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SYSTEMATIC MAP

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The application of allelopathy in integrated pest management systems to control temperate European crop pests: a systematic map

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Abstract

Background Pesticides perform vital roles within agriculture but growing concern for their impact on the environment and non-target organisms has created a market for biopesticides with fewer ecological impacts. One source of biopesticides is allelochemicals, here defined as compounds released by an organism that have an inhibitory or stimulatory effect on neighbouring organisms. The focus of this study is allelopathic plants and their inhibitory effects on invertebrate herbivorous agricultural pests of temperate Europe. A systematic map is required to describe the current state of research and collate evidence.

Methods Two academic databases were searched for relevant studies in temperate climates. The results were imported into EPPI-Reviewer, duplicates removed, studies screened and data extracted into a searchable database following the inclusion criteria and coding tool set out in the protocol. Screening consistency was checked at each stage using 5% of the studies. Critical appraisal was not conducted. Each unique combination of key variables (pest, plant, allelochemical, application method, intervention form) was treated as a separate datapoint or experiment. The data was then analysed and cross-tabulated to produce descriptive statistics and heatmaps.

Results This systematic map produced a database which included 243 studies containing 717 experiments from 5550 initial results. Research was unevenly distributed among all key variables with a distinct bias towards extracted allelochemical experiments under laboratory conditions. Allyl isothiocyanate was the most studied allelochemical and of the 99 identified chemical groups, flavonoids and glucosinolates were the most frequent. A wide range of pest and plant species were identified. Brassicas were the most studied plant family and Lepidoptera the most studied pest order. Physical living plants, as opposed to plant extracts or isolated allelochemicals, were predominantly studied in terms of resistance. Allelopathy application methods were not specified in the abstract of 22% of experiments and only 10% of experiments were conducted under field conditions.

Conclusion Allelopathy has been studied in the context of temperate invertebrate pest control in some breadth but little depth and key pest species have not been targeted. The map highlighted significant gaps in the evidence base and a distinct lack of field studies or studies comparing application methods. It contains insufficient evidence to guide policy or management decisions, but provides a research tool and indicates areas for future studies including highlighting topics for secondary research. Critical appraisal is needed to determine allelopathic affect and future search strings should detail all application methods.

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Protocol registration The a-priori protocol was peer-reviewed and published through PROCEED (Kiely C, Randall N. Collaboration for Environmental Evidence: PROCEED. How have allelopathic plants been used within integrated pest management systems to control European crop pests in arable and field vegetable systems in temperate climates?: A Systematic Map Protocol. 2022. https://www.proceedevidence.info/protocol/view-result?id=14. Accessed 5 Jan 2023.).

Background

Agricultural pests can cause economic losses for farmers and hinder global food production. Insects alone are responsible for yield losses of up to 20% in three major grain crops—rice, wheat and maize—and climate change is predicted to increase these losses by 10–25% per degree Celsius of warming, with the greatest losses experienced in temperate climates (Deutsch et al. 1979). Pest management is, therefore, vital within agriculture and the benefits of pesticides extend beyond yield improvement. Pest management improves the shelf life of products, animal welfare and energy efficiency, as well as providing secondary benefits in farm revenues, food security and reduced land use needs (Cooper and Dobson 2007).

Conventional pesticides, however, often bring difficult trade-offs. For example, broad spectrum or non-selective pesticides can result in toxicity to non-target organisms which share characteristics with target species (Costa et al. 2008). Research has shown pesticides to contribute to population decline for both beneficial and pest insects (Ellis 2018; Dangles and Casas 2019), which has implications for biodiversity. Bees, for example are of particular concern due to their role as pollinators (Cooper and Dobson 2007). There is also evidence that pesticides are toxic to birds and mammals, including humans. Examples include links between exposure to neurotoxic insecticides and neurological diseases, including Parkinson's (Costa et al. 2008; Richardson et al. 2019), and between pesticides and chromosomal changes, immune system problems, endocrine dysfunction, and oxidative stress (Souza et al. 2020). Pesticides entering the wider environment through wind erosion, surface runoff and leaching can accumulate in waterways, harming aquatic ecosystems and increasing human exposure (Sánchez-Bayo 2012). The risk to humans is compounded by several factors: Conventional drinking water treatment does not always remove harmful levels of pesticides, mixtures of pesticides can have a compounding toxic effect (Souza et al. 2020), and residues of pesticides remain in food (Herrman 2010). While pesticides are important in preventing crop losses, their ramifications are driving research into less harmful alternatives such as biopesticides.

Biopesticides are naturally derived chemicals used in crop-protection (Leahy et al. 2014). They are typically more selective and less environmentally persistent than conventional synthetic pesticides, with some evidence to suggest little or no toxicity to birds or mammals (Sánchez-Bayo 2012; Gajger and Dar 2021), suggesting they could be a more environmentally benign alternative. While biopesticides are currently only 5% of the crop-protection market (Damalas and Koutroubas 2018), increased interest in Integrated Pest Management (IPM) and the development of cheaper, more eco-friendly products is driving uptake (Samada and Tambunan 2020) and biopesticide use is increasing internationally by around 10% per year (Gajger and Dar 2021).

Biopesticides are not without risk. Resistance has begun developing in target species of *Bacillus thuringiensis* (Bt), a strain of bacteria used in crop-protection and the most common biopesticide on the market (Jurat-Fuentes et al. 2021; Palma et al. 2014). Bt is also toxic to several orders of non-target invertebrates (Palma et al. 2014). In addition, evidence suggests that some species of herbivorous arthropods develop especially rapid resistance to pesticides as a result of cross-resistance from an evolutionary adaptation to plant allelochemicals. Consequentially, biopesticides based on allelochemicals present an elevated risk due to the similarity of their chemical structure, and pesticide resistance could even enable an expansion of arthropods' host plant range (Bras et al. 2022). While there is great potential for the development of future biopesticides, this variation in risk and the potential for cross-resistance means care must be taken to rigorously assess their outcomes on a case-by-case basis.

Allelochemicals, here defined as compounds released by an organism that have an inhibitory or stimulatory effect on neighbouring organisms, can be used as biopesticides. Plants and microorganisms such as bacteria, fungi and viruses produce or transform allelochemicals which effect a wide range of taxa including invertebrates (Macías et al. 2019). Allelopathy has been extensively studied with 3500 articles published between 2007 and 2018 (Macías et al. 2019). Allelochemicals are usually secondary metabolites, compounds not fundamental to reproduction or growth (Nawaz et al. 2020), but not always. For example, phytic acid, found in many plants to store phosphorous and energy, also has a secondary role in toxicity to lepidopteran species (Green et al. 2001).

Plant allelochemicals are released through foliar leachates, root exudates, volatilization of volatile organic compounds (VOCs), and the breakdown of plant tissue (Xie et al. 2021) and are involved in plant resistance to weeds, invertebrates and pathogens (Xie et al. 2021; Qasem 2013). Some allelochemicals have been shown to have multiple defence benefits and exhibit multi-kingdom functionality (Hickman et al. 2021). Herbivorous invertebrate pests are affected by allelochemicals through antibiosis (attraction of predators, mortality, fecundity and neurotoxicity) and antixenosis (antifeedants, repellents and oviposition deterrents) (Gajger and Dar 2021). Allelochemicals have a number of different purposes other than pest management including plant nutrition, plant-to-plant communication, resistance to abiotic stresses and the detoxification of heavy metal soil contamination (Jabran et al. 2013; Farooq et al. 2013). Allelopathic effects are dose dependent, but some also exhibit a hormetic dose–response, for which there is also evidence outside of just allelochemicals (Scavo and Mauromicale 2021). Hormesis describes a biphasic dose–response relationship, for example, where high concentrations of allelochemicals have been found to suppress plant growth while low concentrations of the same compound promote plant growth (Farooq et al. 2013).

Allelopathic plants can be implemented within IPM in many ways. Plant extracts, isolated allelochemicals and allelochemical analogues can be used in soil amendments, foliar sprays and seed treatments while physical plants can be used as companion plants to susceptible crops, in rotation as cover crops, intercropping, green manures or in dead-end trap crops (Scavo and Mauromicale 2021). Dead-end trap crops created by spraying host plant extracts onto non-host crops could have particularly low risk to non-target organisms because a pesticidal effect is created through the inability of a species to survive on non-host plants rather than direct toxicity. For example, diamondback moths were effectively controlled through the application of kale extracts onto broad beans, thereby using stimulatory chemical cues from their host plant as an attractant to an unsuitable alternative plant where they could not survive (Zhu et al. 2021).

Allelopathy research to date has predominantly focused on plant-to-plant interactions in laboratory conditions and evidence syntheses have mostly been in the form of reviews (Macías et al. 2019; Qasem 2013; Zhang et al. 2021). In order to facilitate implementation at the farm level, future research needs to study specific herbivorous pests and cropping systems (Damalas and Koutroubas 2018), with a focus on field-scale trials, and develop an evidence-based database of allelopathic plants and corresponding herbivorous pests as a simple directory for farmers (Damalas and Koutroubas 2018). Agronomic performance, the interaction of various allelopathic and agricultural methods and the influence of abiotic and biotic factors should be considered when testing under field conditions (Scavo and Mauromicale 2021).

