochemicals identified from eligible articles.

Studies	Donor family/species	Allelochemicals identified
[31]	Poaceae/*Rottboellia cochinchinensis*	ND
[26]	Brassicaceae/*Sinapis alba*	Glucosinolate, thiocyanate
[32]	Myrtaceae/*Leptospermum scoparium*	Leptospermone
[33]	Asteraceae/*Helianthus tuberosus*	Phenolic acid: Salicylic acid (o-hydroxybenzoic acid), p-hydroxybenzaldehyde, o-coumarinic, acid Coumarin
[34]	Poaceae/*Secale cereale, Avena sativa, Lolium multiflorum*	Ferullic acid-Oat and rye grass cv. Midmar Hydroxybenzoic acid-rye grass cv. Midmar and Sophia Benzoxazolin-2(3H)-one (BOA)-Oat and all rye grass
[35]	Poaceae/*Festuca arundinacea*	Pyrrolizidine alkaloids, flavonol glycosides and flavonol, Quercetin 3-O-rutinoside, Isorhamnetin 3-O-rutinoside and Kaempferol 3-O-rutinoside
[36]	Myrtaceae/*Psidium guava*	Phenolic acid: ferulic, coumaric, vanelic, chlorogenic, caffiec
[37]	Fabaceae/*Crotalaria juncea*	ND
[18]	Poaceae/*Sorghum bicolor*	Sorgoleone
[20]	Poaceae/*Sorghum bicolor*	Phenolic acid: Syringic acid, vanillic acid, gallic acid, p-coumaric, ferulic, catechol, p-hydroxybenzoic acid, protocatechuic acid.
[38]	Poaceae/*Secale cereale*	DIBOA and BOA
[19]	Poaceae/*Sorghum bicolor* Polygonaceae/*Fagopyrum tataricum*	Sorgolone
[39]	Apocynaceae/*Alstonia scholaris*	Pentacyclic triterpenoids; including betulinic acid, oleanolic acid, and ursolic acid
[12]	Brassicaceae/*Sinapis alba* Poaceae/*Zea mays*	ND
[40]	Limnanthaceae/*Limnanthes alba*	Glucosinolate glucolimnanthin
[41]	Lamiaceae/*Nepeta meyeri*	ND
[42]	Poaceae/*Oryza sativa*	ND
[27]	Brassicaceae/*Eruca sativa, Raphanus sativus*	ND
[43]	Menispermaceae/*Tinospora crispa*	ND
[28]	Amaranthaceae/*Chenopodium album*	ND
[44]	Asteraceae/*Helianthus annuus* Boraginaceae/*Guizotia abyssinica* Brassicaceae/*Sinapis alba, Raphanus sativus* Cannabaceae /*Cannabis sativa* Fabaceae/*Vicia sativa, Trifolium subterraneum, Pisum sativum, Lupinus angustifolius, Trifolium alexandrinum*. Linaceae/ *Linum usitatissimum* Poaceae/*Avena trigose* Polygonaceae/*Fagopyrum esculentum*	ND

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Studies	Donor family/species	Allelochemicals identified
[45]	Myrtaceae/ *Callistemon viminalis*	Phenolic acid; gallic acid, ferulic acid, syringic acid and coumaric acid
[46]	Lamiaceae/ *Satureja hortensis*	Carvacrol (55.6%) and γ-terpinene
[47]	Poaceae/*Oryza sativa, Zea mays, Sorghum bicolor* Asteraceae/*Helianthus annuus*	ND
[48]	Fabaceae/*Vicia faba*	ND
[49]	Apiaceae/*Apium graveolens*	p-coumaric acid and p-hydroxybenzoic acid
[50]	Apiaceae/ *Cuminum cyminum*	ND
[51]	Solanaceae/*Solanum nigrum* Poaceae/*Avena fatua*	ND
[29]	Brassicaceae/*Sinapis alba*	Thiocyanate, Glucosinolate
[24]	Asteraceae/*Parthenium hysterophorus*	ND
[52]	Fabaceae /*Glycine max* Poaceae/*Zea mays*	ND
[53]	Myrtaceae/ *Eucalyptus citriodora*	ND
[30]	Brassicaceae/ *Eruca sativa*	nd (only reported on the total phenolic and total glucosinolate)
[54]	Lamiaceae/ *Origanum vulgare, Salvia rosmarinus*	ND
[21]	Poaceae/ *Eruca sativa*	ND
[55]	47 families screened; Rutaceae/*Ruta graveolens**	ND
[56]	67 families screened: Lecythidaceae/ *Couroupita guianensis** Phyllanthaceae/ *Phyllanthus emblica**	ND
[22]	Poaceae/ *Sorghum bicolor*	ND
[57]	Poaceae/ *Miscanthus sacchariflorus*	Orientin, luteolin, veratric acid, chlorogenic acid, protocatechuic acid, p-coumaric acid, and ferulic acid
[58]	Fabaceae/ *Ulex europaeus, Cytisus scoparius*	ND
[59]	Lamiaceae/ *Thymbra capitata*	Carvacrol, p-cymene, and -caryophyllene
[25]	Asteraceae/ *Ambrosia artemisiifolia*	Germacrene D (32.92%), β-pinene (15.14%), limonene (9.90%), and caryophyllene (4.49%)
[23]	Asteraceae/ *Ambrosia artemisiifolia* Poaceae/ *Sorghum halepenses*	ND