The 3500 articles published between 2007 and 2018 (Macías et al. 2019) focused broadly on allelopathy and allelochemicals but it is unclear how many specifically targeted allelopathy for invertebrate pest control. With this potentially large body of research and many influencing variables it is necessary to describe current knowledge and collate evidence for future research, for which a systematic map would be appropriate. Systematic maps provide an overview of the quantity and breadth of research within a broad topic or question. This tool has been selected in favour of a meta-analysis or systematic review due to the wide scope of this topic, and the wide variety of possible interventions, outcomes and populations/species studied. Temperate climatic zones have been targeted because of the previously mentioned agricultural yield reductions predicted within these zones as a result of climate change. The definition of allelopathy accepted in this study is compounds released by an organism that have an inhibitory or stimulatory effect on neighbouring organisms. However, the focus here is solely on allelopathic plants and their inhibitory effects on invertebrate herbivorous agricultural pests of temperate Europe.

Stakeholder involvement

This study was developed as part of a scholarship from Certis Europe, a crop protection specialist company, who wanted to fund research into crop protection. The initial question was proposed by the first author and the project was developed through discussions with experts in pest management and agroecology, as well as Certis Europe.

Methods

Objectives of the review

The aim of this study was to systematically map and provide a database of the existing research concerning allelopathic plants and their inhibitory effects on invertebrate herbivorous agricultural pests of temperate Europe, including an overview of chemicals and methods of application. Relevant published research and included publications were recorded in a searchable database with three objectives. The first was to identify knowledge gaps and clusters to direct future primary and secondary research. The second was to inform an agricultural companion planting directory to facilitate farm level implementation of allelopathy for eco-friendly pest management. The third was to highlight allelochemicals with potential for the commercial synthesis of biopesticides.

The primary question was: How have allelopathic plants been used in IPM systems to control European crop pests in arable and field vegetable systems in temperate climates?

The secondary question was: Which methods of allelopathy application within IPM systems have been investigated?

Definition of the question components (PICO analysis)

Population: Temperate European invertebrate pests of the following crops: cereals (wheat, barley, triticale, oats, corn and rye), root crops (potatoes, sugar beet, onions, garlic, carrots, leeks), legumes (peas, beans, lentils, chickpeas, soya beans), and brassicas (white cabbage, cauliflower, broccoli, oilseed rape).

Intervention: Allelopathic plants or plant-derived allelochemicals.

Comparator: Different implementations of allelopathic plants within integrated pest management systems (e.g. companion cropping, intercropping, ploughing of residues into soils, artificial applications), or, an alternative allelopathic plant or no allelopathic plant.

Outcome: Must relate to the impact on the crop (e.g. growth, yield) or the pest (e.g. changes to fitness, reproduction, absolute numbers, mortality of pest species).

The methods used for this systematic map followed the framework for systematic maps set out in James et al. (2016) and Collaboration for Environmental Evidence (CEE) Guidelines (Pullin et al. 2022) and were registered on the PROCEED platform (Kiely and Randall 2022) before starting. ROSES reporting standards (Haddaway et al. 2018) were also adhered to and details can be found in Additional file 1.

The methods outlined below followed the pre-published a-priori protocol, with a few deviations (primarily to streamline the process). The changes from the original protocol can be found in Additional file 2.

Search strategy

The search for relevant literature was conducted using the following bibliographic databases:

1. Web of science all databases (https://webofknowledge.com) which includes:
   i. Web of science core collection (http://webofknowledge.com/WOS)
   ii. BIOSIS citation Index (http://webofknowledge.com/BCI)
   iii. CABI: CAB abstracts and global health (http://webofknowledge.com/CABI)
2. AGRIS, UN FAO (https://agris.fao.org/agris-search/index.do)

In addition, Google Scholar (https://scholar.google.co.uk/) was searched and the first 100 results exported. The search string used was as follows:

(allelopath* OR allelochemical* OR "secondary metabolite*" OR glucosinolate* OR isothiocyanate* OR phenol OR phenols OR phenolic OR alkaloid* OR terpenoid* OR benzoxazinoid*) AND (IPM OR "integrated pest management" OR "weed management" OR "pest management" OR "weed suppression" OR "pest suppression" OR "weed control" OR "crop protection" OR "plant resistance" OR biofumig* OR "insect repell?nt*") AND (arable OR "field vegetable*" OR Cereal* OR Wheat OR Barley OR triticale OR oat* OR rye OR "root crop*" OR potato* OR "sugar beet" OR onion OR garlic OR carrot* OR leek* OR corn OR maize OR brassica* OR legume* OR agricult* OR "agricultural pest*" OR "plant pest*" OR "insect pest*" OR "soil-borne pest*" OR "parasitic weed*" OR "dry peas" OR bean* OR lentil* OR chickpea* OR "soya bean*" OR "white cabbage" OR cauliflower OR broccoli OR "oilseed rape" OR "invertebrate pest*" OR nematode*).

A search for grey literature, defined as any research and information produced that is not controlled by commercial publishing, was conducted using the websites AHDB and Gov.uk. Instead of using the full search string, each intervention term was searched separately. No restrictions were placed on the searches regarding publication date, but the language was restricted to English. The results from all searches were exported into EPPI-Reviewer (Thomas et al. 2010). Metadata about each search, including date and number of results, can be found in Additional file 3: Sheets A and B.

Screening strategy

EPPI-Reviewer-web (Thomas et al. 2010) was used to remove duplicates by assessing each study with a calculated similarity score of 0.7 or greater. EPPI-Reviewer was subsequently used for screening in two stages: titles, then abstracts. If there was not enough information in the abstract to identify whether specific pests, host species or climatic conditions were relevant to the PICO terms, then full texts were examined to confirm inclusion/exclusion, but for consistency were not used for subsequent coding. The inclusion criteria were used to exclude irrelevant studies and is shown in Additional file 4. This was defined in the protocol and expanded during screening to ensure repeatability. The initial protocol and search string included weed pests in the PICO terms, however due to time constraints during screening, the population was restricted to exclude weeds and focus solely on invertebrate pests. CABI Compendium of Invasive Species (CABI 2022) was used to determine the relevance of pests while Plants of the World Online (POWO 2023) was used to find the distribution of plants. Where data was not available in these databases further internet searches were conducted to reach a decision. Screening was carried out by one reviewer with consistency checking by a second reviewer using a random subset of 5% of articles at each stage. A Cohen's Kappa value of 0.6 or greater was used to indicate agreement.

Consistency checks of the title screening initially failed to pass the Kappa threshold. The inclusion criteria were reviewed and clarified, and a second subset of 100 titles (2% of all papers) then passed consistency checking. Following a change to the inclusion criteria at the abstract screening stage (removal of weed pests from included populations), Kappa also passed the threshold for agreement. A detailed account of screening decisions, and consistency checking, can be found in Additional file 3: Sheets C and D.

Critical appraisal

The intention of this systematic map was to describe the breadth of allelopathy research, not to examine the validity of their conclusions, as such, critical appraisals were not conducted, as recommended by the Collaboration for Environmental Evidence (Pullin et al. 2022).

Meta-data extraction and coding strategy

Included studies were coded by one reviewer at abstract according to the prescribed coding criteria in Additional file 5: Sheet A and the searchable database can be found in Sheet B. Bibliographic information was recorded for all included studies, and details were coded regarding the study background and components. Farm details and soil type were coded when appropriate to evaluate if studies had considered the interaction of abiotic factors. Coding decisions not defined by the tool can be found in Additional file 3: Sheet E.

Studies were coded in the database with a separate line for each combination of key variables, pests, interventions (allelopathic plants or compounds) and applications. For example, where one study had conducted experiments concerning two pests, three allelopathic plants and one application method, this was coded across six lines as separate experiments (or datapoints). Where interventions were implemented in combination, including analysis of plant allelochemical profiles, these were assigned one line containing all variables because the effect of each intervention cannot be separated out.

CIS, PoWO, PubChem (Kim et al. 2021) and other internet searches were conducted to complete scientific classifications, chemical information and journals' publication countries. Other missing information was coded as "Not specified", because the timeframe did not allow for contacting authors for information nor for coding to full text. Codes that did not apply were assigned "NA". When multiple pests or plants were studied where some were relevant and others were not, only the relevant species were coded. All scientific classifications were coded to the highest level of detail provided in the abstract, for example, if the allelopathic plant was referred to only as "brassicas" this would be the only scientific classification given.

Coding consistency was checked by a second reviewer using a random subset of 5% of included studies and any inconsistencies corrected.

Synthesis

An excel workbook was used to apply the coding and create the searchable database describing the scope of the research. This was used to generate simple descriptive statistics, graphs and more complex cross-tabulations of key variables. The heatmaps were produced using excel pivot tables with conditional formatting to visually represent knowledge gaps and clusters. The database can be searched and filtered according to any variable and is found in Additional file 5.

Results

Review process

The literature search of bibliographic databases returned 5550 articles. These, along with the first 100 results from the Google Scholar search, were exported into EPPI-Reviewer for screening. The search for grey literature returned no relevant studies, possibly due to the specificity of websites searched. Of the 5550 articles found 170 were duplicates and three could not be exported, leaving 5477 for screening. Title screening removed 3418 articles, leaving 2059 to be screened at abstract. While the initial protocol and search string included weed pests in the PICO terms, as well as invertebrate pests, time constraints during screening necessitated a reduction in the number of studies to be screened. It was therefore decided at the abstract screening stage to further narrow the inclusion criteria to focus on invertebrate pests only, thereby excluding studies which only examined weed pests. Abstract screening removed 1779 articles, 60% of which (1062) were removed as a direct result of this decision to restrict the inclusion criteria and exclude weed pests. Subsequently, 229 articles were directly accepted in the study from abstract screening while 51 articles required further examination and were screened at full text. Of those with accessible full texts 15 (48%) were excluded because the study climate was not relevant, and

13 (42%) were included in the review. Additional file 6 contains a list of all full texts exclusions with reasons for exclusion as well as a list of studies with unobtainable full texts. One article contained two relevant studies with separate abstracts and were included separately, resulting in 243 studies included in the map. The screening process is described in detail in Fig. 1.

Bibliographic information

The majority of the 243 studies (98%) were Journal articles, while three studies were either dissertations or dissertation chapters and one was from conference proceedings. Studies were published in a total of 98 journals (the distribution of these can be seen in Additional file 5:

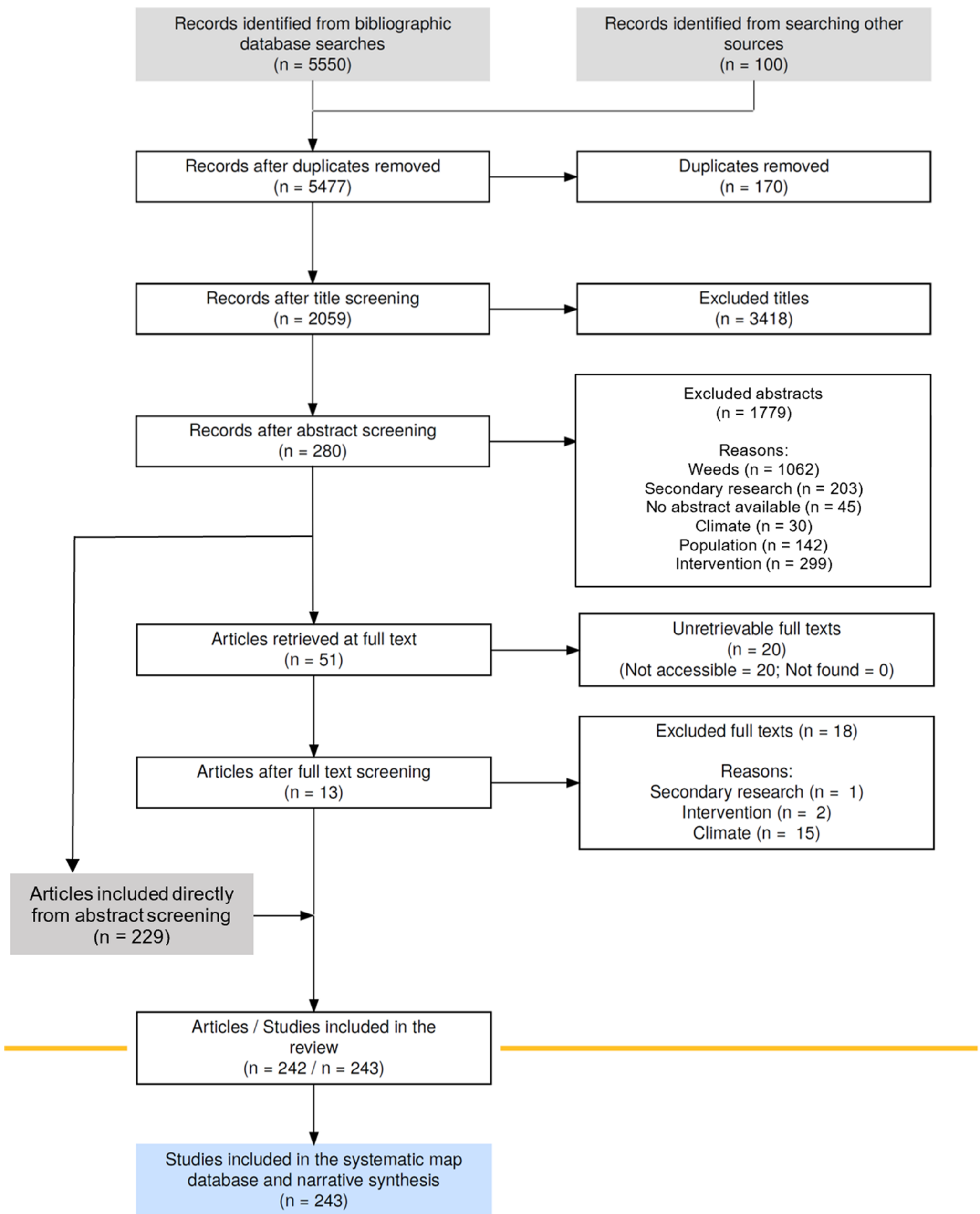

Fig. 1 ROSES flow chart detailing the quantity of studies at each stage of the screening process. Created in accordance with ROSES Reporting Standards for Systematic Evidence Synthesis (Haddaway et al. 2018). 'Records identified from searching other sources' refers to the search conducted using google scholar which was not included within the primary searches because it is not a bibliographic database. The search for grey literature using AHDB and Gov.uk returned no relevant studies

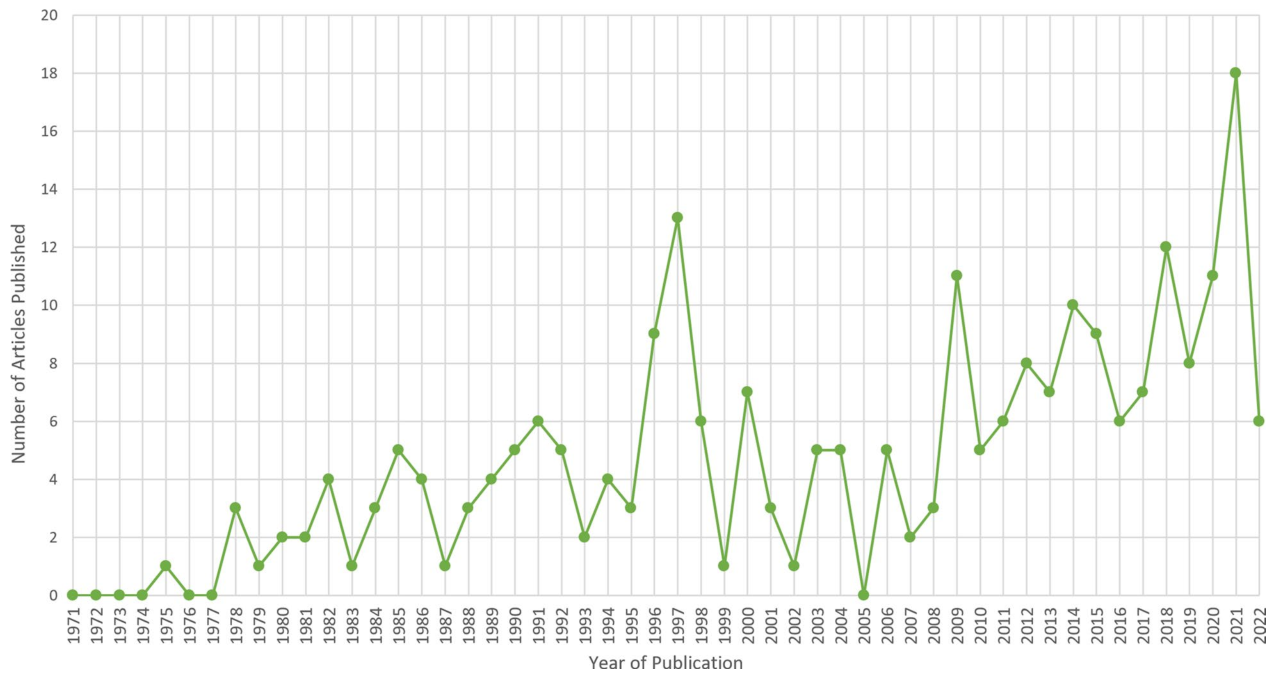

Fig. 2 Chronological distribution of included studies

Sheet G). Just 10% of studies referred to allelopathy by name in either the title or abstract.

Figure 2 shows the chronological distribution of studies. The earliest study was published in 1975 and the general trend has been increasing publications year-on-year, a spike in 1997, and much variability. The availability of digital records may bias publications pre 1990s but the trend still holds thereafter. Less than 5% of studies mentioned the country of origin in their abstracts. With many international journals little can be elucidated through examination of the publication countries.

Study context

The 243 studies in the map produced 717 datapoints and all subsequent synthesis concerns these disaggregated studies, referred to as experiments.

The majority of experiments (69%) were conducted in laboratories while study type was unclear for a further 15%. Figure 3 shows the full breakdown of study type, including the minority of experiments conducted in glasshouses (5%). Just 10% of experiments were under field conditions, but none described details of the study background such as soil classification, local climate or farm inputs, and only 24% mentioned the country of origin. Nine other experiments (1%) specified the soil classification.

45% of experiments tested extracted allelochemicals, 35% used a physical plant (including in the form of macerated leaves or seed meal) and 16% tested plant extracts (e.g. essential oils or root exudates). An additional 28 experiments (4%) tested physical allelopathic plants in combination with extracts. Figure 4 shows the distribution of study types for these interventions. Plant extracts and extracted allelochemicals were mostly tested in the laboratory (83%), while 43% of physical plant experiments were implemented in laboratories and 21% in the field. However, the study type for physical plants was unclear in 29% of experiments.

The intervention was applied to crops in 14% of experiments, with potatoes, soybean and maize the most commonly tested (25%, 14% and 13% respectively). Some experiments (6%) did not specify the species of crop tested while others gave broader taxa information such as 'legumes' or 'beans'. This does not include experiments where crops were the source of allelopathy, for example, where cultivars of a crop were tested for resistance.