*ND: not determined.

4. Discussion

Initially, our review found 371 studies based on the search string. However, articles that studied the allelopathic activity of donor plants under field trials and greenhouses are scarce based on the search. Most articles in the initial search focused on the screening and bioassay experiment conducted in the laboratory setting. Based on our findings, we believe keywords like field trials, greenhouse and allelopathy activity should be included in future articles for database identification.

Allelopathy can be used in conventional, low-input or sustainable agricultural systems [60]. For example, *Satureja hortensis* [46] has shown great success inhibiting *Amaranthus retroflexus* and *Chenopodium album*; thus, more research should be conducted on this plant to understand the allelopathic activity and its potential in weed control.

4.1. Allelopathic activity and weed control

Based on the articles we reviewed, several studies have successfully suppressed weeds under field trials. Soil incorporated with plant donor or mulch showed up to 100% weed inhibition under field conditions [31,35,38,44,57]. Farmers in northern Thailand (Lampang) use itchgrass (*Rottboellia cochinchinensis*) as mulch in their fields, and according to a field survey conducted by Meksawat and Pornprom [31], weeds are inhibited in the mulched area. At the same time, Tabaglio et al. [38] found that rye mulch inhibited broadleaves weeds (96% inhibition) due to the presence of 2,4-dihydroxy-1,4(2H)-benzoxazin-3-one (DIBOA) and 2(3H)-benzoxazolinone (BOA) from the mulch breakdown. Mulch or cover crop application on the farm can reduce weeds through allelochemicals released during the decomposition process and cause physical injury to the weeds. Three studies on the phytotoxicity of isothiocyanates (SCN^-) on weeds have produced positive results [26,29,40]. However, these articles did not clearly describe the mode of action. The ability of plants to withstand allelopathic interference varies even within the same family. According to Staszek et al. [11], the application of cinnamic acid on *Cucurbita lanatus* increased ROS generation and scavenging activities, leading to high cell viability and membrane integrity. The same treatment, however, hindered the *Cucumis sativa* due to an increase in ROS accumulation.

In addition, allelopathic plants can help reduce the growth of herbicide-resistant weeds. Frabboni et al. [54] reported that the treatment of undiluted oil of (*Origanum vulgare* L.) and rosemary (*Rosmarimum officinalis* L.) reduced the *Papaver rhoeas*, which are resistant to traditional chemical herbicides up to 70%. At the same time, Alsaadawi et al. [20] found that a combination of sorghum residue and a half dose of trifluralin reduced weed density significantly compared to the total dosage of trifluralin recommended by the manufacturer. The results were in agreement with Kordali et al. [41], which reported that Nepeta meyeri essential oil was as effective as trifluralin towards *Amaranthus retroflexus* and *Sonchus arvensis*. Thus, the findings demonstrate that the allelopathic effect can be used in weed management to replace or reduce the use of the synthetic herbicide. Furthermore, weed suppression also depends on the dosage of the allelochemicals. Different treatment concentrations will have varying effects. It has been reported that as the dosage increases, weed inhibition may also increase [27].

Allelopathy activity is affected by plant parts and the stage at which they are extracted (fresh or dry). El-Rokiek et al. [36] have recorded that the extract of fresh leaves of *Psidium guava* had maximum inhibitions on purslane compared to the dry leaves extract. El-Rokiek et al. [28] have reported that *Chenopodium album* leaves extract was more effective for *Setaria viridis* suppression than its other parts extracted. Sodaeizadeh et al. [61] suggested that the availability of phytotoxins in different parts of a plant contributed to this effect. Furthermore, the drying and extraction process can also affect the stability of flavonoids.