Organisms and taxonomic distribution

In total, 102 species of pests were studied from 14 orders and three phyla (84 arthropods, 15 nematodes and three molluscs). Figure 5 shows the distribution of studies among pest orders and the number of species from each order. Lepidoptera were the most frequently studied order and the most species were from Coleoptera. 44% of species were studied only once or twice while the two most studied species, *Meloidogyne incognita* and *Frankliniella occidentalis* were studied 51 and 46 times respectively. 25 experiments (3%) did not specify pest species

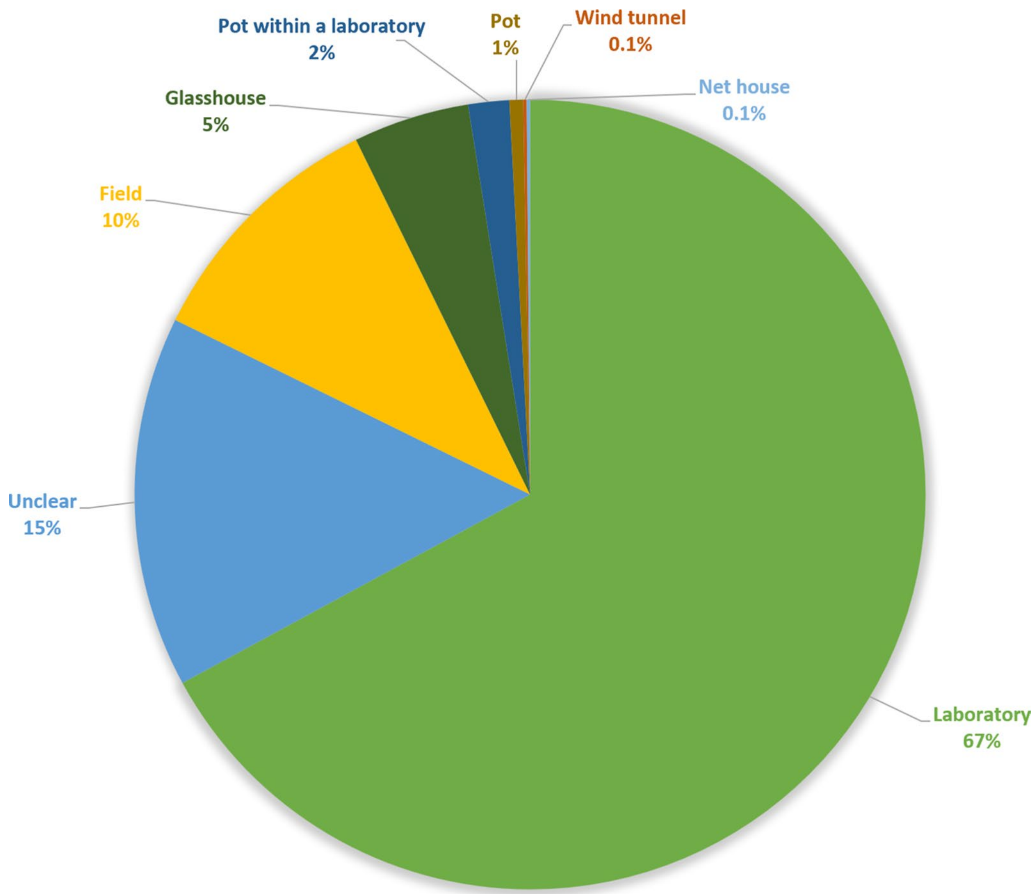

Fig. 3 Distribution of experimental conditions of included studies. Experimental conditions were categorised according to authors description in the abstracts of studies included in the systematic map. Where bioassays were mentioned the conditions were assumed to be laboratory

in their abstracts but were determined to be relevant through full text screening. In addition 4% of experiments tested the effect on non-target organisms including beneficial nematodes, earth worms, mice, parasitoids and natural predators of invertebrate pests like ladybirds.

Allelopathic plant species were coded to the highest level of detail provided in the abstract, so some include the subspecies or variant and subsequent data relates to this level of detail. 184 plant species were identified as either the physical plant intervention or as the source of extracts. 14 experiments did not specify the plant and 27% of experiments used allelochemicals with no defined origin, coded 'NA'. Most plants (72% of species) were studied no more than twice while the most common species, *Brassica juncea* and *B. Napus*, were studied 28 and 19 times respectively. Figure 6 shows the distribution of studies among plant families and the number of species from each family. Brassicas were studied significantly more than other families (25% of experiments) and accounted for 34% of species.

Where the intervention was 'extracted allelochemicals', 198 distinct compounds or blends of compounds were identified, belonging to 99 chemical groups. Flavonoids and glucosinolates were the most common, with 23 and 19 experiments respectively. Experimental frequency was evenly distributed among chemicals with the majority of chemicals (98%) appearing in fewer than five experiments. Ally isothiocyanate was the most studied allelochemical but only occurred in eight experiments and 15% of experiments did not specify the chemical used. A full list of pests, plants and chemicals studied, as well as their experimental frequencies can be found in Additional file 7: Sheet A.

Application methods

Application methods were categorized according to authors stated method. Where the abstract had not stated an application method, the following definitions were used to code applications from detail provided in the abstract:

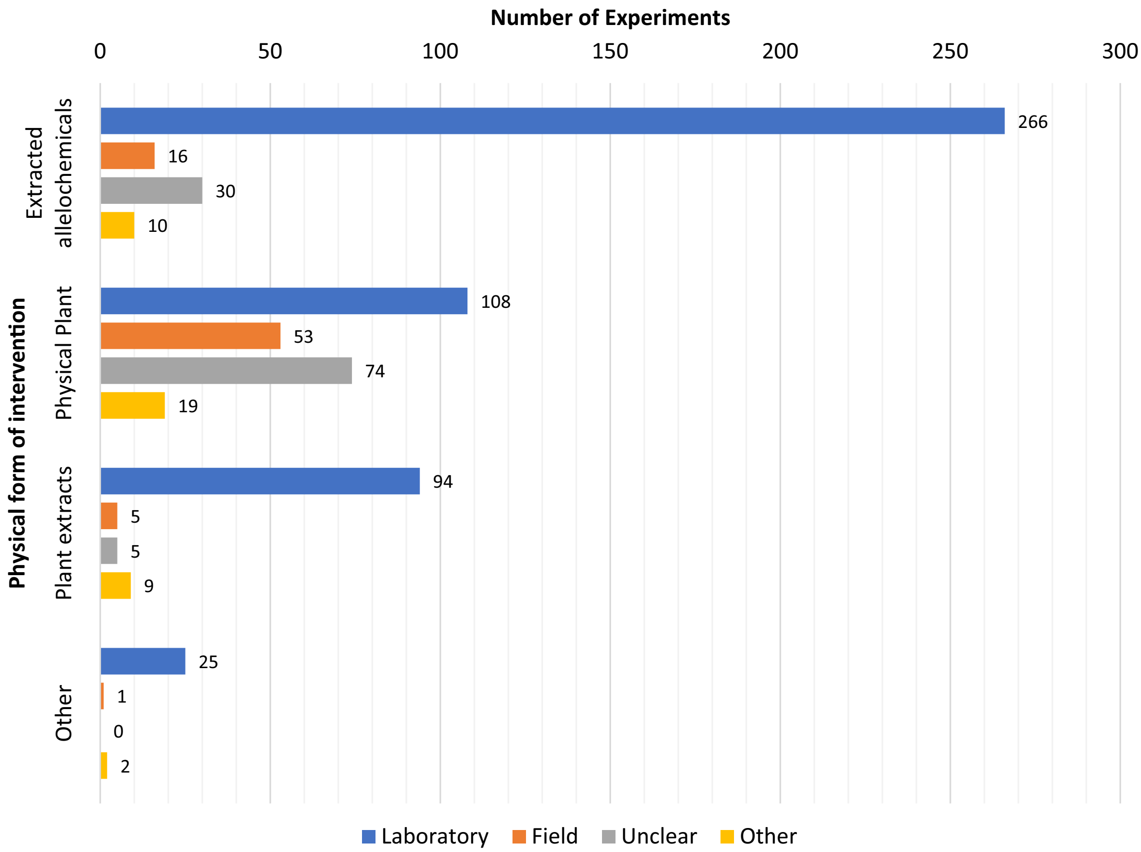

Fig. 4 Number of experiments included in the map in terms of intervention form and experimental conditions. The physical form of intervention is the format in which allelopathy has been implemented in the experiment, coded in the database as either extracted allelochemicals, plant extracts or physical living plants. "Other" intervention forms refers to experiments where physical plants were tested in combination with plant extracts and/or extracted allelochemicals. The data is disaggregated by the experimental conditions

- Green manure: Cover crops incorporated into soil at the end of the growth period
- Soil amendment: Any addition to soil to improve crop health
- Biofumigation: Macerated fresh plant material incorporated into soil
- Diet: Fresh plant material fed to pests
- Artificial pest diet: Extracts applied to pests' diet or fed directly to pests
- Not specified: Where insufficient detail existed to make a judgement

Figure 7 shows the distribution of the 26 identified application methods disaggregated by intervention form. Extracted allelochemicals were predominantly applied in artificial pest diets (18%), bioassays (16%) and foliar sprays (13%), while the majority of allelopathic plant experiments studied resistance (57%), biofumigation (8%) and soil amendments (7%). Resistance studies tested the allelochemical concentrations or profiles of a species of plant with varying levels of resistance to a pest and accounted for 21% all experiments. The application method was not specified in 161 experiments (22%) suggesting it was not a key comparator. Nearly half of all field studies (43%) where the application method was identified studied resistance, followed by biofumigation (13%), baited traps and green manures (11% each). The comparator in 1% of experiments was alternative application methods, half of which compared intervention forms, the other half compared timing and depth of incorporation for soil amendments and green manures.