Table 4. Effect of treatment towards crops.

Crop	Response to donor plants				Comments	Reference
	Biomass	Germination	Growth Inhibition	Yield		
Barley	ns	ND	15%	ND		[19]
Broad bean	ND	ND	ND	(↓61%) 5.3 t/ha	Compared to control	[20]
Carrot	ND	ns	ND	ND	With all the treatment	[37]
Chamomile				Season 1 ↓6.6% (T1) ↓6.9% (T2) ↓1.8% (T3) ↓2.3 (T4) Season 2 ↓11.3% (T1) ↓13.6% (T2) ↓3.1% (T3) ↑0.9% (T4)	T1 = 50% diluted oil of *R. officinalis*; T2= 50% diluted oil of *O. vulgare*; T3 = undiluted oil of *R. officinalis*; T4 = undiluted oil of *O. vulgare*.	[54]
Chinese cabbage	ND	ND	10%	ND		[19]
Cucumber	ND	ND	20%	ND		[19]
Lettuce	ND	ND	91% (Sun hemp leaf) 90% (Sun hemp stem) 95% (Sun hemp root) 58% (Rye leaf)	ND	Pre-emergence treatment	[37]
	↑200% to 700%	ND	ND	ND		[40]
Maise	ND	ND	ND	(↑53%) 4.76 t/ha	Yield in 2006	[34]
	ND	ND	10%	ND		[19]
	ND	ND	ND	ns		[22]

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Crop	Response to donor plants				Comments	Reference
	Biomass	Germination	Growth Inhibition	Yield		
	ns	ND	ND	ns (gorse treatment) ↑40% (yield%; scotch treatment)	Compared to control	[58]
Onion	ND	ND	30% injured	ns	4.5 MT/ha treatment (highest injury)	[26]
Pea	ND	ND	ND	↑3–64% of yield	Compared to control	[53]
	↑2–5% (shoot extract) ↑1.4–4% (shoot powder)			↑41–128% of yield (shoot extract) ↓24% of yield (highest treatment of shoot powder)	Compared to control	[30]
Perilla	ND	ND	10%	ND		[19]
Radish	ND	ND	15%	ND		[19]
Red pepper	ND	ND	15%	ND		[19]
Rice	ND	ND	10%	ND		[19]
	↑7.9–16% (straw dry weight)	ND	ND	↑11–14.8% of yield	Result based on field trials	[43]
	↑10 %	ND	ND	ND		[45]
Sesame	ns	ND	ND	ND		[21]
Soybean	ND	ND	20%	ND		[19]
Sunflower	↑56 %			↑96.5 (weight of head/plant)		[36]
Sunflower	↑14.0–29.0% (ESSP) ↑14.0–29.0% (RSSP)			↑9.8 and 12.9 % (ESSP)↑7.3 and 11.7%, (RSSP)	ESSP-*Eruca sativa* seed powder. RSSP-*Raphanus sativa* seed powder.	[27]

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Crop	Response to donor plants				Comments	Reference
	Biomass	Germination	Growth Inhibition	Yield		
Tomato	ND	ND	10%	ND		[19]
Wheat	ND	ND	15%	ND		[19]
Wheat	ND	ND	ND	↑155% (4437 kg/ha)	Highest yield: Leaf extract (Pre-emergence);	[24]

*ND: not determined, ns: not significant.

Applying synthetic herbicides seems worth it to local farmers, as it improves crop productivity against weeds; however, it has caused environmental hazards and the evolution of herbicide resistance in weed species [38]. Therefore, farmers cannot just rely on chemical herbicides; they ought to switch to naturally occurring weed control. One strategy to lessen the mentioned adverse effects is producing herbicides from naturally occurring plant herbicides [31]. The manipulation of allelopathic plants, which can counteract the negative impact of current weed control measures, is easy to introduce, as farmers are willing to accept methods that protect their crop yields, especially for resource-poor farmers. [21,50]. According to the screened articles, several crops have shown allelopathic potential during field study, such as *S. bicolor* [18–22]. Thus, these data could help the agricultural body to promote these crops through intercropping or mulching. In addition, crops or plants with allelopathic properties will aid in weed control by releasing allelochemicals into the soil. According to Wathugala and Ranagalage [42], incorporating paddy residue into the soil could reduce barnyard grass by more than 40%. Allelopathic research findings can also assist organic farmers in selecting plants for cover crops. Cover crops such as *Sinapis alba* [12,26,29,44], *Secale cereale* [34,38] and *Avena sativa* [34] can be planted and have shown great success in reducing weed density. Hence, plant extracts are the preferred method for allelopathy since some countries use them as a natural herbicide, offering great promise for novel organic herbicides [14,49]. Keeping that in view, farmers are recommended to use water extract, which is easy to produce by utilising possible allelopathic plants already present near the area.