Knowledge gaps and clusters

A heatmap of all plant and pest species can be found in Additional file 7: Sheet B, depicting mostly evidence gaps, and therefore highlighting numerous areas for future primary research. The average number of experiments per pest-plant pair was calculated to be 1.7 (rounded to two) and a focused heatmap was then created of species with greater than average experimental frequencies, shown in Fig. 8, to highlight potential clusters. This heatmap covers 29% of all experiments and included 34 plant and 28

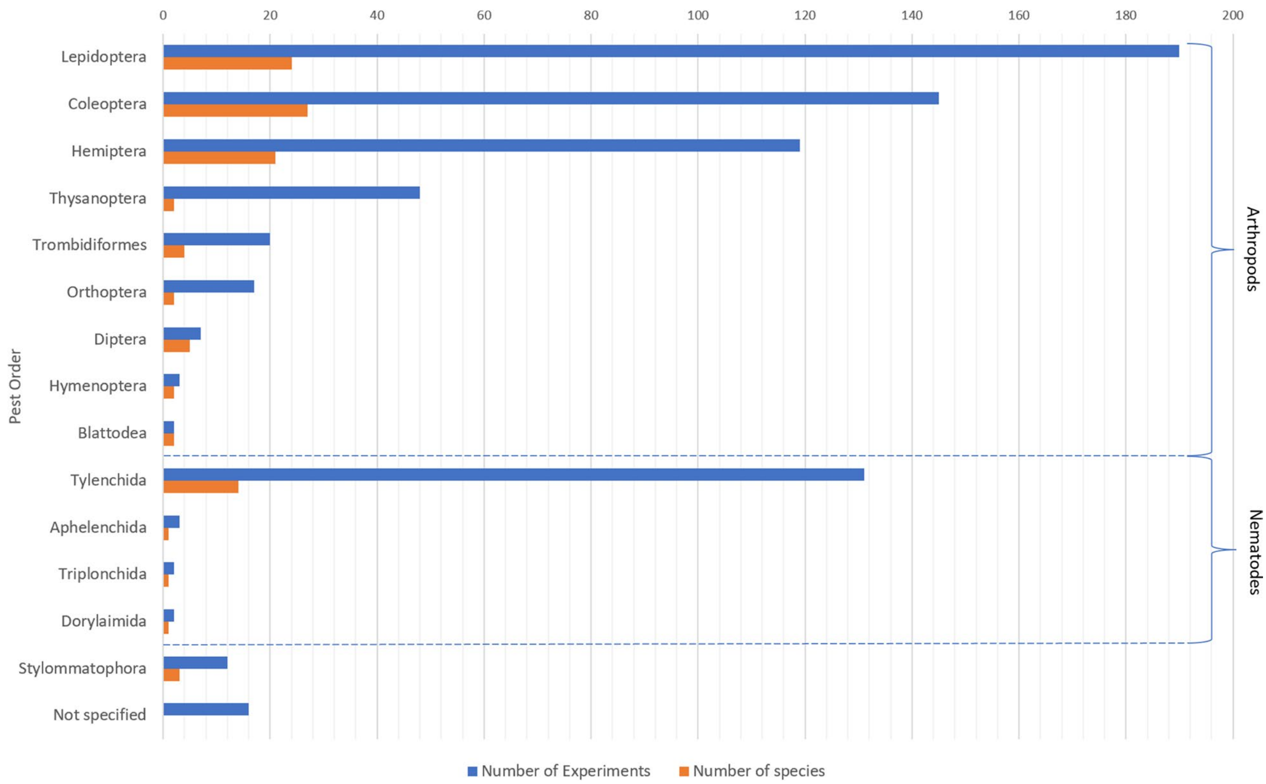

Fig. 5 Number of experiments included in the map in terms of pest order. The number of unique species studied within an order is also included to show the breadth and depth or research relating to each order of pest

pest species. Even this focused heatmap contained more evidence gaps than clusters and only four pest-plant pairs appeared in more than six experiments:

- *Globodera pallida* & *Brassica juncea*—7
- *Schistocerca gregaria* & *Cichorium intybus*—7
- *Sitobion avenae* & *Triticum aestivum*—7
- *Popillia japonica* & *Malus genus*—8

The quantity of studies for these pairs may not be sufficient to conduct secondary research, particularly as these figures refer to experimental frequency rather than study frequency, so the number of studies could be significantly lower. Consequently these pairs cannot be identified as true clusters, so further heatmaps were developed using higher taxonomic rank.

Pest orders and plant families were cross-tabulated to produce the heatmap shown in Fig. 9, again depicting more evidence gaps than clusters, even at this reduced resolution. It is worth noting that allelopathic affects can differ greatly, even between closely related species (Gabrys and Tjallingii 2002), therefore it is difficult to generalise from these higher taxonomic rank heatmaps. However, four main evidence clusters were identified containing enough experiments to be a potential topic of secondary research:

- Brassicas & Tylenchida—61
- Brassicas & Lepidoptera—58
- Brassicas & Coleoptera—41
- Poaceae & Hemiptera—48

A separate heatmap of species within each of these four clusters can be found in Additional file 7: Sheet C.

The control of some orders of pests has been studied under a broad range of allelopathy application methods, illustrated by the heatmap in Fig. 10. Allelopathy was applied in the control of Coleoptera using 14 methods, Lepidoptera and Tylenchida with ten, and Hemiptera with nine, however most orders of pests have been studied under fewer than six application methods. Evidence clusters were identified containing enough experiments to be a potential topic of secondary research:

- Lepidoptera & Artificial pest diet—31
- Lepidoptera & Foliar spray—27
- Lepidoptera & Resistance—56
- Coleoptera & Resistance—21

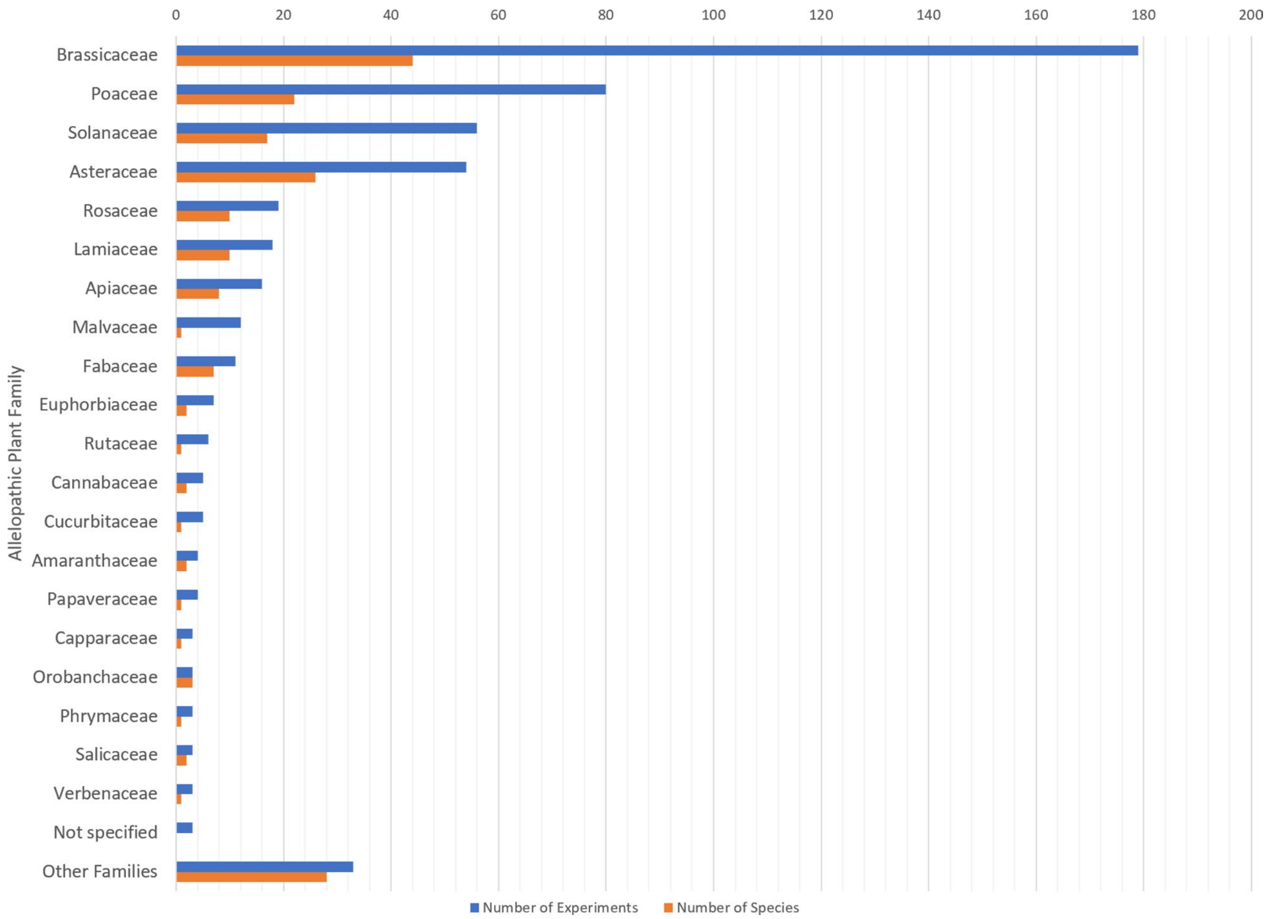

Fig. 6 Number of experiments included in the map in terms of allelopathic plant family. The number of unique species studied within an order is also included to show the breadth and depth or research relating to each order of allelopathic plant

- Coleoptera & Bioassay—31
- Hemiptera & Resistance—39
- Thysanoptera & Olfactometer assay—25
- Tylenchida & Soil amendment—20

Discussion

The focus of this study was to produce a systematic map and corresponding database documenting the current state of plant allelopathy research in temperate agriculture for invertebrate pest management. This map showed that while allelopathy itself may have been extensively studied there are relatively few papers concerning its direct application in IPM in temperate agriculture. 5550 results were returned by this study's search string and another study found 3500 allelopathy papers published between 2007 and 2008 (Macías et al. 2019), yet just 242 were included in the final map. The main reason for excluding papers returned by this study's search string was because the population, intervention or application was not relevant to this study's aims. The 242 experiments in the final map mainly studied extracted allelochemicals in the laboratory, and were generally not tested on crops or in IPM systems. Experiments are also unevenly distributed among all key variables: pests, plants, allelochemicals and application methods. The number of yearly publications is increasing, but experiments under natural conditions remain infrequent, accounting for only 10% of experiments included in this study's database.

Field studies are crucial to ascertain the true effectiveness of an allelopathic intervention because laboratory results often do not translate into the field (STURZ A v. 2006; Tacoli et al. 2018 Sep) due to the influence of abiotic factors, the interaction of other chemicals and the dispersion and degradation of compounds (Scavo and Mauromicale 2021; Lord et al. 2011; Koschier et al. 2017). Studies suggest that factors like diurnal and seasonal temperature fluctuations (Himanen et al. 2015; Stamp and Yang 1996), atmospheric $C0_2$ concentration (Gou et al. 2022), and field cropping history (Menges 1988) all affect allelopathy. Few experiments in the map conducted field studies, and those that did examined plants'

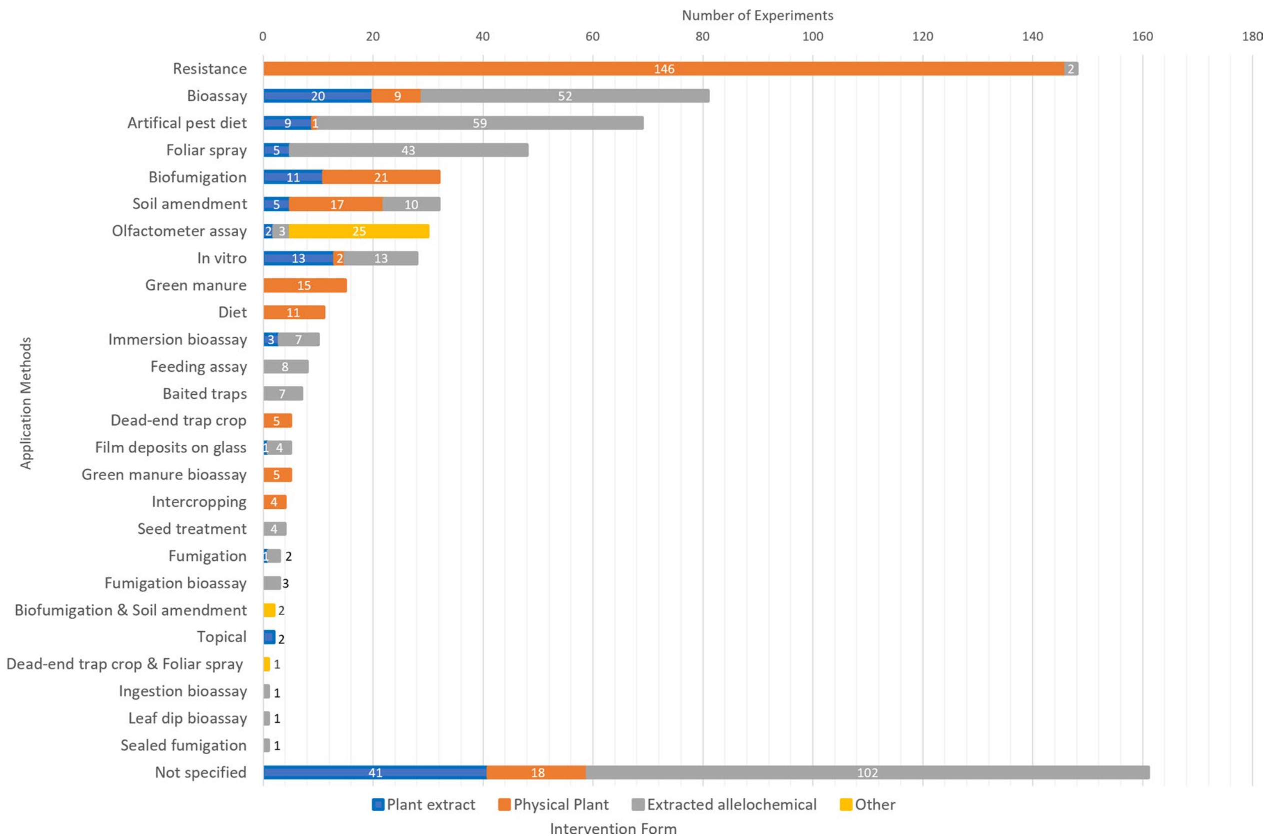

Fig. 7 Distribution of studied allelopathy application methods disaggregated by intervention form. Intervention Form refers to the physical format in which allelopathy has been implemented in the experiment, coded in the database as either extracted allelochemicals, plant extracts or physical living plants. "Other" intervention forms refer to experiments where physical plants were tested in combination with plant extracts and/or extracted allelochemicals

allelochemical profiles in relation to their resistance to pests. While this has potential in the application of breeding programs, breeding allelopathic resistance may not be possible for all plants and has potential trade-offs. Evidence suggests that plants prioritise defence traits to the detriment of growth, and vice versa, which is known as the growth-defence or defence-fitness trade-off, and has profound implications for agricultural yields (Huot et al. 2014; Herms and Mattson 1992). Alternative applications of allelopathy could avoid this trade-off while providing secondary benefits, for example, intercropping cash crops with allelopathic plants for IPM can improve resilience and provide a second revenue source (Alcon et al. 2020; Huang et al. 2015). Resistance studies also do not directly answer the question as to whether allelopathy is effective in the control of specific pests in IPM systems. Other field applications were biofumigation (13%), baited traps (11%) and green manures (11%) but only 1% of all experiments compared application methods and data was incomplete for 22%. This shows that application methods have not been considered to be a key variable in allelopathic effectiveness despite it significantly affecting the outcome (Zhang et al. 2021).

The map contains 184 allelopathic plant species with Brassicas, particularly *Brassica juncea* and *B. Napus*, studied most, and 102 pest species, with Lepidoptera and Coleoptera studied most frequently. However most pest and plant species appeared in fewer than half a dozen experiments and the average number of experiments for each pest-plant pair was less than two. While *Meloidogyne incognita* (Root-knot nematode) and *Frankliniella occidentalis* (Western flower thrips) were extensively studied, some other major temperate European pests of the focus crops do not appear in the database:

- *Ceutorhynchus pallidactylus* (cabbage stem weevil), *Contarinia nasturtii* (Swede midge) and *Autographa gamma* (Silver Y moth)—Brassica pests (EIP-AGRI Focus Group IPM for Brassica 2016)