4.2. Impact of allelopathy interference on crops

Application of allelopathic plant extract/residue can also affect crops. Thus, data regarding the effect of allelopathic activity on crops should be considered before being incorporated into weed management. Some allelopathic plants can cause injury to the crops in the post-emergence application. However, the level of injuries is acceptable when weed suppression is achieved [26]. Mulching using sun hemp and rye has also inhibited germination of weed and crop (lettuce) under field conditions [37] However, larger seed crops such as maize have less effect on the presence of plant residue, as reflected by Bezuidenhout et al. [34], due to the reserved storage in the seeds [62]. Thus, growing sun hemp in rotation with crops tolerant of the allelochemicals will lead to greater weed management effectiveness [37]. The transplanting method should be implemented for soil incorporated with plant residue or mulching technique to reduce injury and inhibit the crops [40].

Simultaneously incorporating the allelopathic plant into weed management has a favourable effect on crops. Several studies have reported that the yield of the crops increased as the weed was suppressed by the allelopathic treatment [20,27,43]. Furthermore, the plant residue decomposition from the donor plant contributed to nitrogen availability in the soils, as reflected in the total N in the crop studied [40]. Aslani et al. [43] reported that the allelochemical of *Tinospora crispa* did not affect rice growth but significantly reduced the germination and biomass of weeds.

4.3. Limitation of review and future recommendation

The allelopathic approach is one option that can be used in weed management. However, laboratory data does not perfectly represent the actual performance of in the field [63]. Therefore, field experiments should be conducted to validate the effects of allelochemicals on crops and weeds in the environment. Furthermore, identifying and isolating allelochemicals that are involved in the inhibition process will provide valuable information for further usage [64].

In addition, environmental factors should also be considered when choosing the allelopathy approach. Furthermore, the influence of competition in the field experiment should not be underestimated and has been discussed attentively by Mahé et al. [65]; this is to prevent inadequate data on allelochemical action on the field. The fate of allelochemicals in soil should be studied when involving soil incorporated with plant residue because factors such as shelf life of allelochemicals and microorganisms can impact allelochemicals [2]. This information will help establish allelopathy in weed management by providing stability data of allelochemicals and frequency of application. Research efforts should also focus on water extract treatment as a cost-effective and safer option [22], especially for organic farmers.

5. Conclusions

This review contains 43 studies published between 2010 and early 2021 that emphasised laboratory allelopathy experiments with greenhouse or field experiments as supporting data. It demonstrates a growing trend to study allelopathy in the greenhouse and field. Thus, this review shows the importance of greenhouse and field trials as complementary data for bioassay studies. Application methods are essential in ascertaining allelopathy's effect on target plants. Based on the review, plant-incorporated/mulch and extract spraying methods are the researchers' most common treatments. The direct contact of allelochemicals on the plant organs, such as leaves and roots, will influence the results. Allelopathy demonstrates great potential in controlling weeds. However, the potency of some donor plants is not as good as synthetic herbicides. Therefore, combining the extract with an herbicide will increase the extract's efficacy and reduce herbicide usage. The review also found that the combination of herbicide and plant extract is as effective as a synthetic herbicide at full dosage. More field research on the effect of aqueous and organic solvent extracts on weeds should be conducted to understand the inhibition effect. Furthermore, proper methods should be identified when conducting field research to minimise other influences affecting the experiment and allelochemicals. Additionally, the extraction method using water is cost-effective and may reduce costs for farmers as well as be an eco-friendly substitute for weed control. Several factors should be considered before including the allelopathic plants in weed management. Allelochemicals also depend on the plant parts, stages and application method. The efficacy of allelochemicals is dose-dependent; different concentrations determine the extent of suppression on the weed. Thus, the most potent treatment should be identified for successful weed suppression under field conditions.

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Conflict of interest

The authors stated that there were no conflicts of interest in the study.

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