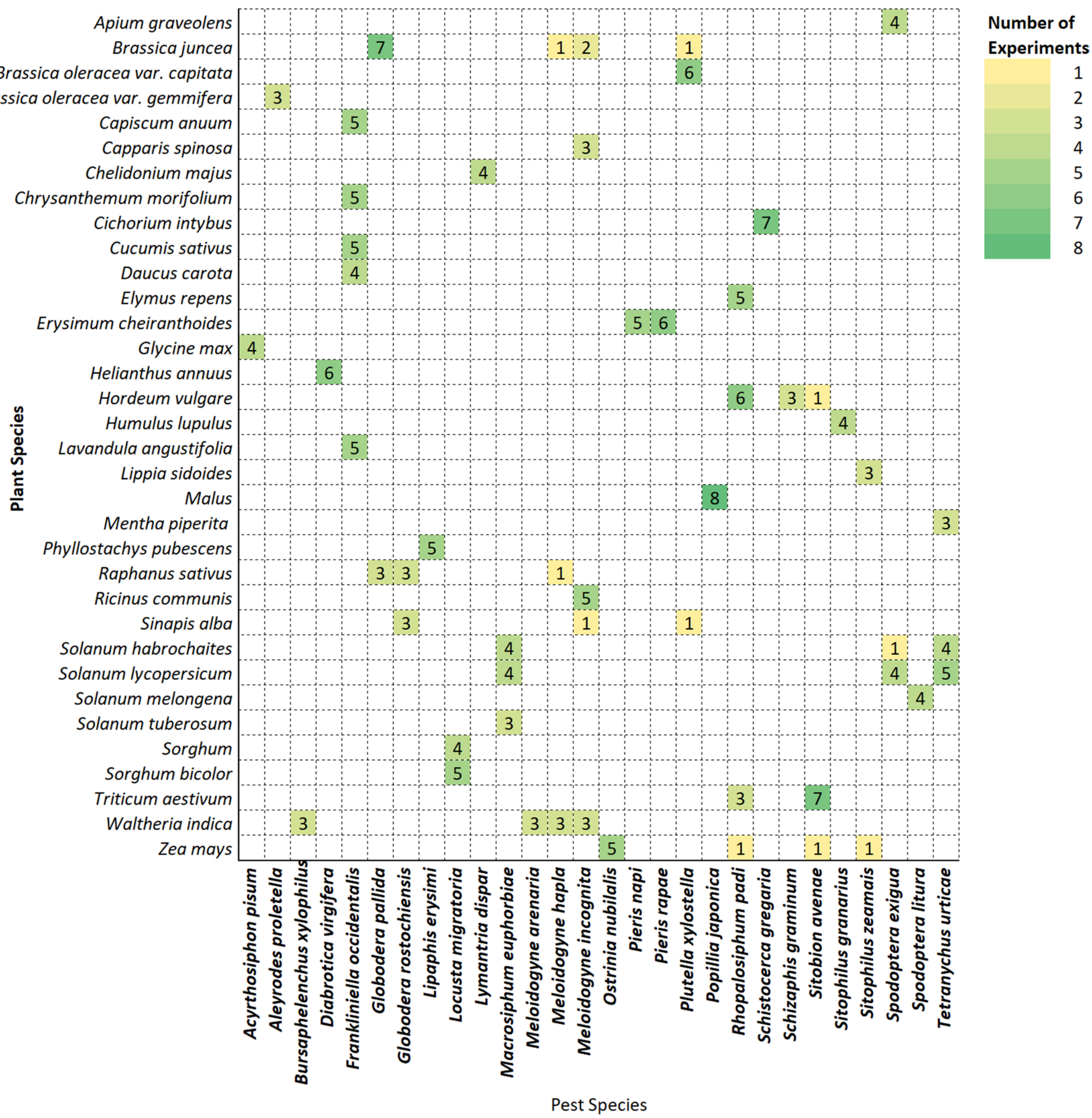

Fig. 8 Heatmap of pest and allelopathic plant pairs with above average experimental frequencies. The average number of experiments per pest-plant pair was calculated to be 1.7. "Above average experimental frequency" was defined as any pest-plant pair with 2 or more experiments, which were selected to create this focused heatmap

- *Metopolophium dirhodum* (Rose-grass aphid) and Elateridae larva (Wireworms)—Cereal pest (Tomanović et al. 2022; Bažok et al. 2018)
- *Maruca vitrata* (Spotted pod borer), *Bruchus pisorum* (Pea weevil) and *Mylabris* spp (Blister beetles)—Legume pests (Sharma et al. 2010)
- *Phytomyza gymnostoma* (Allium leaf miner), *Agrotis ipsilon* (Black cutworm), *Psila rosae* (Carrot fly) and *Delia antiqua* (onion maggot)—Root crop and Allium pests (Bažok et al. 2018; Collier 2016; Laznik et al. 2012)

It is unclear why these pests have not been studied in relation to allelopathy, or why some pests and plants have been extensively studied while others significantly less so, but it may be due to a variety of reasons including funding priorities, the economic impact of specific pests or the relative ease of building upon existing work. We

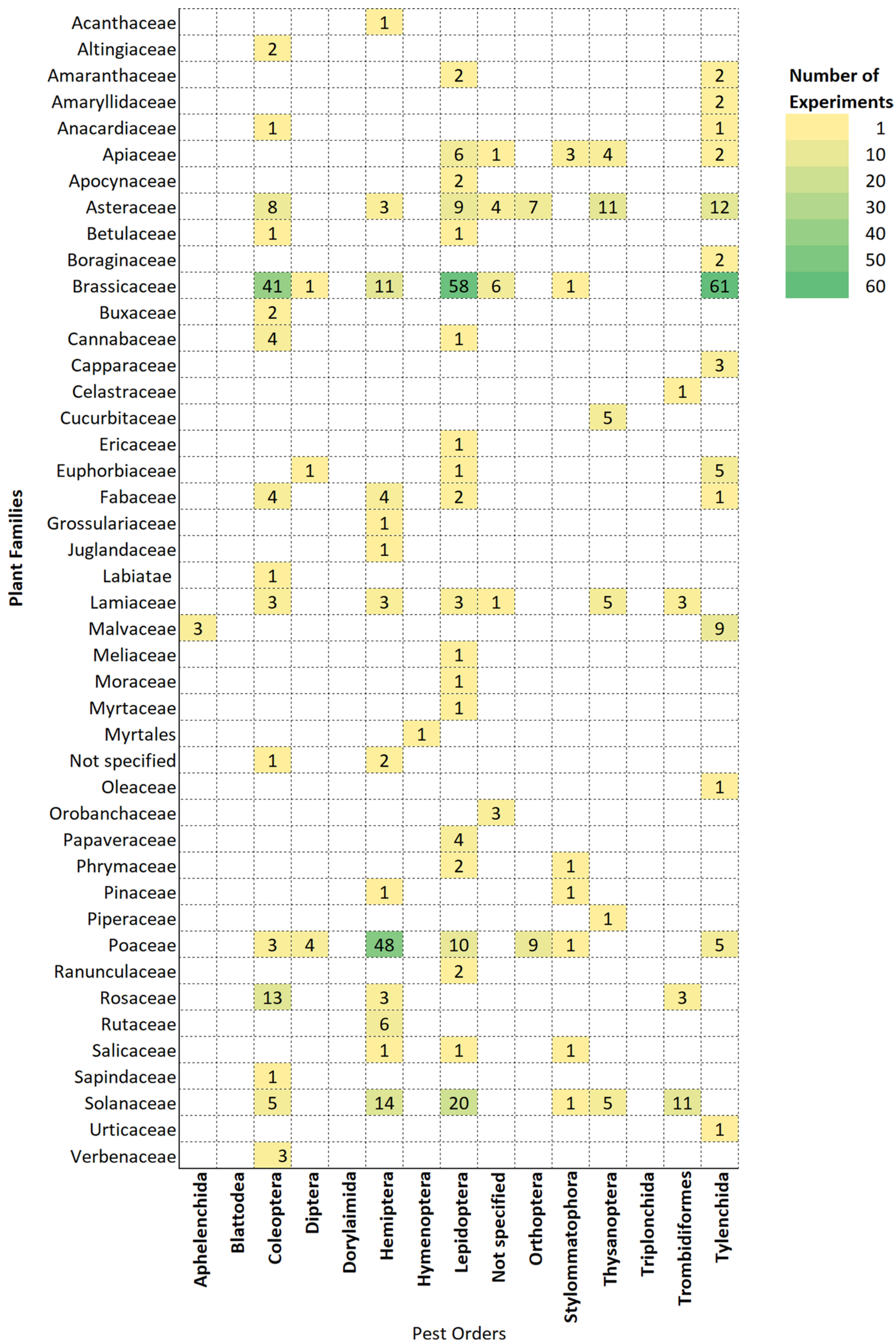

Fig. 9 Heatmap of experimental frequencies for pest orders in relation to plant families

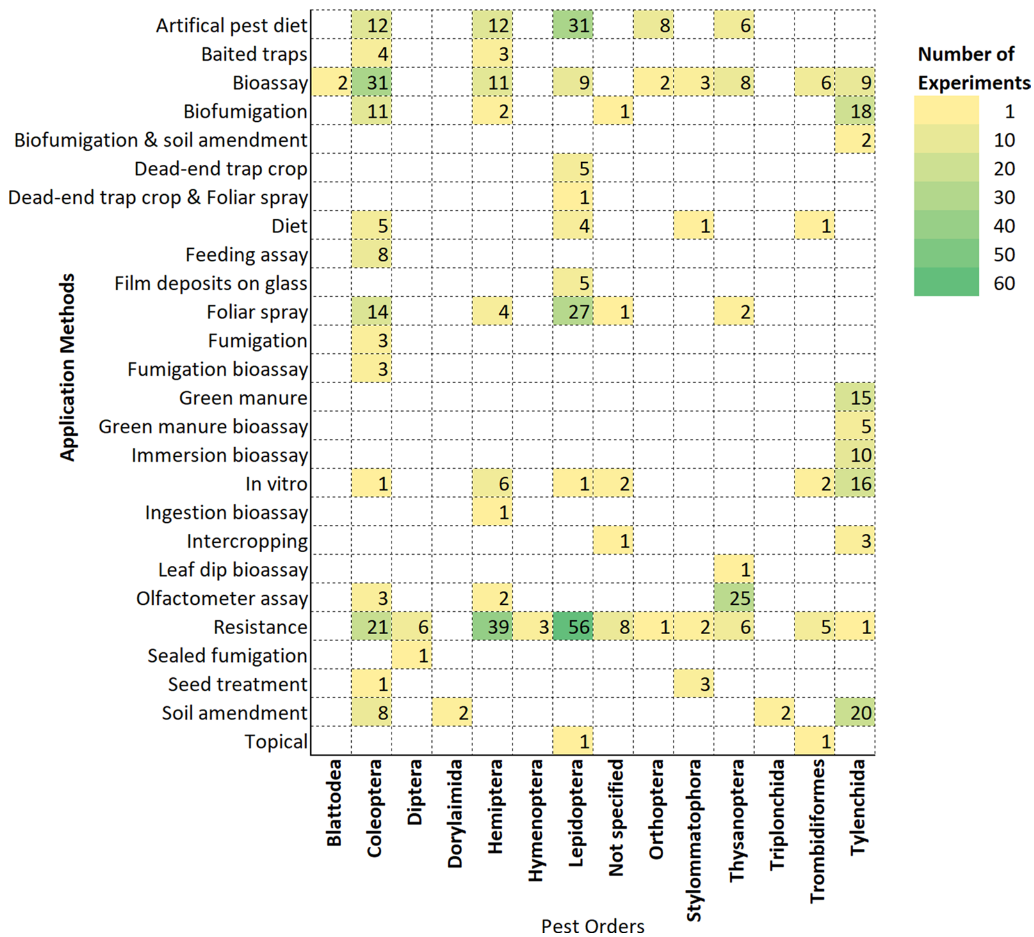

Fig. 10 Heatmap of Experimental frequencies for allelopathy application methods in relation to pest orders. Application methods were categorised according to authors own descriptions in the abstracts of included studies

recommend further relevant research into these important pest species, as responses can vary even between closely related species. Sinigrin, for example, is stimulatory to some species of aphids and inhibitory to others (Gabrys and Tjallingii 2002). Furthermore, studies rarely examined effects on non-target organisms, although this was not explicitly searched for. There is some evidence for low toxicity of allelochemicals to humans, notably: pyrethroids, neonicotinoids, avermectins, Spinosad (Sánchez-Bayo 2012), monoterpenoids, limonoids (Gajger and Dar 2021), and isothiocyanates (Trott et al. 2012). However, the vast majority of allelochemicals remain untested, the effects of chronic exposure remain unknown (Trott et al. 2012) and impacts to beneficial invertebrates are polarised. For example, parasitoids can be harmed by some allelochemicals and attracted by others (Reitz and Trumble 2003; Roy and Barik 2014) which highlights the importance of including beneficial non-target organisms in experiments.

Limitations of the map and evidence base

Due to logistic and time constraints, only two academic databases were used in the search strategy; AGRIS and Web of Science. While this is the minimum according to CEE guidelines, this may have affected our results because relevant articles may have been missed and future systematic maps would benefit from a diverse project team from a range of institutions providing access to all the relevant bibliographic sources. In addition, less than 1% of the search results from Google Scholar were exported for screening grey literature. Nevertheless, the WoS Platform is an extensive database covering nearly 200 million records (Clarivate 2022).

The search string contained a broadly defined population, initially designed to encompass any and all relevant pests, however, this necessitated a great deal of research during screening to confirm relevant pests, such as consulting CABI Invasive Species Compendium (CABI 2022) to determine geographic distribution and crops affected.

The repeatability of the map is therefore more limited than had relevant pests been predetermined and defined in the search string. This is demonstrated by the inadvertent exclusion of *Myzus persicae*, despite it being a major pest of several crops defined in the population, which has created an artificial gap in the database. Additionally, 'resistance' was the only application method named in the search string which may have biased results.

The search string also defined the intervention using 'allelopathy' and related terms, as well as allelochemical groups, however the database revealed that 90% of the included papers did not mention allelopathy in the title or abstract. Allelopathy may have been picked up through subject or key word search, or this may suggest that most papers appeared in the search results through mention of allelochemical groups which was not an exhaustive list and may have biased results. It also highlights a limitation of the evidence base: the lack of consensus surrounding the definition of allelopathy. When the term was originally coined in 1937, allelopathy referred only to inhibitory plant-to-plant interactions (Molisch et al. 1938). The definition was later expanded to include all chemically mediated interactions between plants, invertebrates and microorganisms, however some scientists have returned to the original definition (Willis 2007). The expanded definition has been used in this study, but the focus is solely allelopathic plants and their inhibitory effects on herbivorous invertebrate.

Screening was conducted by a single reviewer, which can result in 8% of relevant papers being missed (Edwards et al. 2002) however this risk was mitigated by a second reviewer carrying out a kappa analysis for consistency checking. The inclusion criteria excluded any paper not conducted in temperate climates but did not make an allowance for studies conducted in controlled environments such as laboratories where the effect of local climate is negated. Allelochemical analogues were also excluded to focus only on plant sources. Both decisions may have removed eligible studies. Furthermore, time constraints prohibited the screening of review papers, which could be a valuable source of additional studies.

Coding from abstract reduced the amount of useful data extracted from each study such as geographic location, detailed application methods, farm information and experimental design, which could have better informed future systematic reviews. Furthermore, the value of the chemical information may be limited as there may be alternative names and/or classifications used by different study authors for some chemicals which were not standardized during coding. These limitations in coding prevent this study from fully addressing its third objective; to highlight allelochemicals with potential for the commercial synthesis of biopesticides. However, the heatmaps highlight evidence clusters of experiments relating to allelochemical compounds for which secondary research may be possible—a first step towards fulfilling this objective.

The absence of critical appraisal limits the conclusions that can be drawn from the map, and its use as a companion planting database. Although this is accepted procedure for systematic maps (Pullin et al. 2022) the robustness and quality of included studies is unknown and therefore the success of interventions is not discussed. Despite the limitations resulting from a lack of critical appraisal this study does address its second objective—to inform an agricultural companion planting directory—as it provides an initial database upon which future research can build.

Conclusion

This systematic map provides the first database of research pertaining to the application of allelopathy in IPM for the control of invertebrate pests in temperate Europe. The map is up-to-date to July 2022 and can be updated following the methods set out in the protocol. Critical analysis of the included studies was not carried out and as such, no indication is given of the reliability of study conclusions. Therefore the map cannot provide information on the effectiveness of allelopathy as a pest management intervention but describes the evidence base, providing direction for future primary and secondary research.

Overall, the map highlights gaps in the evidence base across all key variables and a distinct lack of field studies or of studies comparing application methods. Plants' resistance to invertebrates was the main focus of field studies which is useful in directing crop breeding programmes, however breeding allelopathic resistance may not be possible for all species and can cause trade-offs in yield. Studies testing the allelopathic effects of brassicaceous plants are numerous but other plant families are yet to be investigated to the same extent. Reasons for this are unclear but may relate to funding priorities or the relative ease of building upon existing work. All of which provides a great deal of topics for future primary research.

Implications for future research

This systematic map has identified field experiments and application methods as the priority gaps in the evidence base, as well as the application of physical living allelopathic plants for IPM. Future studies should test allelopathy in IPM under a wide variety of environmental, management and agricultural conditions. In addition, future research should focus on major pests of key crops, which constitute gaps in the evidence base. Researchers should not assume that research on related species is applicable in these cases due to the variation in response from closely related species. While there are insufficient studies for most variables to facilitate secondary research, a few pest orders and plant families were identified for which syntheses may be possible. Systematic reviews and/or meta-analyses may be possible in answering whether Brassicas are effective in the management of Tylenchida, Lepidoptera and Coleoptera, or Poaceae in the management of Hemiptera, although, again it may be difficult to draw conclusions due to the differing response of closely related species.

To improve upon this map, future evidence syntheses should use a search string containing a predetermined list of relevant pest species and all possible application methods. This should reduce the bias towards resistance studies, increase the repeatability and reduce the possibility of inadvertently excluding relevant pests. Additionally, studies should be coded to full text and critical appraisal should be conducted with a view to creating a companion planting database.

Implications for research funding, policy and management

The body of evidence in the database is insufficient to guide policy or management decisions but does provide a research tool. It can be used to collate research on specific pests, plants, chemicals and application methods or to cross-tabulate a variety of variables. Stakeholders who are interested in the topic should examine the full texts of the studies included in the database to evaluate their validity, as no critical appraisal has been conducted. Further development of the database to include critical appraisal would enable its use as a companion planting database for the implementation of allelopathic plants in IPM by farmers. The database, in the form of an excel workbook, can be searched and filtered according to any variable and is found in Additional file 5, along with a data dictionary in sheet A.

Current research appears to be biased towards extracted allelochemicals and laboratory experiments, possibly indicating prioritized funding from agrichemical companies looking to produce biopesticides, which suggests the need for greater funding for the application of allelopathic plants in field trials.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-023-00183-1.

Additional file 1: ROSES for Systematic Map Reports. The completed ROSES form required to accompany systematic maps according to the CEE guidelines (Pullin et al. 2022).

Additional file 2: Derivations from the protocol. A list of methodological derivations from the initial protocol (Kiely and Randall 2022) along with details of additions to and subtractions from the initial coding strategy.

Additional file 3: Search metadata. Contains metadata relating to the methodology of this study. **A** search information including the search string used and date of searches. **B** Information regarding search result extraction, file format and content. **C** Screening decisions made that were not covered by the initial inclusion criteria set out in the published protocol. **D** Consistency checking meta data including the Kohen's Kappa coefficient at each stage. **E** Coding decisions made that were not covered by the coding tool set out in the published protocol.

Additional file 4: Inclusion criteria. A detailed breakdown of the inclusion criteria.

Additional file 5: Searchable database. The systematic map produced from this research. A searchable database containing three sheets. A data dictionary, bibliographic information about all papers included in the study, and the datapoints extracted from each paper according to the coding tool.

Additional file 6: Papers excluded at full text. A full list of all papers excluded at full text screening and the corresponding reasons for exclusion.

Additional file 7: Heatmaps. Contains pivot tables created from the searchable database and the heatmaps they produced.

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Author contributions
The primary question and research objectives were conceptualised by CK. NR proposed the systematic map approach, helped in defining the PICO terms and discussed, guided, and reviewed the study design, methodology and analysis. CK drafted the initial protocol, performed the research, and wrote the final manuscript. MK-D performed the consistency checking for both the screening and coding. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets supporting the conclusions of this article are included within the published article (and its additional files). All methodological details are set out in full, including development of the search string and scoping study, in the published, peer-reviewed a priori protocol (Kiely and Randall 2022).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Certis Europe have given consent for publication.

Competing interests
The authors declare that they have no competing interests.

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